LOAD TRANSFER MECHANISM IN PUNCHED METAL PLATE TIMBER CONNECTIONS

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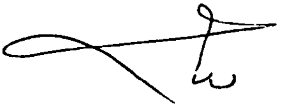
DECLARATION

No portion of the work referred to in this thesis has been submitted in support of an application for another degree or qualification of this or any other university or institute of learning



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ABSTRACT

The load capacity of the punched metal plate timber joints is established, in general, by empirical means as a result of destructive testing in accordance with relevant national standards. The basis of tests is tensile or compressive loading applied parallel and perpendicular to the grain of the timber. In general, the design-analyses of trusses are based on the assumption that joints behave as pins due to the concentration of fasteners in a small area limiting the moment arm.

A number of testing methods and apparatus were developed to determine the behaviour of the punched metal plate timber joints under different types of loading (tension, compression and moment). A combined programme of experimental and analytical work was carried out to evaluate the semi-rigid characteristics of the punched metal plate timber joints with respect to the level of translation and rotational rigidity under short term loading. The effects of different parameters such as load and deformation rates, number and length of bites, thickness of the plates and the orientation of the plates and timber grains were considered. The load-displacement and moment-rotation characteristics were studied and empirical models were developed to simulate displacements up to failure loads.

The study results show that the strength and stiffness of the joints can be expressed in terms of connector parameters. Increasing deformation rate, number of bites, length of bites, thickness of the plates and decreasing plate and grain orientations would increase the strength and stiffness of the joints. Also, the results show that the punched metal plate connections can possess a considerable moment capacity.

A statistical technique was used to classify the level of importance of parameters such as number of bites, length of bites and grain direction on the performance of the punched metal plate timber joints. All the specimens were tested under both tension and compression loads up to failure. From the tests and analysis carried out it was found that the grain direction had significant effect on the performance of the joints under tensile loading and the effectiveness of the grain direction was less when joints were subjected to compressive loading. There was a strong indication that the effect of the number of bites was dominant when joints were subjected to compressive loading.

A design flowchart for punched metal plate timber joints is provided incorporating the research findings into a design/analysis process.

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PUBLICATIONS

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CHAPTER ONE

INTRODUCTION

1. INTRODUCTION

1.1 Timber as a structural material

Timber is one of the oldest known materials used in construction, it was probably the first construction material used by man. Timber was used extensively for buildings during the second-world war to fulfill the various needs of the military, which required building with large open floor space. Thus, long-span timber trusses were the main structural systems used. These structures required long timbers with large cross sections. Connection in these trusses were not achieved using bolts alone, timber connectors such as split rings, and shear plates were used, [Halloran, 1992; Quenneville and Charron, 1994,1996; Cheng, 1991; Quenneville et al., 1993; Jackson and Dhir, 1988; Somayaji, 2001].

Timber is a cellular, brittle anisotropic material, it has different strength properties when loaded in different directions e.g. parallel or perpendicular to the grain and when loaded in tension it produces sudden brittle failure. Timber engineering today is a growth industry and much of this expansion has been made possible by the developments that have taken place in timber jointing. The revolution in house roofing has taken place with the development of the trussed rafter and the innovatory truss connector plates, [Mercer, 1982; Mamlouk and Zaniewski, 1999].

The behaviour of wood structures is very complex because of non- linearity, sensitivity to creep, biological degradation, and variability of the material and connections. Therefore, accurate analysis of wood structures call for an applications of sophisticated procedures, especially when evaluating ultimate load and deflections at over-load conditions. [The sub-committee on wood research, 1986]. The behaviour of wood members in a load-carrying system depends on the material properties of wood and on the connection between the members. The serviceability and the durability of a structural system depend mainly on the design of the joints between the elements.

1.2 Timber roof trusses

Trussed rafters have been used in United Kingdom since the later half of the 1960s. They have been used mainly for roofs of domestic buildings but increasing use is being made of them for larger buildings such as schools, institutional buildings and industrial premises, [Mayo et al., 1983; Ransom, 1979].

Timber engineering today is a growth industry and, therefore, much of the recent expansion has been made possible by the developments that have taken place in timber trusses. Conventionally, connecting the joints in these timber trusses are made by the use of bolts, split rings or shear plates. The revolution in house roofing has taken place with the development of the trussed rafter and the innovatory truss connector plates, [Mercer, 1982].

The invention of the punched metal plate fasteners (PMPF's) in the USA in mid 1950's brought about the ability to make strong / stiff in-plane connections which were as strong as the timber members being joined. The benefits of the prefabrication and material efficiency led to rapid penetration into the domestic roof market, [Whale, 1991].

The traditional use of nail plates has been in the fabrication of roof trusses and so successful has it been that an industry has developed based on that application. This industry is well established worldwide and features sophisticated analysis and design computer packages and highly automated fabrication processes. The output of these process is a reliable precision product of high uniform quality, [William, 1994].

1.3 Timber connections

Assembling of building structure with timber members involves great amount of joining and connecting, this assemblage is typically achieved by use of various types of connecting devices, called fasteners which vary with regard to the form of the connected members. Joints often are the weakest link in timber structures. A joint is an assembly of two or more structural elements which transfer shear, axial (compression or tension) loads and moments from one member to another. There are several joint types used for timber structures, most of them mechanical, which allow on-site installation regardless of environmental conditions. The serviceability and the durability of timber structures depend mainly on the design of the joints between the elements. The selection of fasteners is not only controlled by the loading and the load-carrying capacity condition but also includes some construction consideration such as aesthetics, the cost efficiency of the structure and the fabrication process. The erection method and the preference of the designer or the architect are also involved. The simpler the joint and the fewer the fasteners, the better is the structural results, [Natterer, 1992; Racher, 1995a].

Joints are often the most critical components of any engineered structure and can govern the overall strength, serviceability, durability, and fire resistance, [Smith and Foliente, 2002]. All the engineering design spent on getting the right truss member sizes and spans may be for naught, because if the buildings are subjected to extreme loads, the joints could fail and the building will be severely damaged. This can happen due to less concern about the design of connections. On the other hand, the opposite might happen. Having too stiff and very strong joints might lead to the fact that timber members would fail to hold due to their brittlness. Unlike steel, timber failure is inherently brittle and can lead to catastrophic system failure. Although it is not a regular habit, it is quite possible to design ductile connections, [Madsen, 1998; Rodd, 1998]. Therefore, a balance must be considered between the behaviour of both the members and the joints when designing for such structures. This leads to the importance of doing detailed study of joint connectors.

The traditional mechanical fasteners are divided into two groups depending on how they transfer the forces between the connected members. The main group corresponds to the dowel type fasteners. Here, the load transfer involves both the bending behaviour of the dowel and the bearing and shear stresses in the timber along the shank of the dowel. Staples, nails, screws, bolts and dowels belong to this group. The second type includes fasteners such as split-rings, shear-plates, and punched metal plates in which the load transmission is primarily achieved by a large bearing area at the surface of the members, [Racher, 1995; Kermani, 1999].

1.3.1 The Punched Metal Plate Timber Fasteners

The punched metal plate timber fasteners (PMPTFs) are now available in a wide variety of sizes and types from several different manufacturers in the United Kingdom as well as other countries. They are manufactured from pre-galvanised mild steel or stainless steel strips. A punched metal plate fastener is defined in prEN1075 " Timber structures - test methods – joints made of punched metal plate fasteners" as a fastener made of metal plate of nominal thickness not less than 0.9mm and not more than 2.5mm, having integral projections punched out in one direction and bent perpendicular to the base of the metal plate, being used to join two or more pieces of timber of the same thickness in the same plane.

Punched metal plate fasteners are suited to factory prefabrication and are able to transfer member forces with smaller connection areas than are possible with hand-nailed plates. They are widely used for light-framed timber trussed rafters and also for in-plane joints in other components. Such components are handled with care since the joints are flexible out-of plane and can be damaged during erection. Guidance on handling is contained in BS5268 Part 3 and in prEN 1059. Load is transferred in punched metal plate fasteners from the timber member into plate teeth, then from the teeth into steel plate and across the joint interface, then back down into the teeth in the other member. Joints are designed and fabricated with pairs of plates on opposite faces of the member, [TRADA, 1996].

The strength and stiffness of the punched metal plate timber joints depends on several parameters, some of which are related to timber properties such as (wood species, geometry of wood, moisture contents, and wood density). Other parameters are related to the plate properties such as (plate size, plate thickness, number of bites, length of bites and plate direction). Also loading properties such as load rate, deformation rate, direction of load, type of load, duration of load may influence the strength/stiffness characteristics of a timber structure, [Quaile and Keenan 1979; Lau 1977,1987; Suddarth et al. 1979; Wigh 1977; Wilson 1978; Kirk et al. 1989].

In the UK, there are mainly four system owners, namely, in alphabetic order, Gang-Nail, MiTek, Trusswal / Twinaplate and Wolf. The largest proportion of the UK market is supplied by MiTek and Gang-Nail. MiTek owns both the Hydro-Air and Bevplate trade names, Trusswal and Twinaplate have recently merged. The system owners supply the firms they license with connector plates, computer software and general advice on manufacturing methods, [Bellamy, 1994].

1.4 Timber design codes

In the United Kingdom timber design is currently going through a major period of change as a result of the introduction of EC5 and BS5268: Part 1, both limit state design codes rather than the permissible stress approach used by BS 5268: Part 2. In anticipation of the introduction of the new codes the Timber Research and Development Association (TRADA) conducted a review of design practice for timber joints and established research data that was needed to support joint design to the new EC5 design code. The review highlighted the general lack of joint embedment response data available which is needed to facilitate joint design to EC5 [Larsen, 1992; Claisse and Davis, 1998].

Joints have proved to be the biggest stumbling block in design and therefore, have been the subject of many and varied researches. One reason is that the behaviour of the joints is not fully understood.

The load capacity of the punched metal plate is established, in general, by empirical means as result of destructive testing in accordance with relevant national standards. The basis of tests is tensile or compressive loading applied parallel and perpendicular to the grain of the timber. Most national codes do not even detail information on shear tests. In general the design-analyses of trusses are based on the assumption that joints behave as pins due to the concentration of fasteners in a small area limiting the moment arm. At present time connections are assumed either rigid or pinned. In either of these two conditions, the forces obtained are unreliable and do not represent the actual structural behaviour. Design under either of the two assumptions are also inefficient and lead to over design or under design members. The actual behaviour of many connections is a partially rigid condition.

This research concentrates on the behaviour of punched metal plate timber connections under different types of loads. Moreover, study of the characteristics of these plates would lead to better understanding of their behaviour when tested accordingly. Also, empirical models are always desired to facilitate the stiffness and strength prediction of the connected joints.

1.5 Research objectives

The overall objective of this research programme was to investigate the behaviour of the punched metal plate timber connections, and to examine some of the main factors affecting connection performance. The objectives of this research programme were as follows.

1- To review all research effort on the subject to date.

2- To develop simple repeatable test methods and apparatus for testing the punched metal plate timber joints, subjected to tension, compression and moment forces.

3- To characterize factors that influences the load-carrying capacity and performance of the punched metal plate timber fasteners and to classify the level of importance of these factors.

4- To evaluate the semi-rigid characteristics of the connections and the influence of connection rigidities on the structural behaviour and performance of truss/frame systems.

5- To assess the influence of change in deformation and loading rates on the strength and stiffness of punched metal plate timber connections.

6- To develop empirical models that simulate the moment anchorage capacity, the load-deformation and moment-rotation characteristics of punched metal plate timber connections in timber structures.

7- To provide a design flowchart for the punched metal plate timber joints and to fulfil the short-comings in the design codes.

1.6 Contents of the thesis

This thesis consists of 9 chapters. Chapter 1 gives an introduction to the thesis; general background to the subject and research objectives.

Chapter 2 details a review of the general research work carried out on timber joint structures. Particular attention was made to the structural behaviour of the punched metal plate timber connections.

Chapter 3 describes the details of the laboratory work and testing needed to be carried out in order to investigate the behaviour of the punched metal plate timber joints. This chapter includes testing program and methodology of tests on joints subjected to tension, compression and moment loads. Also, it describes the different parameters that were tested.

Chapter 4 describes a series of tests carried out on timber joints made with punched metal plate timber fasteners in which the load was applied parallel to the grain of the timber. The specimens were loaded to failure both in tension and compression, in order to determine the influences of deformation and loading rates on the behaviour of the joints. Empirical models describing the stiffness of the joint when load is applied at different deformation rates are presented.

Chapter 5 provides details of the experimental work investigating load-displacement characteristics of the joints subjected to tensile loads, in which the effects of different parameters such as number of bites, length of bites, plate thickness and grain directions were considered. Empirical models were established to calculate the stiffness of the joints based on load-displacement relationships. These models have been compared with the experimental results.

Chapter 6 is similar to the previous chapter in terms of structure. However, this time joints were subjected to compression loads instead of tensile loads.

Chapter 7 investigates factors influencing the behaviour of the punched metal plate timber joints, a statistical technique was used to classify the level of importance of these factors on the performance of the joints. In addition, this chapter presents a comparison of the stiffness of the joints in relation to the grain direction between the empirical models developed in chapter 5 and 6 and the procedure described by previous research. Also, this chapter describes the effects of the teeth directions on the performance of the joints.

Chapter 8 describes details of the experimental work investigating the moment-rotation characteristics of the joints, using punched metal plates with different parameters such as number of bites, length of bites, plate thickness and grain directions. Empirical models that calculate the rotational stiffness based on moment-rotation relationships were developed. The models vary according to grain direction or plate parameters involved in the equation. Also, an empirical model that calculates the moment anchorage stress of the plate was developed. These models have been compared with the experimental results.

Chapter 9 outlines a summary of the conclusions and recommendations for future research.

CHAPTER TWO

LITERATURE REVIEW

2. LITERATURE REVIEW

2.1 INTRODUCTION

The load transfer mechanisms in timber trusses and the semi-rigid characteristics of the timber connections have appeared in the literature in the past. The semi-rigid behaviour of the punched metal plate timber joints depend on several parameters, some of which are the wood species, geometry, moisture contents, and the interlayer gap in the joint members. In this chapter, an overview of the research work carried out on the structural behaviour of punched metal plate timber joints is made. Various factors affecting the behaviour of the timber joints, in particular punched metal plate timber joints are discussed. Commonly used mechanical joints and use of a high performance jointing system are detailed in section 2.2. In section 2.3, a description of the uses, design, and manufacture of trussed rafters are investigated, as well as their behaviour and structural characteristics. The background related to the development of the mechanical timber joints codes such as Eurocode 5 and the British standard BS 5268 is given in section 2.4. The future development, recommended design procedure, and review of design practice are also discussed in this section. The analysis of anchorage moment capacity of mechanical timber joints is presented in section 2.5. The load-displacement characteristics of timber joints as appeared in the literature are discussed in section 2.6. The overall behaviour of the load and moment capacity of the mechanical timber joints is presented in section 2.7. Reviews of the efforts on the strength and stiffness behaviour of timber joints are described in section 2.8. Section 2.9 summarises the duration and rate of loading effects under short and long duration loading. Section 2.10 describes the research efforts on the effects of the number of nails and size of the joints. Section 2.11 details the grain direction effects on the performance of the joints. Finally, a brief summary of this chapter is given in section 2.12.

2.2 CONNECTION SYSTEMS

Timber connectors have been in use for over a century and more than 60 different types were patented in Europe and the United States prior to 1930. The first connector patented in the United States was in 1889 and it was a toothed metal plate [Thomas, 1982 ; Faherty, 1995].

Development of timber connectors occurred more rapidly in Europe, primarily the result of the need to use wood for many new tasks related to world war I. Development in the United States occurred during the thirties and was greatly accelerated as the result of the need for many structures during world war II where over one billion square feet of new structures were built in the first six months of 1942. Many of these structures used a trussed roof system and the members of the truss were joined by timber connectors, such as split rings [Faherty, 1995].

The use of a high performance jointing system has the potential to achieve substantial reductions in the volume of timber used in conventional structures such as roof trusses. A number of different jointing systems exist for large timber structures ranging from laterally loaded dowel-types to a range of timber connectors and those employing structural adhesives [Claisse and Davis, 1998].

The use of timber in the construction industry has been hampered by the weakness of the jointing system used. It is clear that, as the structural capabilities of modem timber products become more widely realised, high performance connection systems must be available to facilitate the exploitation of these materials. The use of traditional connections such as bolts and nails in conjunction with steel plates in an exposed fashion can result in very unsightly, bulky and inefficient connections in larger structures. The type of fastener used with a timber connector in a joint has an effect on the capacity of the joint. When a lag screw is used in place of a bolt, a reduction in the design value may be appropriate. This is dependent on the specific gravity of the wood and the diameters of penetration of the lag screw into the member holding the point of the lag screw. As the length of penetration of the lag screw decreases below a certain length, the stiffness of the joint decreases.

Timber joints can be categorized as those made with dowel-type fasteners, and surface connections [Madsen, 1998]. The traditional mechanical fasteners are divided into two groups depending on how they transfer the forces between the connected members. The main group corresponds to the dowel type fasteners. Here, the load transfer involves both the bending behaviour of the dowel, bearing, and shear stresses in the timber along the shank of the dowel. Staples, nails, screws, bolts and dowels belong to this group. The second type includes fasteners such as split-rings, shear-plates, and punched metal plates in which the load transmission is primarily achieved by a large bearing area at the surface of the members [Racher, 1995a]. Examples of mechanical fasteners are shown in figure 2.1.

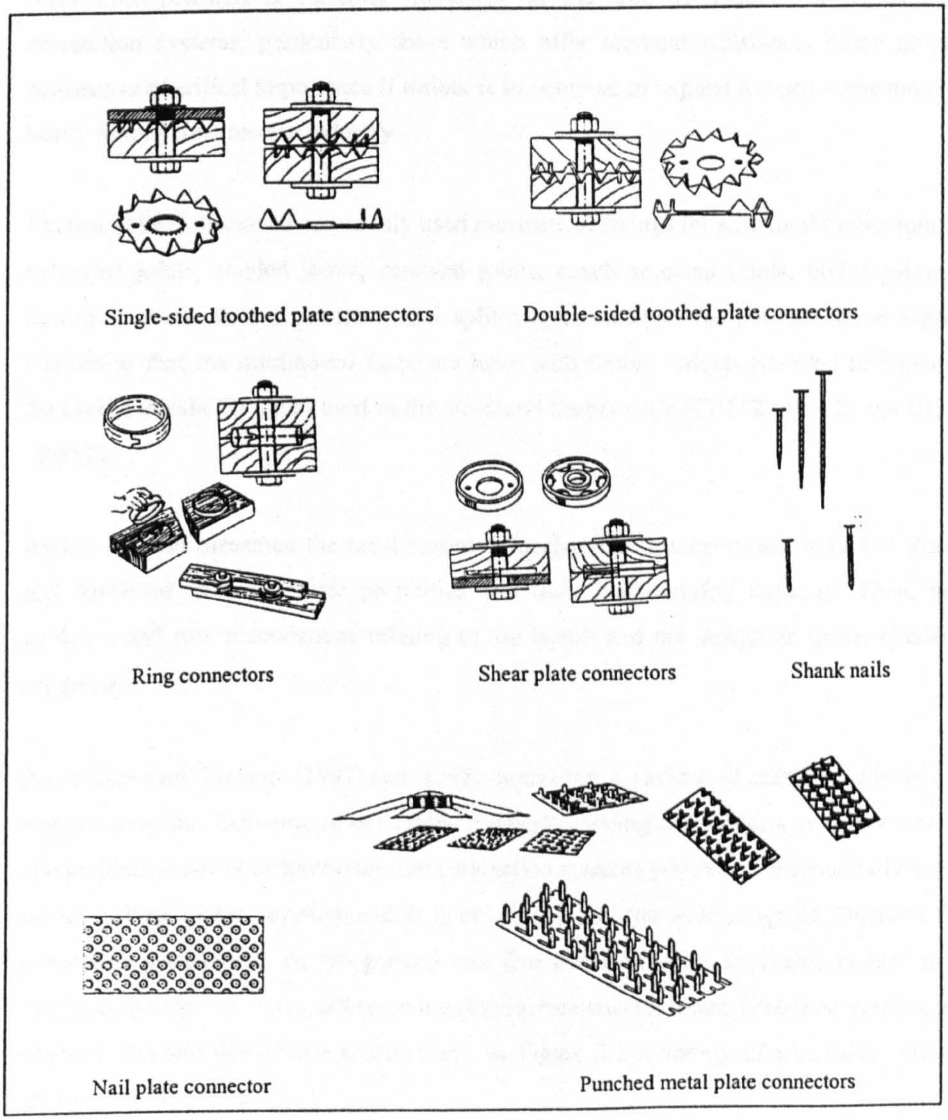


Figure 2.1 Examples of mechanical timber fasteners.

Very little research is currently underway in the area of member to member timber connection systems, particularly those which offer moment resistance. Some proprietary research is of critical importance if timber is to continue to expand its uses in the moderate to heavy timber construction industry.

Thomas (1982) discussed commonly used mechanical fixings for structural timber joints such as nailed joints, stapled joints, screwed joints, coach screwed joints, bolted joints, steel dowels, toothed plate connectors, and split-ring connectors. He outlined some aspects of interaction that the mechanical fasteners have with timber, which provided information on the basic formula (SI units) used in the structural timber code (CP112 : Part 2) and (BS 5268 : Part 2).

Racher (1995a) presented the most common mechanical fasteners used in timber structures and described fasteners basic properties and their load-carrying capacity. Then, general guidance and recommendations relating to the layout and the design of timber connections are given.

Bainbridge and Mettem (1997 and 1998) presented a review of methods which can be employed for the formation of concealed moment-resisting connections in timber structures. The review considers technologies and connection systems which are commercially available and also those under development. It is concluded that the wide range of structural timber connection systems can be categorised into five generic types : concealed bonded-in rods, concealed bonded-in plates, adhesive bonded surface contact joints, timber connectors within lapped joints and dowel-type connections. In Figure 2.2 a variety of concealed connection systems are illustrated.

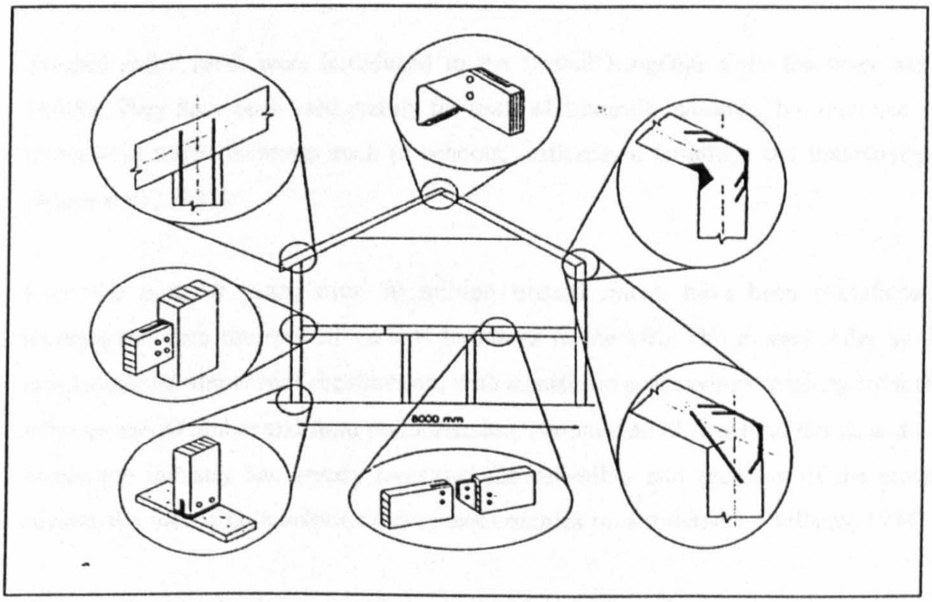


Figure 2.2 a variety of concealed connection systems.

In current timber design, member sizes are often determined by the need to have adequate section sizes for jointing. The use of a high performance jointing system has the potential to achieve substantial reductions in the volume of timber used in conventional structures such as roof trusses. Claisse and Davis (1998) tested four different jointing systems which are suitable for large timber sections (standard black bolts, split ring / shear plates, resin bonded steel dowels, and butt joints with bonded uni-axial glass (GRP) reinforcement). The results shown that the shear plates and the glass-reinforced joints offered the best performance.

The selection of fasteners is not only controlled by the loading and the load-carrying capacity conditions but also includes some construction considerations such as aethetics, the cost-efficiency of the structure and the fabrication process.

2.3 TIMBER TRUSSED RAFTERS

Trussed rafter roofs were introduced to the United Kingdom since the latter half of the 1960's. They have been used mainly for roofs of domestic buildings, but their use is on the increase in larger buildings such as schools, institutional buildings and industrial premises [Mayo et al., 1993].

Over the past 30 years, over 50 million trussed rafters have been manufactured and incorporated into the roof of various buildings in the UK. The trussed rafter system has revolutionized timber roof construction, with significant cost savings resulting from the more efficient use of timber and from prefabrication. Automation of structural design and detailing within the industry has greatly increased the reliability and accuracy of the process and permits the successful handling of evermore complex roof structures. [Bellamy, 1994]

The term "truss rafter" covers prefabricated timber roof trusses, beams and other components constructed to individual design requirements. The design of trussed rafters in the UK is covered by BS 5268 : Part 3. They are manufactured from stress-graded softwood timber with moisture content not exceeding 22% [Newton, 1985].

The use of punched metal plates in the fabrication of roof trusses has been so successful that an industry has developed on that application. This industry is established world-wide and has developed sophisticated software packages capable of designing complex engineered components. The design of trussed rafters is based on the results of extensive research and testing and on the experience gained with the use of trussed rafter roofs in the United Kingdom and other countries.

The behaviour of punched metal plate connected wood trusses can be characterized as semi-rigid. These joints allow some relative movement (axial, translation, and rotation) between the joined members in the plane of the truss due to concentric or eccentric forces in the members. Joint deformation can be responsible for a substantial proportion of the overall deformation of the structure and it often has a significant bearing on the internal force distribution.

Gupta and Gebremedhin (1990) developed a method for testing of an actual metal plate connected to wood truss joints using a truss- joint testing apparatus. The testing apparatus provided the flexibility to test different truss joints without major modifications. The three types of joints tested were the tension splice, heel, and web at the bottom chord. Load-displacement characteristics and failure modes of metal plate connected wood truss joints were presented. In-plane loads were applied to simulate the loads carried by truss members. The computerised testing apparatus and methods showed potential as an efficient testing procedure to assess joint behaviour. The failure of the heel joints was characterised as ductile, and that of the tension splice and web at the bottom chord joints as brittle. The failure of the joints was a combination of wood and teeth failure. The results were useful for semi-rigid joint analysis and design of metal plate connected wood trusses.

The trussed rafters have been designed to achieve minimum use of raw materials, maximum off-site prefabrication, reduction in erection time, care of quality control, and a sharp reduction in cost of roofing. The truss plate was developed in the mid 1950's in the USA and was used extensively there by 1960. It was introduced into UK in 1962 and, within 6 years, 80% of house roofs incorporated trussed rafter construction. There were approximately eight plate manufacturers and over 200 truss fabricators. The structural testing laboratory came to the conclusion that there was little difference in the performance of plates supplied by different manufacturers [Mercer, 1982].

Structural characteristics of the joints must be derived from full scale load tests to be used as input for improved analysis and design of trusses. Several researchers (Quaile and Keenan1979; McLain 1983; Gupta and Gebremedhin,1988; Hansen and Mortensen, 1991) have emphasized the need for testing actual truss joints to determine their structural characteristics and failure modes.

Foo (1993) investigated the behaviour of many aging and deteriorating timber Warren truss buildings built in early 1940. Sixteen full-size wooden Warren trusses were tested to failure to determine their load-carrying capacities and a total of four different joints typical of those found in a Warren truss structure were tested. The truss members were generally connected with split ring and bolt. The tests provided experimental confirmation that the repaired timber Warren truss hanger can be considered safe in withstanding specified loads, and satisfies both the strength and the serviceability requirements of the canadian building codes. Test results also indicated that gusset plate reinforcement at the joints has beneficial effects in increasing the load-carrying capacities of the trusses.

Bellamy (1994) described the design, manufacture and use of trussed rafters and discussed the interaction of structural engineers with the industry, emphasizing the importance of clear allocation of design responsibilities.

Zhong et al. (1996) provided a practical approach to model trusses and roof truss systems by using a commercially available software, ETABS. The model developed in this study takes into account the system behaviour from load sharing and composite action, the semi-rigidity of the metal-plate-connected joints, and joint eccentricity. The model was verified by comparing the predicted deflections, member internal forces, truss strengths, and the load sharing of roof systems with the full-scale experimental results available in the literature.

Vatovec et al.(1997) developed a three dimensional (3-D) finite-element joint model and several two-dimensional (2-D) joints models. A beam element based finite-element model, with different joint-stiffness assumptions (pinned, rigid, and semi-rigid), was used to analyze the full-scale behaviour of a metal-plate-connected (MPC) wood scissors truss. The truss displacement and force results were investigated for sensitivity with respect to the modeling approach. To validate the assumption that the overall truss displacement predictions from different models were realistic, the results were compared to and shown to be within 10% of the experimental results. Greater variability existed between the truss member forces and moment results, as predicted by various models, depending on the modeling approach used. The 3-D models prediction of moments at the heel joint were significantly higher than the predictions of the 2-D models. The differences in results demonstrated the importance of selecting a modeling approach capable of accurately predicting member forces and moment distributions. The 3-D model, developed primarily for detailed analysis of individual MPC joints, was successful in predicting selected displacements of the test truss. Its use demonstrated a potential for future applications of such models in the analysis and design of MPC trusses.

Li et al.(1998) investigated a practical approach to model trusses and roof truss systems using a commercially available software program, ETABS. The model developed in this study took into account the system behaviour from load sharing and composite action, the semi-rigidity of the metal plate connected joints and joint eccentricity.

2.4 TIMBER JOINTS DESIGN CODES

The design of timber joints using mechanical fasteners has changed over the years. The need for more economic structures has exercised the mind of many design engineers, and those experienced in timber engineering. The serviceability and durability of the structures depend mainly on the design of the joints between the elements [Aasheim,1995]. Figure 2.3 shows key elements needed to develop or support a design procedure for timber joints.

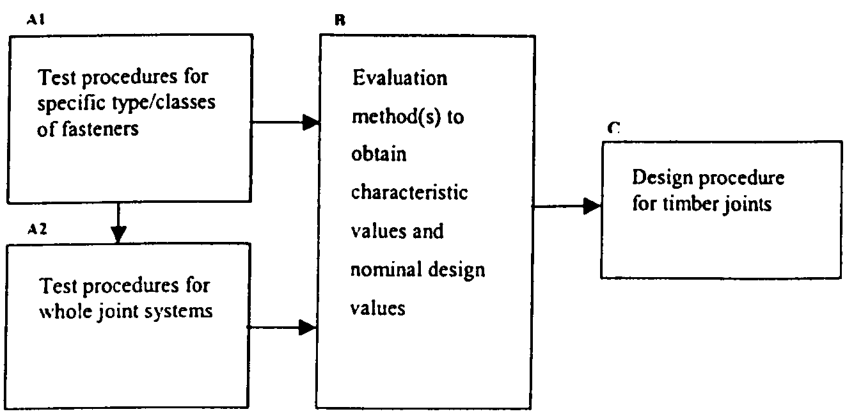


Figure 2.3 Key elements needed for joint design procedure (Smith and Foliente, 2002).

The approach to the design of timber joints in the Eurocode 5 (EC 5) differs radically from that used in British codes (BS 5268). The design philosophy in BS 5268 is based on permissible design (working stress), whereas the EC5 is based on limit state design. The approach used in BS 5268 is based on empirical data, whereas the EC5 is based on ultimate load theory developed by Johansen (1949) [Hilson and Whale, 1990].

The EC5 used Johansen's theory as the basis for the calculation of the ultimate strength of joints made from nails, staples, screws, bolts, and dowels but used simplified forms of the equations. For example, in nailed joints the code imposes lower limits on penetration depth in order to enforce a mode 3 type of failure. Therefore:

$$R = \sqrt{2.M_y.f_b.d} \qquad (2.1)$$

where

R : is the ultimate resistance per shear plane.

M_y : is the plastic moment of resistance for the fastener.

f_b : is the embedment stress

d : is the fastener diameter.

Substituting the values of f_b, M_y, f_y in equation (2.1)

$$f_b = 0.09 . \rho . d^{-0.36} \ \text{N/mm}^2 \qquad (a)$$

$$M_y = f_y . {}^{d^3}\!/_{6} \ \text{N.mm} \qquad (b)$$

and $$f_y = 50 (19 - d) \ \text{N/mm}^2 \qquad (c)$$

Equation (2.1) yields to $$R = 5.34 \sqrt{1 - \tfrac{d}{19}}.d^{1.82} \sqrt{\rho} \qquad (2.2)$$

where

ρ : is the density of the timber or sheet material kg/m^3

Equation (2.2) approximates to $R = 6.4\ d^{1.6} \sqrt{\rho}$ the form of the equation used in EC 5.

2.4.1 BS 5268 – Part 2 : 1996

The permissible load for a nailed joint is determined as the sum of the permissible loads for each nail in the joint, where each permissible nail load, F_{adm} is calculated from the equation :

$$F_{adm} = F \times K_{48} \times K_{49} \times K_{50} \qquad (2.3)$$

where

F : is the basic load for a nail.

K_{48} : is the modification factor for duration of loading.

K_{49} : is the modification factor for moisture content.

K_{50} : is the modification factor for the number of nails in each line.

For duration of loading :

K_{48} = 1 for long term loads.

K_{48} = 1.25 for tempered hardboard-to-timber joints: medium-term loads.

K_{48} = 1.40 for particleboard-to-timber joints: medium-term loads.

K_{48} = 1.12 for other than tempered hardboard-to-timber and particleboard-to-timber joints: medium-term loads.

K_{48} = 1.62 for tempered hardboard-to-timber joints: short-and very short-term loads.

K_{48} = 2.10 for particleboard-to-timber joints: short-and very short-term loads.

K_{48} = 1.25 for other than tempered hardboard-to-timber and particleboard-to timber joints: short-and very short-term loads.

For moisture content :

K_{49} = 1.00 for lateral loads in joints in service class1 and 2.

K_{49} = 0.70 for lateral loads in timber-to timber joints in service class 3.

K_{49} = 1.00 for lateral loads using annular ringed shank nails and helical threaded Shank nails in all service class conditions.

K_{49} = 1.00 for withdrawal loads in all constant service class conditions.

K_{49} = 0.25 for withdrawal loads where cyclic changes in moisture content can occur after nailing.

For the number of nails in each line :

Where a number of nails of the same diameter, acting in single or multiple shear, are symmetrically arranged in one or more lines parallel to the line of action of the load in a primarily axially loaded member in a structural framework, then :

$K_{50} = 1.0$ for $n < 10$.

$K_{50} = 0.9$ for $n \geq 10$.

Where n is the number of nails in each line. In all other loading cases, where more than one nail is used in a joint :

$K_{50} = 1.0$

The latest revisions of BS 5268 and EC 5 both provide guidance on the design of dowel-type fasteners, but are limited when designing full connections with other factors, such as the general state of stresses in the connection area, proportions of load carried by each fasteners, dowel slenderness and fabrication tolerances, needing additional assessment by the designer.

Canadian wood design standard 086.1-94 "Engineering design in wood (limit state design)" (CS 1994), provides the following equation for determination of connector strength.

$$P_r = \Phi\ P_u\ (K_D\ K_{SF}\ K_T)\, n_F (J_G\ J_C\ J_T J_O\ J_P) \qquad (2.4)$$

where

Φ : resistance factor (0.6 for timber connectors)

P_u : is the connector specified strength parallel-to-grain.

K_D : load duration factor.

K_{SF} : service condition factor for fastenings.

K_T : treatment factor.

n_F : number of fastenings.

J_G : factor for groups of fastenings.

J_C : connector configuration factor.

J_T : thickness factor.

J_O : factor for connection orientation in grain.

J_P : factor for lag screw penetration.

In anticipation of the introduction of the new codes the Timber Research and Development Association (TRADA) in England, conducted a review of design practice for timber joints and established research data that was needed to support joint design to the new EC5 design code. The review highlighted the general lack of joint embedment response data available which is needed to facilitate joint design to EC5.

Hilson and Whale (1990) summarised the background to the clauses for joints in EC5 and discussed possible future developments. They outlined the theoretical basis of the Eurocode approach and made comparisons with BS 5268. They then suggested a modified approach for future codes.

Whale (1995) highlighted some design principles appropriate to joints made with punched metal plate fasteners based on the design method given in EC5. The principal factors influencing the strength of punched metal plate fastener joints are introduced. The test method used in EC5 to establish required plate sizes for joints is based on both their anchorage strength and their net cross-sectional steel strength. Finally, some general plate dimension rules are given, along with a description of the means by which the slip of punched metal plate fastener joints can be predicted under load.

Baraldi and Junior (1996) developed test method for the new Brazilian standard for timber structures (NBR 7190/1996-Design of timber structure), to determine the strength, stiffness and to verify failure modes of timber joints made with metal plate connectors (PMC). Timber joints were subjected to shear, tension and withdraw resistance.

O'Regan et al.(1998) presented a design procedure for determining the steel net-section capacity of metal-plate connected (MPC) tension splice joints subjected to combined tension and bending. Several common wood truss splice joint configurations were tested in combined tension and bending. All of the joints tested failed in the steel net-section of the truss plates.

Three models were developed to predict the ultimate strength of the steel net-section of the splice joints tested. A design procedure for determining the allowable design capacity of the steel net-section of a splice joint subjected to combined tension and bending was developed based on the most accurate model. The recommended design procedure was then compared with two alternative design methods for checking the safe capacity of the steel net section of tension splice joints of MPC wood trusses subjected to combined tension and bending.

Reffold et al.(1999) described tests carried out on timber joints, formed with punched metal plate fasteners subjected to tension force perpendicular to the grain. The work was undertaken at the Building Research Establishment (BRE) in three phases. (1) development of a test rig and testing of full-scale girder trussed rafters.(2) development of a test rig and testing of concentrically loaded trussed rafter components. (3) development of a test rig and testing of eccentrically loaded trussed rafter components. The recently published BS 5268 Part 3 : 1998 code of practice for trussed rafter roofs contains a design formula for the first time that provides a method for establishing the adequacy of nail plate joints subject to tension forces perpendicular to the grain and is a result of the work carried out in phase (1) of this investigation. The results are presented and compared with design guidance given in the 1997 draft BS 5268 : Part 3.

The mean failure loads (F_{ult}) are compared with calculated failure loads (T_{cal}) given by the following formula from BS 5268 Part : 3

$$\sigma_{t,90,K} = K_e \left[\frac{3T}{b(w+16d)} \right] \qquad (2.5)$$

where

$\sigma_{t,90,K}$: characteristic tension stress perpendicular to the grain, taken as $1.1 \, N/mm^2$.

T : net tension force at the joint interface in the direction perpendicular to the grain (N) .

K_e : 1.0 in this instance but varies between 1.33, 2.00, and 3.00 for 2, 3 and 4 ply eccentrically loaded members respectively.

w : length of the nail plate measured parallel to the grain of the chord member (mm).

b : member thickness (mm).

d : fastener (nail plate) bite (mm).

Based on this comparison a revised design formula was presented as :

$$\sigma_{t,90,K} = T / b[w + 4.2d \times (d / 45)^{0.4}] \quad (2.6)$$

At the time of writing, BS 5268 : Part 3 : 1998 was published and the term 'b' (member thickness) was removed from the design equation. The published equation is :

$$\sigma_{t,90,adm} = K_e[\,0.06T / (w + 16d)] \quad (2.7)$$

Smith and Foliente (2002) presented a review of international practice for design of mechanical timber joints, and discussed the scope of work needed to elevate load and resistance factor design of joints so it is on a comparable to load and resistance factor design of timber members. Suggestions are made regarding actions necessary to place member and joint design on an equal footing.

2.5 MOMENT ANCHORAGE CAPACITY

The analysis of anchorage moment capacity of nail plate joints has shown that the plastic theory may be used in the calculation of anchorage stresses and in the strength verification of combined force-moment loading. The new European pre-standard for design of timber structures, Eurocode 5 (EC5) includes also the design rules for the moment capacity of nail plate joints for both the design in joint line and for the anchorage design between plate and timber member.

Kevarinmaki (1996) has presented a non-linear method to simulate the moment capacity and the rotational stiffness behaviour of nail plate joints. Over 500 punched metal plate fastener joints test results, where the failure mode was moment anchorage, were analysed with the elastic and the plastic theory methods. The anchorage capacity in moment loading was analysed and an alternative design method to that of Eurocode was presented. The problem of moment anchorage was handled in two phases : the force and moment stress distributions between plate and timber was determined first and then the anchorage strength (lateral resistance of the embedded projections) was checked for the combined force and moment anchorage stresses. The analysis methods of both of these phases may be divided to two categories : the elastic or plastic theory methods.

(1) Elastic stress:

The moment anchorage stress $\tau_{M,el,i}$ may be calculated, based on the elastic theory in the actual point (i) of the effective nail plate area, from

$$\tau_{M,el,i} = \frac{M_A r_i}{I_p} \qquad (2.8)$$

where

M_A : is the moment acting at the centroid of the effective area.

I_p : is the polar moment of inertia of the effective area.

r_i : is the distance from the centroid to the actual point of the effective area.

(2) Plastic stress:

When the moment anchorage stress τ_M is supposed to be constant according to the plastic theory in the whole area A_{ef} the stress $\tau_{M,pl}$ from moment M_A acting at the centroid of the effective area is:

$$\tau_{M,pl} = \frac{M_A}{W_p} \qquad (2.9)$$

where W_p is the plastic rotational section modulus defined as :

$$W_p = \int_{A_{ef}} r \, dA \quad \text{.......} \quad (2.10)$$

Noren (1981) presented an approximate solution of W_p for quadrilateral joint areas of nail plate surfaces :

$$W_p = \tfrac{1}{4} \, A_{ef} \, d \quad \text{.......} \quad (2.11)$$

where

d : is the diagonal length of the effective area. It may be calculated from.

$$d = \sqrt{(\tfrac{A_{ef}}{h}) + h^2} \quad \text{.......} \quad (2.12)$$

where

h : is the maximum height of the surface perpendicular to the longest side.

The rotational stiffness and the rotational capacity of nail plate joints have been verified based on the translation stiffness modulus and the ultimate slip values determined by standard axial load tests and compared with shear, eccentric tension and bending test results. Acceptable simplifications from the theoretical situation are presented for both the moment capacity and the rotational stiffness design. The result of analysis of the effect of timber to timber contact in chord splices is shown and the general simplified method to determine the force and moment components acting on the plate in both tension and compression loaded chord splices with the bending moment has been derived.

Noren (1981) presented criteria for anchorage design using the following approximation in the form :

$$\left(\frac{\tau_F}{f_{a,\alpha,\beta}}\right)^2 + \left(\frac{\tau_{M,PL}}{F_{a,0,0}}\right)^2 \leq 1 \quad \text{.......} \quad (2.13)$$

Using this criteria, no other design criteria is needed in the anchorage design. The loading direction with the nail plate (α) and with the grain direction (β) are always taken into account in term $f_{a,\alpha,\beta}$. Noren suggested that the anchorage strength in the main direction $\alpha=\beta=0°$ ($f_{a,0,0}$) would be generally a suitable maximum value for the plastic moment anchorage stress $\tau_{M,PL}$.

Kangas and Kevarinmaki (1995) have presented a comparison of the anchorage theories with 292 shear, 116 bending and 44 eccentric tension test specimens of the anchorage failure. The analysis shows that the plastic theoretical moment anchorage stress τ_M design is in better agreement with the test results and would be a better method than that based on the elastic theory as used in EC5.

Induced stresses from both direct forces and moment acting on punched metal plate area may be calculated as follows :

$$\tau_F = \frac{F_A}{A_{ef}} \qquad (2.14)$$

$$\tau_M = \frac{M_A r_{max}}{I_p} \qquad (2.15)$$

where

F_A : is the resultant direct force acting at centroid of A_{ef}.

M_A : is the total moment acting at the centroid of A_{ef}.

2.6 LOAD-DISPLACEMENT CHARACTERISTICS OF TIMBER JOINTS

Many different shapes of load-displacement relationships are produced in literature from tests on timber joints of various types. The load-displacement relationship of timber joints is influenced by factors such as geometry and material properties for the connector and the joint members, method of fabrication, environment conditions, load duration, rate of loading and other factors [Smith, 1982; Wilkinson, 1971; 1972].

The structural component of mechanical timber joints subjected to lateral loading is normally assessed with respect to their strength and displacement characteristics. This information may be obtained by type testing specific arrangements. A sufficient number of replicates should be tested to yield reliable estimates of any parameter used to define the distribution of load values corresponding to given joint displacements. Joint displacement is considered to be the relative displacement of the adjacent of a joint specimen. [Smith, 1982]

Previous load history has a significant effect upon the load-displacement relationship of a joint specimen [Stluka, (1960); Wilkinson, (1971, 1972); Mc Lain, (1975); Erki (1991)].

Analytical solution for the prediction of the load – displacement relationship for timber joints with dowel type connectors subjected to lateral loading have been presented by a number of research workers. They considered a joint as a two dimensional arrangement in the x and y plane which can be represented by a one dimensional beam on a winkler or discontinuous foundation (Hetenyi, 1939). For a winkler type foundation the force per unit length beneath the connector is taken to be directly proportional to the displacement at all points along the length of the connector. The problem reduces to the solution of the differential equation :

$$\frac{d^2M}{dx^2} = q \qquad (2.16)$$

where

M : is the bending moment.

q : is the force beneath the connector.

Foschi (1974) used a non-linear finite element model for the prediction of the load-displacement relationship for single shear nailed timber joints with lateral loading. He assumed that the nail is an ideal elastic-plastic material and that the load-deformation relationship for the foundation, which is assumed discontinuous, is of the form :

$$P = (P_0 + P_1 w) (1 - \exp (- {Kw}/{P_0})) \qquad (2.21)$$

where

w : is the nail displacement.

P_0, P_1 and K are constants

Later Foschi (1974) and Foschi and Bonac (1977) modeled the load-slip characteristics of nailed joints with predrilled steel plates, commonly used in the 1970's, by the finite-element method. Foschi et al.(1975) presented a semi-analytical, finite-element technique that predicted strength based on the failure of plate fasteners.

Smith (1983, 1988) also used the non-linear form of Foschi and Bonac (1977)'s model to describe foundation behaviour in an interactive finite-element model that included effects of bolt / wood friction, friction between wood members and fasteners. Load-displacement curves predicted by the model were good predictors (± 10%) of characteristic connection loads for displacements greater than 2 mm (0.08 in), but less accurate predictors (± 20%) for characteristics joint loads below 2mm (0.08 in). The model predicted connection load-displacement curves up to 4 mm (0.16 in).

Erki (1987) developed a model using one-dimensional finite element approximation to predict the short-term load-displacement response of a single fastener joint. The model treats the elasto-plastic behaviour of the fastener as well as the non-linear, non-elastic properties of the timber. It also accounts for some of the distinctive behaviour of timber joints such as fastener withdrawal, joint interface characteristics, and combined fastener bending and axial tension.

Richard *et al.* (1990) developed a finite-element analysis procedure applied to laterally loaded nails to give accurate load deformation relationships for a variety of nail joint details. Nonlinear nail and wood material properties from simple tests on nails and wood were used as inputs for the analysis. Analytical results for a wide range of joint details were presented. The results indicate how the basic design-code values should be modified to allow for differences in behaviour between nail plate joints with thick steel, thin steel, or plywood joint plates. The effect of factors, such as nail head size and shape as well as direction of loading with respect to the wood grain, were also considered. Finite-element analysis, with simple material tests on nails and wood as inputs, give reliable predictions of laterally loaded nail joint behaviour over the complete joint deformation range. The analyses were in agreement with the experimental tests.

Davalos and Pellicane (1992) developed a mathematical model to predict the load-deformation relationship of single-bolted connections in wood structures subjected to bending / tension loading. Analysis were made using a plane-stress, two-dimensional, orthotropic, linear-elastic finite-element model.

Ying et al.(1998) presented a non-linear finite-element model for predicting the load-slip response of a single-shear nailed timber joint under reversed cyclic loading. A comparison of test data with model predictions demonstrates the validity of the model. The presented theory can be extended to analyse timber joints containing other dowel-type fasteners.

2.7 LOAD AND MOMENT CAPACITY OF TIMBER JOINTS

In timber construction, it is customary to design the connection as simple connection, i.e. no moment resisting capacity for the connections. This causes not only the use of more timber, but also the need for a bracing system, thus reducing the competitiveness of timber in construction [Cheng, 1996; Racher, 1995b].

The behaviour of timber members in load – carrying systems is dependent on the material properties of the timber and on the connections between the members [The subcommittee on wood research, 1979]. The behaviour pattern for moment – resisting connections can be described in terms of the connection types, component arrangement and the centre of rotation relative to the components of the connection [Smith, 1982; Faherty and Williamson, 1989].

Load is transferred in a punched metal plate fastener from the timber member into the plate teeth, then from the teeth into the steel plate and across the joint interface, then back down into the teeth in the other member. Joints are designed and fabricated with pairs of plates on opposite faces of the member.

BS5268 Part 3 gives positioning rules and rules for load capacity for punched metal plate. Permissible load for use with the code were determined by testing and are given in technical approvals. EC5 includes a number of equations which predict the strength of joints based on certain key characteristic plate strength properties. These plate properties should be established from standard tests whose basis is given in pr EN 1075.

Mortensen et al. (1994) described tests and preliminary analysis of Knee joints of timber frames with mechanical fasteners in the form of nail-plate and nailed steel gussets. They presented their ongoing test program and theoretical work aiming at developing a finite element program that will predict the stiffness properties of moment resistant joints with punched metal plate fasteners (nail-plates). The moment capacity of the Knee joints were determined and rotational stiffness values applicable in the serviceability state were calculated for three different Knee joint designs using a 2-D finite element modeling. The alternative design with nail-plates resulted in an increase of the moment capacity and the rotational stiffness of the joint. It was found that future testing and more sophisticated analytical models would be needed for a better prediction of the behaviour of moment resistant joints, especially joints with nail-plate connectors.

Mauro et al. (1996) studied the moment resistance in metal-plate connectors having a semi-rigid behaviour. Experimental results were evaluated to determine the partial fixing coefficient and the rotational stiffness coefficient.

Cheng (1996) presented a new glulam rivet moment connection and its performance under monotonic and cyclic loading. Full-scale glulam butt-joint moment connections were developed and constructed using steel gusset plate and glulam rivets, and were then tested under monotonic and cyclic loading. The connections exhibited significant moment capacity and ductility under both monotonic and cyclic loading.

2.8 STRENGTH AND STIFFNESS OF TIMBER JOINTS

The strength and stiffness of timber joints, depend on several parameters some of which are the wood species, geometry, moisture content, and the interlayer gap in the joint members.

Basic data on the strength and stiffness characteristics of the punched metal plate timber joints can only be obtained from laboratory tests. Early research on the strength characteristics of timber connectors was carried out by Perkins et al. (1933), Stern (1940, 1941), Mehringer et al.(1943), Scholten (1938,1944) and Gloss(1947).

Joints are often the most critical components of any engineered structure and can govern the overall strength, serviceability, durability, and fire resistance. Assessments of timber buildings damaged after extreme wind and earthquake events often point to inadequate connection as the primary cause of damage [Folient, 1998].

The emphasis of research on timber joints focus only on strength and nobody seems to care about stiffness and ductility. This is probably due to the old allowable stress calculation method which disregards the structural behaviour at the ultimate limit state (ULS). However as the ULS method is increasingly adopted world wide, the combination of strength, stiffness and ductility are becoming all more important (Leijten and Virdi, 1996).

Mack (1966) studied the strength and stiffness of nailed joints under short duration loading, and defined their load-deformation relationship as :

$$P = K\,(A\delta + B)(1 - e^{-C\delta})^{D} \qquad (2.17)$$

where

P : is the load per nail in single shear (N) at displacement δ (mm) (for $0 < \delta < 2.54$mm).

K : is a function based on nail diameter and timber species.

A,B,C and D : are curve-fitting constants.

Later Mack (1977) modified his equation to a simpler form for joints subjected to displacements of up to 0.5 mm :

$$P = 0.19\, d^{1.75}\, \rho\, \delta^{0.46} \qquad (2.18)$$

Rodd (1973) Presented a theory for the strength of circular dowel timber joints when loaded parallel to the grain. The theory is based upon the compressive strength of timber both parallel and perpendicular to the grain and upon the coefficient of friction between the surface of the dowels and the timber. The theoretical predictions were in good agreement with the experimental tests.

Hilson (1969) developed a theory for the crushing strength of timber joints with split ring connectors when loaded parallel to the grain. The theory includes contribution from the split ring and the bolt. Hilson conducted over 100 tests on joints with 2.5 inch split rings. These tests indicated two principal modes in some joints made from thin timbers. When multiple timber connector units are placed in a joint, the failure mode was highly dependent on the spacing provided between connectors, both parallel and perpendicular to the grain. In addition, the amount of end and edge distances provided also played a significant role in the type of failure mode.

Maraghechi and Itani (1984) presented the influence of joint stiffness. A total of five specimens were tested to obtain the axial stiffness of the connection (K_1), two pieces of nominal 2×4 Douglas fir were connected by two toothed metal plates. The applied force versus joint deformation was found to be non-linear. For linear analysis, a line was fitted to the pooled data for all fir specimens using the method of least squares. The following equation was obtained :

$$P = 451.562\ \delta \qquad (2.19)$$

where

P : is the axial force in lbs.

δ : is the slip deformation in inches.

A stiffness of 451.562 lb/in was used for this plate size. The coefficient of correlation r, was 0.96 . This stiffness was used for axial tensile and compressive behaviour of the joint. It was assumed that no lateral buckling of the metal plates would occur at the loads to be imposed and that the ends of the connected members would not come to bear on one another when loaded in compression.

Later Maragechi and Itani (1984) tested tension splice joints in pure axial tension, pure shear, and pure bending to obtain the stiffness of the joints. They reported that the axial and rotational stiffness of a joint have an appreciable influence on the members end forces, while shear forces have little effect. Lau (1987) obtained the strength and stiffness value for heel joints from actual tests to use in a computer program for analysis of timber frames.

Vatovec et al.(1996) tested five different types of metal plates connected to timber joints (MPC) from a scissors truss to evaluate their behaviour. All joints were tested in a unique testing apparatus where in-plane loads along with moments were applied to simulate loads carried by the truss members. Strength, stiffness and failure modes for bottom chord splice joints at web (BSJ), heel joints (HJ), crown joints (CJ), bottom chord ridge joints (BRT), and top chord splice joints at web (TSJ) were reported. The average strengths of BSJ, HJ, CJ, BRJ, and TSJ were 51200 N, 49800 N, 33000 N, 52300 N, and 43100 N, respectively. The average values of the rotational stiffness were 245440 kNmm/rad, 249600 kNmm/rad, 103700 kNmm/rad, and 33800 kNmm/rad for BSJ, HJ, BRJ, and TSJ, respectively. Average transitional stiffness values were 61.7 kN/mm for BSJ, 29.2 kN/mm for HJ, and 40.2 kN/mm for BRJ. The majority of bottom chord joints failed in plate tearing, whereas top chord joints generally failed in web member withdrawal mode. The joint stiffness data were used in preliminary finite element analysis of the same truss, and the analytical results compared well to actual full-scale test results.

2.9 THE EFFECTS OF DURATION AND LOADING RATE

The duration and rate of loading are parameters that significantly influence the joint behaviour. The evaluation of this effect is of interest to those dealing with test procedures and the design of the punched metal plate joints subjected to dynamic loads, e.g. impact and impulsive loading. The effect of load duration is a well-known phenomenon in wood. This effect is expressed in the so-called Madison curve, [Girhammar and Andersson, 1988].

Timber experiences a significant loss of strength over a period of time. The strength value to be used in design of timber members for long-term permanent load are approximately only 60% of the strength values found in a short-term laboratory test. The background to this 0.6

modification factor dates back to the 1940's when duration of load experiments were carried out at the forest products laboratory in Madison, Wisconsin, U.S. [Wood 1947,1951].

The first attempt of modern times to quantify load-duration effects in timber was made by Wood (1951). Wood's model, sometimes referred to as the Madison curve, is the basis for the load-duration factors prescribed in the national design specification for timber construction in U.S.(1991). The relationship, termed the "Madison curve", is illustrated in Figure 2.4 and is a plot of stress ratio against logarithmic time to failure load. Since that time, a significant amount of work has been conducted on modelling the time-dependent strength behaviour of structural timber. Several different types of models have been developed including damage accumulation, fracture mechanics, and strain energy models. Currently, damage accumulation models are the more popular approach to predicting load-duration effects.

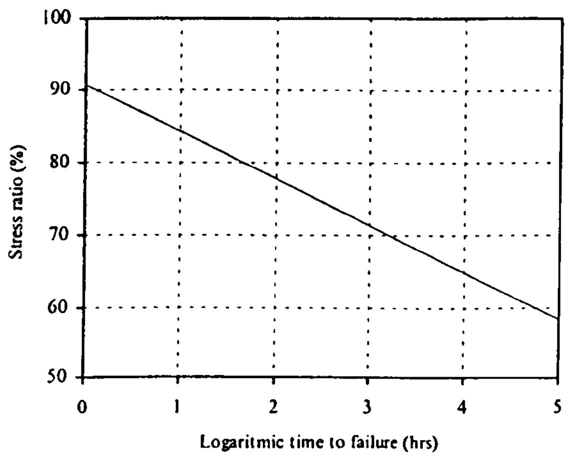


Figure 2.4 Stress ratio (%) as a function of logarithmic time to failure (hours) for small clear specimens subjected to bending (Wood, 1951).

To date, there has been no comprehensive or conclusive treatment of timber effects in timber connections. Although some experimental work in this area has been conducted in the United States, the majority of the recent work appears to have been conducted in Europe and Japan. Rosowsky (1992) collected the available fatigue data on various timber connections and considered, in a preliminary way, the concept of duration of load effect for connections. In addition, the applicability of current damage accumulation models for lumber subjected to fluctuating load such as wind and earthquake was investigated. It was shown that for timber members to fail under these types of loads in a reasonably assumed duration, the load magnitudes would have to be many times greater than that for which the member was designed. Therefore, the issue of load-duration when considering transient fluctuating loads, should be treated in the design of the connections, rather than the members. Rosowsky and Fridley (1995) summarized the researches up to date which discussed the effects of the duration of loads on the timber joints.

Kuilen (1995) provided background information on the influence of load- duration on the long-term load-carrying capacity and deformation behaviour of timber joints with mechanical fasteners. Furthermore, the effect of load level on the long-term capacity of joints made with nails, toothed-plate and split-ring connectors is shown. Two examples are includes, one showing the effect of load level on the long-term load-carrying capacity and another on the long-term deformation. Test results are compared with the design rules given in EC5. It is concluded that the influence of long-term loading on the load-carrying capacity of timber joints appear to be in the same order of magnitude as for timber members.

Nielsen and Kousholt (1980) presented a load-duration strength model for timber based on viscoelastic fracture mechanics. The fracture mechanics model developed by Nielsen and Kousholt was reviewed and presented again by Johns and Madsen (1982) with particular reference to full-size lumber. Fridley et al. (1992) developed a strain energy model to predict load-duration effects in timber.

Extensive studies of load duration effects for long-term loading have been carried out and some are underway [e.g., Barrett and Foschi, 1978a, b; Fewell, 1986; Gerhards, 1986; Madsen, 1986; Karacabeyli, 1988; and Rosowsky and Ellingwood, 1991].Very few, if any, studies have been made of this effect for very short-term loading. Girhammar and Andersson

(1988) addressed the loading or deformation rate effect on the yield loads of nailed timber joints. Four different types of joints, which differed with respect to the thickness of the member and the angle of load to grain, were tested. The bearing strength of the wood and the bending strength of the nails were also tested in order to analytically verify the dynamic ultimate capacity of the joints. All tests were run with deformation rates from static loading values up to approximately 1m/s. The pilot study results show that the strength of the nailed joints can be expressed in terms of the deformation rate. A logarithmic expression for the strength of the joints was obtained from regression analysis of approximately 200 results. The values obtained analytically agreed well with the experimental ones for the various joints tested.

Various models have been developed to predict load-duration effects. Many of these models have been used to develop time-effect factors for design. Rosowsky and Reinhold (1999) presented the results from a test program that attempts to quantify rate of load and short term duration of load effects for timber fasteners such as nails and screws subjected to withdrawal or lateral loads .The result from this preliminary study suggests that no obvious rate-of-loading effects exists for nailed connections subjected to either lateral or withdrawal loading. This has particular significance, for example, in the design of roof sheathing systems and roof to wall connections to resist high-wind uplift loads. Although, this study by no means provides a complete treatment of the topic of the duration of load effects in fasteners, it serves to highlight differences between connection and timber member time effects. It has been suggested that duration of load effects in connections differ substantially from those in timber members and that the factors developed using a cumulative damage model based on tests of timber members in bending (i.e. creep rupture) are not appropriate for the design of connections.

2.10 EFFECT OF NUMBER AND CONNECTORS SIZE

The size and type of timber connector plays a significant role in the magnitude of the design value. For example, a 6 to15 mm shear plate has less bearing area than a 100 mm shear plate. Therefore, assuming factors other than size do not control the design value of the 6 to 15 mm shear plate, it is considerably less than the value for the 100 mm shear plate. The effect of size and type of timber connector are included in design by providing separate design values for each size and type [Faherty, 1995; Erki and Huggins, 1983]. Sheppard (1969) tested heel joints and compared six different sizes of metal-plates. He reported that the most common mode of failure was teeth withdrawal.

Cramer *et al.* (1990) presented a model for the tensile and bending analysis of metal plate-connected wood-splice joints. The model employed a non-linear, plane stress finite element formulation to allow computation of the internal deformations, stress conditions, and ultimate strength for these joints. The individual stiffness contribution of the wood in the contact area, the steel plate, and the tooth-wood interface were considered in the analysis. Application of the model showed a strong plate size effect in the lateral load resistance of plates computed in the standard manner on a per-tooth basis. The theoretical mechanical behavior associated with the size effect was also presented. The work also showed that current design assumptions represent a realistic approximation of the behavior for relatively small plate connections, but unrealistic for connections involving larger plates. As a result, the technique may be useful for refining the design procedure of longer span trusses containing larger metal-plate connectors. The ability to model bending behaviour and assess the effect of gap closure between members was included.

Leslie and Polensek (1992) developed a theoretical model predicting mechanisms of load transfer between a wood member and a metal die-punched truss plate. The model, which treats a truss-plate tooth as a beam on an inelastic foundation of wood and applies Runge-Kutta numerical analysis to solve the governing differential equations, predicts the load-displacement trace and ultimate load of truss-plate joints. The model was verified with eight truss-plate joint types, three of which varied the number of teeth, and five, the plate and grain angle. Theoretical and experimental load-displacement traces showed good agreement.

Rodd (1995) described the effect of plate size on the maximum strength per nail of punched metal plate timber fasteners (PMPTF's). A series of tests (three different widths of three different lengths of plates were used in each set of tests) were carried out on timber joints made with punched metal plate timber fasteners (PMPTF's) in which the load was applied perpendicular to the grain of the timber to investigate that the size of plate used in basic tests of this type influences the results obtained. The results have implications for those involved in drafting the standards intended to control such tests and raise issues for truss designers concerning the use of different size of plates in this particular load to grain orientation.

The choice of plate width and length can have a large effect on the maximum load per nail value obtained from punched metal plate timber joint tests. The values are likely to be much higher if obtained from the use of narrow plates with long embedded length than if obtained from the use of wide plates with short embedded lengths [Rodd, 1995].

O'Regan et al.(1998) presented a design procedure for determining the required plate length to prevent lateral-resistance (tooth-withdrawal) failure of a metal-plate-connected (MPC) tension splice joint using a truss plate with the calculated minimum required length. This was to ensure that the joint would fail in the steel net-section, where the bending moment present at the joint were explicitly included in the design. In addition to the recommended procedure, a simple rule-of-thumb is given that will yield a conservative value of the required plate length.

Kermani and Goh (1998) evaluated the semi-rigid characteristics of nailed timber joints, with respect to the level of translation and rotational rigidities under short and medium term loading. Their work details experimental and analytical study investigating the load-carrying characteristics of multi-nailed joints under short duration lateral loading in which the effects of different nailing configurations and components subjected to shear were considered. The effects of connection rigidity were examined by increasing the number of nails in the joint from one per side up to the maximum allowable number of nails for a predetermined joint size, and also by varying their positions with respect to the centre of geometry of the nail group. A total of 700 connection specimens were tested and their load-deformation characteristics were studied. A model was developed to simulate the load-deformation characteristics of multi nailed timber connections up to failure. Comparisons were presented between design solutions produced by applying this research and those available in the literature, and also using EC 5 design rules.

They presented a model to simulate the non-linear load-deformation behaviour of the multi-nailed timber connections subjected to single shear using the following general formula expressing the load function :

$$F = A\, f_1(N)\, f_2(S)\, f_3(\beta)\, f_4(\delta)\, f_5(t)\, f_6(E\nu) \quad \ldots\ldots \quad (2.20)$$

where

F : is the load carried by a multi-nailed timber joint.

A : is a curve-fitting constant.

$f_1(N)$: is a nail function.

$f_2(S)$: is a timber species function.

$f_3(\beta)$: is a gusset plates function.

$f_4(\delta)$: is a displacement function.

$f_5(t)$: is a time function (the duration of applied load).

$f_6(E\nu)$: is an environmental function.

2.11 Effect of grain direction

Grain refers to the general arrangement of the vertically aligned cells, it is the longitudinal direction of the main elements of timber, these main element being fibres or tracheids, and vessels in the case of hard wood. Timber is anisotropic material, its strength properties are heavily dependent on the orientation of stress in relation to the grain directions. Timber is much stronger in compression parallel to the grain than in compression perpendicular to the grain [Illston et al., 1979, 1987; Taylor, 1991; Smith and Ronald, 1979, Illston, 1996; Kermani, 1999].

The strength properties in any direction to the grain can be approximated using Hankinson formula as follows:

$$N = \frac{PQ}{P\sin^2\theta + Q\cos^2\theta} \quad (2.21)$$

where

N : is the strength in compression at an angle θ of load to grain.

P : is the strength in compression parallel to the grain.

Q : is the strength in compression perpendicular to the grain.

The strength of timber is high when loaded parallel to the grain, whereas perpendicular to the grain the strength properties are low. The tension strength of timber parallel to the grain is about 40 times greater than the tension strength perpendicular to the grain [Steer P.J., 1995].

Freas and Scholten (1946) investigated the effect that angle of load to grain has on the strength of shear plates. It was found that the variation in joint strength with the angle of load to grain corresponded, at both the maximum and proportional limit loads, with the Hankinson formula. However, for loads at a slip of 0.1mm or less, the variation is linear.

Foschi (1977) developed a model based on Hankinson equation (2.21), predicting the relation between punched metal plate timber joint stiffness to plate orientation with respect to grain direction of the timber member and the load direction.

Edlund (1995) described the strength and stiffness of timber loaded in tension and compression at different angle to the grain under short-term loading. It is concluded that the tensile strength is larger than the compressive strength and the lowest strength for timber is in tension perpendicular to the grain. He compared the results obtained with Hankinson equation (2.21), which gives good agreement with test results.

Kermani (1996) investigated the influence of grain direction on in-plane strength properties of plywood. An extensive experimental programme were made to determine the tensile, compressive, bending and shear strength properties of the plywoods with respect to their grain orientations. A semi-empirical equation based on Hankinson's formula was developed which permits the calculation of the strength properties of plywoods with respect to their face-grain orientations. It was found that plywood grain orientation has considerable influence on strength and stiffness of the joints.

Reffold et al. (1999) observed that, joints where the nail plate direction is parallel to the grain of the chord member performed better than joints where the nail plate was oriented perpendicular to the grain of the chord member.

2.12 SUMMARY

In recent years, rising costs of structural materials and the need for more efficient use of timber resources has increased the necessity for timber components to be more light-weight and more material efficient. With a better understanding of material properties and joint load carrying characteristics, the size of components can be streamlined, hence reducing the cost of raw materials and increasing the efficiency of the connections.

Timber engineering today is a growing industry and much of this expansion has been made possible by the developments that have taken place in timber jointing. It is clear from the literature that much research has been carried out to understand and predict the behaviour of mechanical timber joints.

The semi-rigid behaviour of mechanical timber joints is complex and depends on several parameters such as type and system of joints, the load and deformation rate, the duration of load, the number of fasteners, the size of the plate, connection orientation and grains directions, and connection configuration factors. The types of connectors and their material properties can influence the load-displacement characteristics, the load carrying capacity, the moment carrying capacity, as well as the strength and stiffness of the joints.

The design philosophy in BS 5268 is based on permissible stress design, whereas the EC5 is limit state design philosophy is based on limit states theory developed by Johansen (1949). Design of punched metal plate timber joints are not yet fully covered in EC5 and BS 5268. The basic data on the strength and stiffness characteristics of the punched metal plate connectors can only be obtained from laboratory tests.

CHAPTER THREE

LABORATORY WORK AND TESTING PROGRAM

3. LABORATORY WORK AND TESTING PROGRAM

3.1 INTRODUCTION

This chapter describes details of the research program carried out in this thesis. The work was carried out at the school of built environment at Napier University involving experimental and analytical investigation on punched metal plate timber connections. The work includes detailed experimental investigation of parameters effecting the structural behaviour of punched metal plates timber fasteners (PMPTF's) such as number and length of bites (nails), thickness of plates, grain direction, deformation and loading rates. The specimens were loaded to failure in tension, compression and moment forces to investigate the performance of the joints.

The objectives of this work are as follows ;

1- To develop a simple test methods and apparatus for testing the punched metal plate timber joints, subjected to tension, compression and moment forces.

2- To determine the strength, stiffness and to characterise failure modes of timber joints made with punched metal plate connectors under tension, compression, and moment forces.

3- To characterise factors influencing the load-carrying capacity and performance of the punched metal plate timber fasteners.

4- To investigate the influence of the various parameters such as number and length of bites, thickness of the plate, grain direction, deformation and loading rates on the structural behaviour and performance of the joints.

The performance of timber structural systems depends on the material properties of the timber and on the connection between the members. The serviceability of timber structures depends mainly on the efficiency of the joints between the elements. The load capacity of the punched metal plate (nail-plate) is established, in general, by empirical means as result of destructive testing in accordance with relevant national standards. The basic of tests is tensile/compression loading applied parallel and perpendicular to the grain of the timber.

3.2 LABORATORY WORK

The strength and stiffness of the punched metal plate timber connections subjected to tension, compression and moment forces were determined on the basis of destructive testing according to the EC5, the load carrying capacity and the stiffness characteristics of the connections were determined from tests according to British Standards (EN 1380, EN 1381, EN 26891, EN 28970 and prEN 1075).

3.2.1 MATERIALS

3.2.1.1 Timber

All the joint specimens were manufactured using selected TR26 grade European whitewood obtained from a local timber merchant. The timber sections were visually inspected and as far as possible defect free timber were selected. Particular attention were made to select specimens that were of uniform quality, free from knots, free from split and resin pockets and had relatively straight grain that could influence the results. The European white wood stored indoor in a well-ventilated storage for several weeks before individual specimens were made. After the conditioning period the specimen were sawn and planed. Care was taken to ensure that no knots, split or resin pocket coincided with the position of the fasteners in the full size pieces. The moisture content and density of the timber were measured after each test by cutting out small cubes of timber from the specimens. These cubes were weight, measured, dried at 100°C for 24 hrs and reweighed. The mean moisture content at the time of testing was 12% and the mean density was 475 kg/m^3.

3.2.1.2 Fasteners

The punched metal plate timber fasteners (PMPTFs) are now available in a wide variety of size and types from several different manufacturer in the United Kingdom as well as other countries. They are mechanical fasteners manufactured from pre-galvanised mild steel or stainless steel strips. A punched metal plate fastener is defined in prEN1075 ' Timber structures - test methods – joints made of punched metal plate fasteners' as a fastener made of metal plate of nominal thickness not less than 0.9mm and not more than 2.5mm, having integral projections punched out in one direction and bent perpendicular to the base of the metal plate, being used to join two or more pieces of timber of the same thickness in the same plane.

Tests were performed on joints made with punched metal plates produced and supplied by MiTek Industries Ltd manufacturer. MiTek is one of the largest punched metal plates manufacturer in the United Kingdom, and owns both the Hydro-Air and Bevplate trade names. There are many types and size of punched metal plate timber connections. The properties of different plates used in manufacturing of the specimens are shown in table 3.1. The plates are pressed into the timber members on each side of the joints allowing the teeth to act as nails in transferring load from a timber member into steel plates and into the adjacent timber member. Type, size of the fasteners and dimension of the joints of each samples were recorded.

Plate ref. number	Plate properties (mm)		
	Length	Width	Thickness
M20/0310B	101	25	1
B90212	120	30	1.2
M14/1333	133	38	2

Table 3.1. Properties of different plates used in specimen joints.

3.2.2 FABRICATION OF TEST SPECIMENS

The fabrication of test specimens were in accordance with prEN1075:1997. The joints were made of two pieces of timber joined together with two fasteners positioned parallel to each other and symmetrically opposite faces of the joint. The fasteners were positioned on the members so as to minimise the effect of moment rotation. The plates were pressed into the timber members on each side of the joints. The projections of the fasteners were fully embedded in the timber so that the contact surface of the fastener was flush with the surface of the timber.

The size and geometry of the test pieces were dependent upon the fasteners size and the properties being measured, the length of the test piece loaded in tension were such that the ends of the test machine grips were not less than 200mm from the ends of the fasteners. Where necessary, the ends of the test piece were reinforced to avoid premature failure or slip at the grips. The test pieces were fabricated so that the pieces of timber in the test were separated by a gap of not less than 4 mm for compression and moment capacity testing and not less than 2mm in case of the tension capacity testing.

The difference in thickness between adjoining pieces did not exceed 0.5mm, for each test pieces the two joining members were cut from the same plank to ensure a test piece of balanced density. The dimensions, densities, and moisture contents of each timber samples were recorded.

3.3 TESTING PROGRAM

The behaviour of the joints depends on the type of applied loading. In order to determine the effects of different parameters on the performance of the joints, a variety of tests were carried out on joints with different parameters subjected to different loading (tension, compression, and moment) conditions.

3.3.1 Tension test

Tension test samples were generally made of two pieces of timbers dimensioned as 73mm×300mm and 73mm×80mm by 45mm thickness, joined together with two punched metal plates positioned parallel to each other. The sample thickness of 45mm was considered to be suitable to ensure that the timber used had a thickness of not less than 33mm or twice the length of the projection plus 5mm, whichever was the greater to satisfy the recommended value given in the British Standard prEN 1075:1997 and to minimise the effect of fastener bending and produce the desired embedment. The test pieces were fabricated so that the pieces of timber in the test were separated by a gap of not less than 2mm. A typical tension test specimen is shown in Figure 3.1. The difference in thickness between adjoining pieces did not exceed 0.5mm, for each test pieces the two joining members were cut from the same plank to ensure a test piece of balanced density. The dimensions, densities, and moisture contents of each timber samples were recorded.

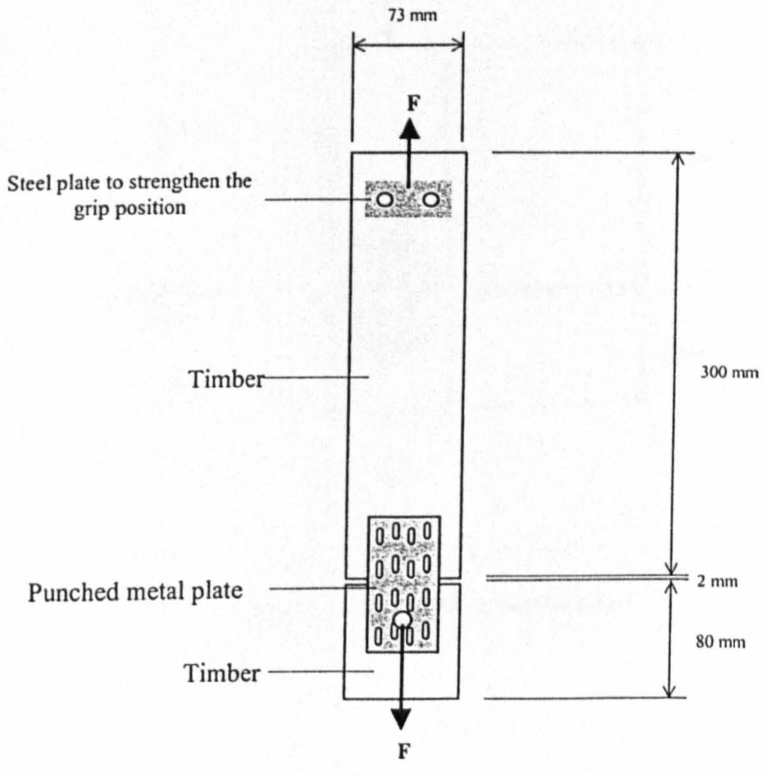


Figure 3.1 Tension test specimen.

3.3.2 Compression test

Compression tests samples were generally made of two pieces of timber dimensioned as 73mm × 170 mm and 73 × 67 mm by 45 mm thickness, joined together with two punched metal plates positioned parallel to each other. The test pieces were fabricated so that the pieces of timber in the test were separated by a gap of not less than 4mm. A typical compression test specimen is shown in Figure 3.2.

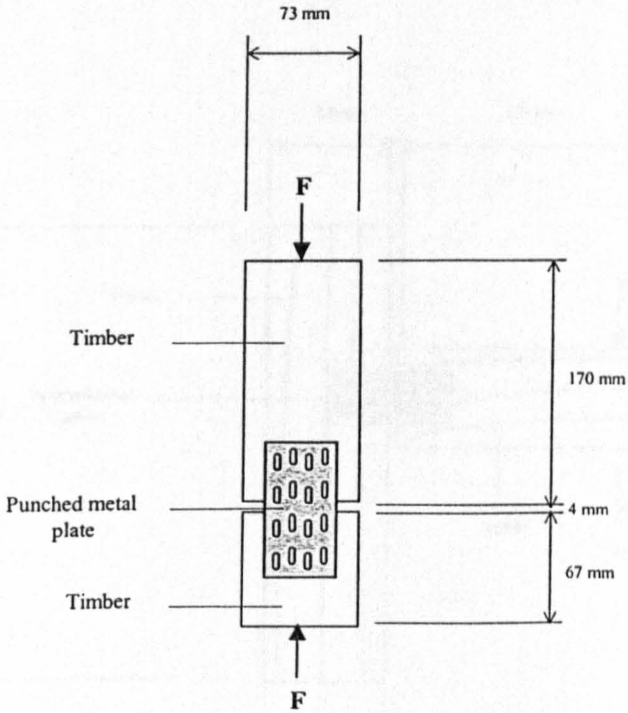


Figure 3.2 Compression test specimen.

3.3.3 Moment test

Moment test samples were generally made of two pieces of timber dimensioned as 65mm×300mm and 65mm×130mm by 45mm thickness, joined together with two punched metal plates positioned parallel to each other. The test pieces were fabricated so that the pieces of timber in the test were separated by a gap of not less than 4mm. A typical moment test specimen is shown in Figure 3.3.

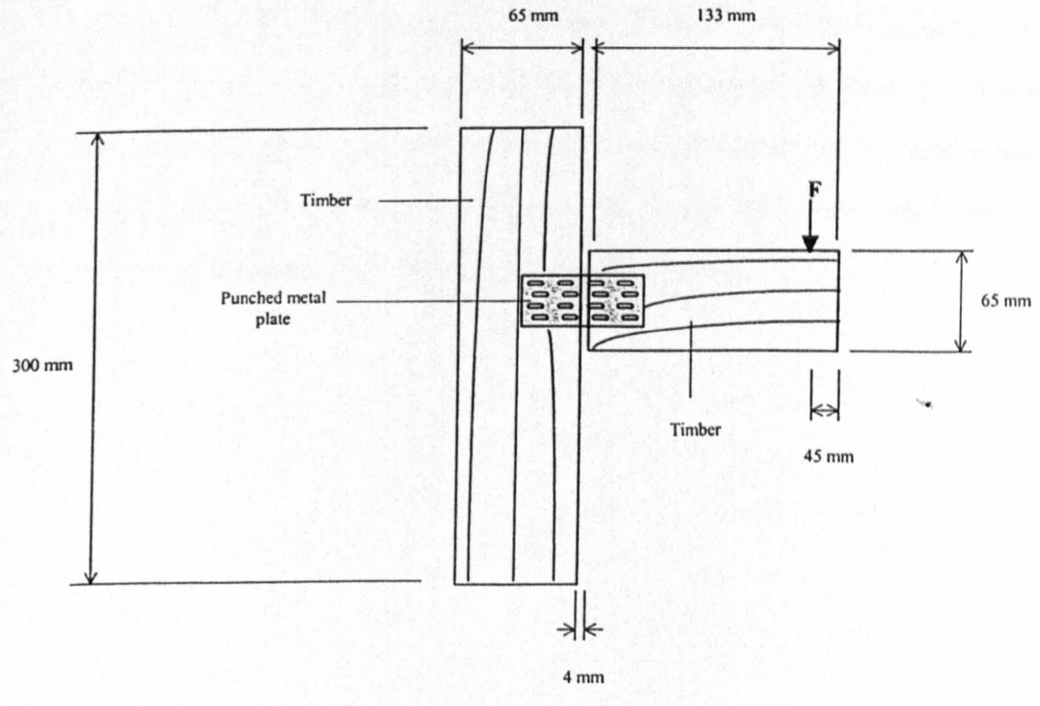


Figure 3.3 Moment test specimen.

3.4 INSTRUMENTATION

The tests were conducted using Lloyd universal testing machine with a combined loading and data acquisition facility as shown in Figure 3.4, the load cell and strain gauge based transducers were connected to a PC. The load-deformation data was continuously recorded by the on-board computer until failure occurred. Load cells and transducers were all calibrated and wired into the systems prior to the series tests. Measurement were taken by means of a computerized data acquisition system with an accuracy of ± 1% for load and slip.

Two symmetrically transducers were used during each test, they were installed as shown in Figure3.5. One transducer was placed on each side of the joints on seating angles screwed to the timber and attached to the vertical member to measure the joint slip, defined as the relative movement between the two members of the connection in the direction of loading at any given time during testing. The signal from the two transducers were averaged to remove any deformation in the system that would be due to specimen twist. Typical set-ups for tension, compression and moment tests are shown in Figure 3.6.

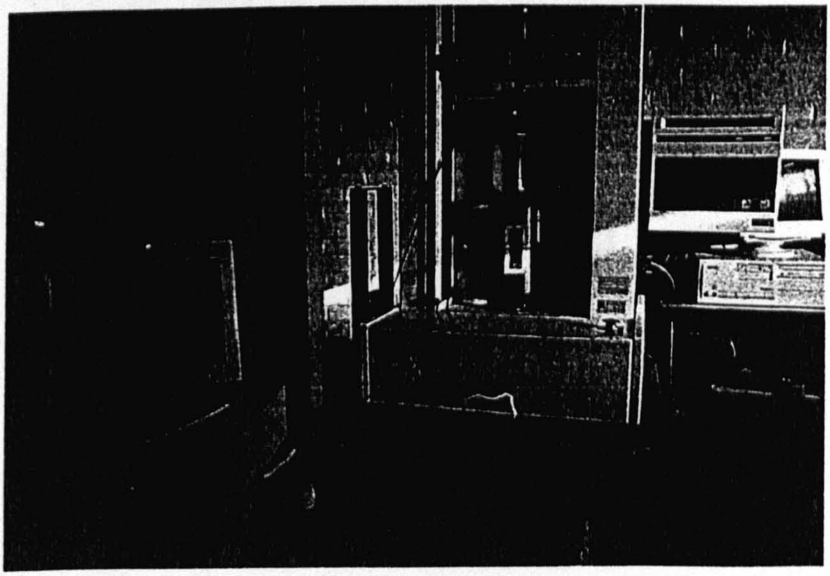


Figure 3.4 Lloyd Universal Testing Machine with a combined loading and data acquisition facility.

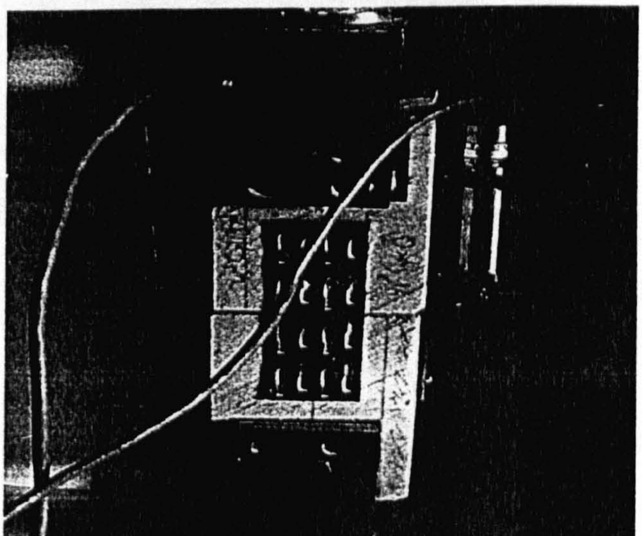


Figure 3.5 Transducers installation in tension test.

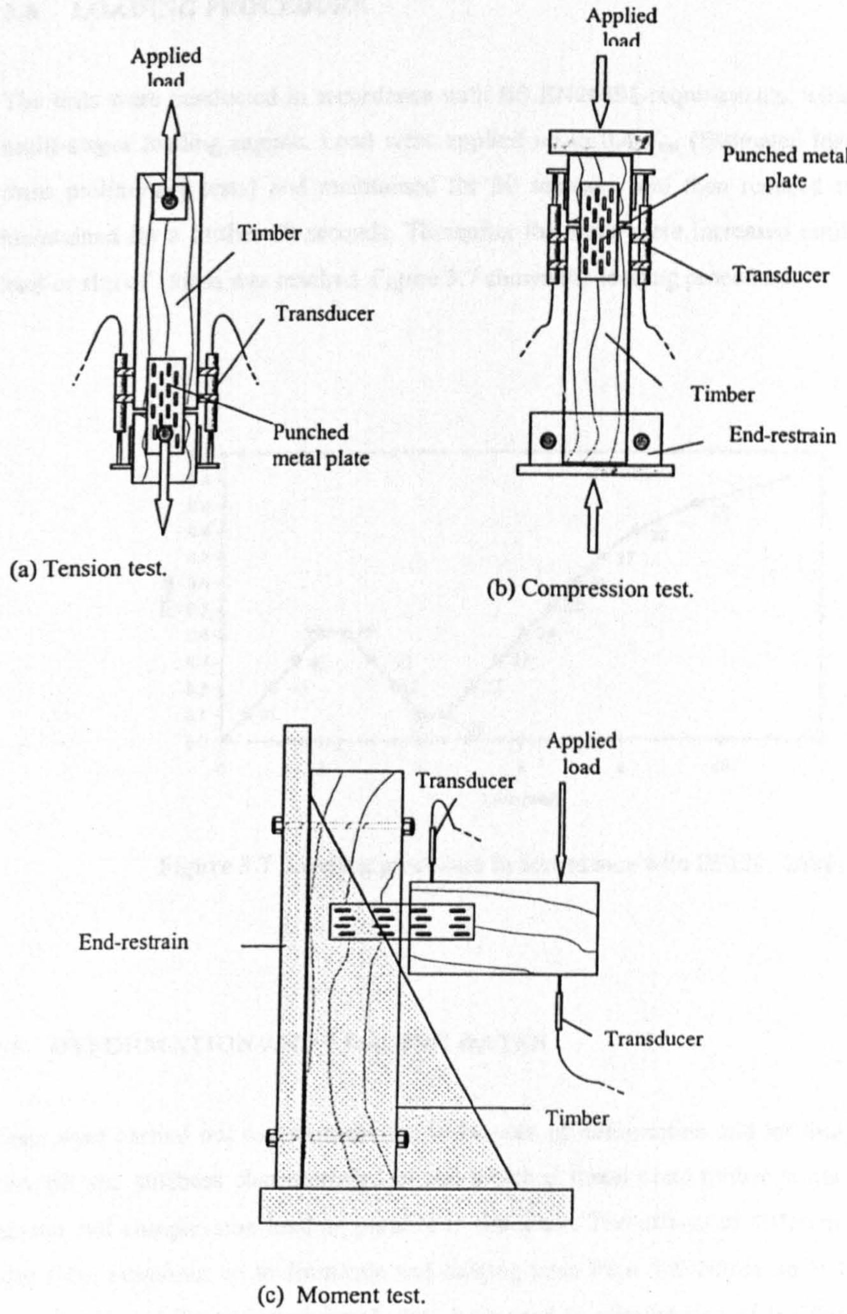


Figure 3.6 Typical tests set-up.

3.5 LOADING PROCEDURE

The tests were conducted in accordance with BS EN26891 requirements, which involved a multi-stages loading regime. Load were applied up to 0.4 F_{est} (Estimated load determined from preliminary tests) and maintained for 30 seconds, and then reduced to $0.1F_{est}$ and maintained for a further 30 seconds. Thereafter the loads were increased until the ultimate load or slip of 15mm was reached. Figure 3.7 shown the loading procedure.

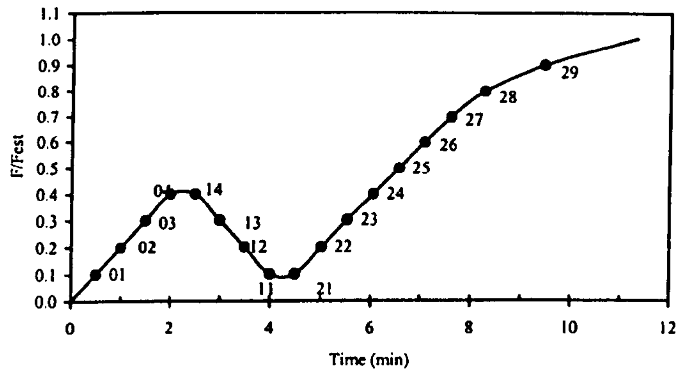


Figure 3.7 Loading procedure in accordance with BSEN 26891.

3.6 DEFORMATION AND LOADING RATES

Tests were carried out to determine the influences of deformation and loading rates on the strength and stiffness characteristics of the punched metal plate timber joints subjected to tension and compression loading parallel to the grain. The effects of different deformation rates from 1mm/min up to 5mm/min and loading rates from 500 N/min up to 10000 N/min were examined. The punched metal plate type used in construction of the joint specimens was B90212 (120mm×30mm×1.2mm).

3.7 CONNECTION CONFIGURATIONS

In this section the description of the connection with different parameters (number and length of bites, grain direction, plate thickness) tested are discussed.

3.7.1 Number of bites

Tests were carried out to determine the influences of number of bites (teeth) on the strength and structural behaviour of the punched metal plate timber connections. Connection with different number of bites subjected to tension, compression and moment forces were considered. The effects of number of bites in the joints from one per side up to eight per side were examined. Connections with different number of bites configurations, which were selected for testing, are shown in Figure 3.8. The punched metal plate type used in construction of the joint specimens was M20/0310B (101mm×25mm×1mm). The chosen bite number/position combinations were designed to examine the influence of symmetrical/asymmetrical distribution of loads in the plates.

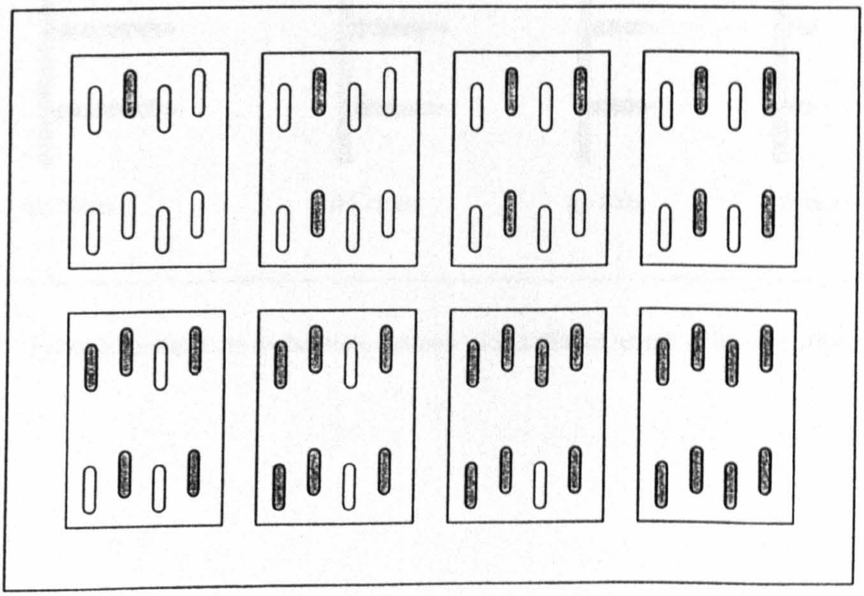


Figure 3.8 Punched metal plate timber connections with different number of bites configurations.

3.7.2 Length of bites

Tests were carried out to determine the influences of length of bites (teeth) on the strength and structural behaviour of the punched metal plate timber connections. Connection type with different length of bites subjected to tension, compression and moment forces were considered. The effects of length of bites in the joints from 5mm up to 20mm were examined. Connections with different length of bites configurations are shown in Figure 3.9. The punched metal plate type used in construction of the joint specimens was a small strip (130mm×38mm×2mm) which cut from plate number M14/1333 as supplied by MiTek industries.

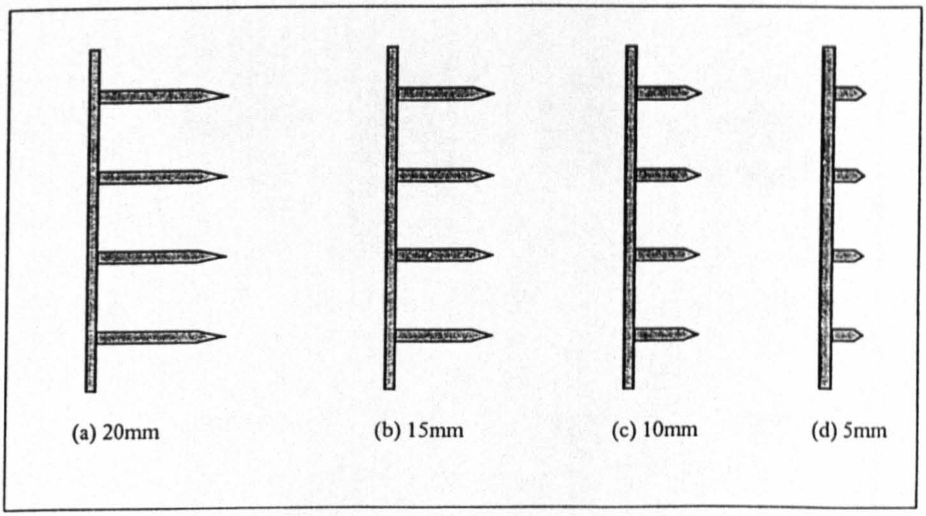


Figure 3.9 Punched metal plate timber connections with different length of bites configurations.

3.7.3 grain direction

Tests were carried out to determine the influences of the grain direction on the strength and structural behaviour of the punched metal plate timber connections. Connections with different grain direction subjected to tension, compression and moment forces were considered. The effects of angle of grains of 0 , 30 ,60 and 90 were examined. Connections with different grain direction configurations are shown in Figure 3.10. The punched metal plate type used in construction of the joint specimens was M20/0310B (101mm×25mm×1mm).

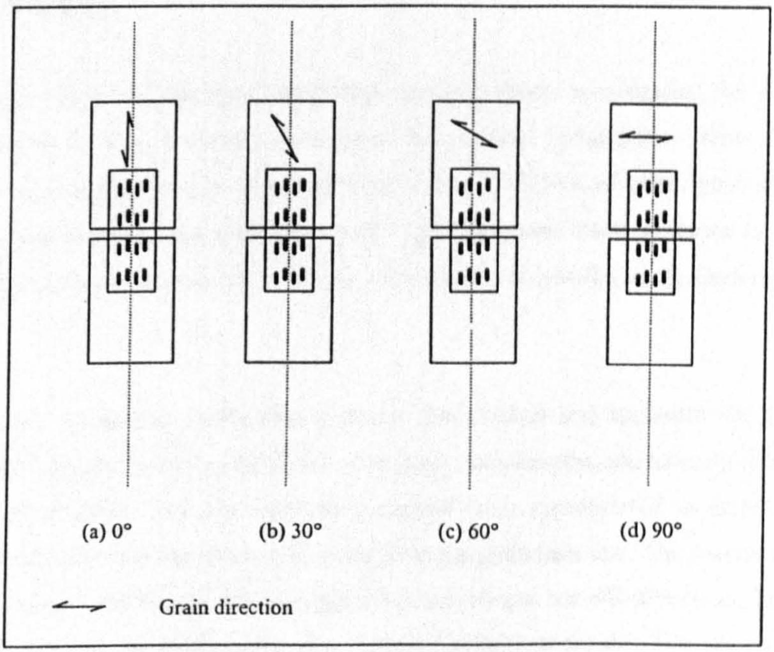


Figure 3.10 Punched metal plate timber connections with different grain direction configurations.

3.7.4 Thickness of the plate

Tests were carried out to determine the influences of the thickness of the plate on the strength and structural behaviour of the punched metal plate timber connections. Connection type with different plate thickness subjected to tension, compression and moment forces were considered. The effects of plate thickness (1mm and 2mm) were examined. Joints were made of two different plates. The first group made of punched metal plates M20/0310B with 1mm plate thickness and the second group made of small strip of punched metal plate M14/1333 with 2mm plate thickness.

3.8 SUMMARY

In this chapter details of laboratory work and testing program investigating the effects of some parameters on the structural behaviour of the punched metal plates timber fasteners (PMPTF's) such as number and length of bites (nails), thickness of plate, grain direction, deformation and loading rates were described. The specimens were subjected to tension, compression and moment forces up to failure, with the aim to investigate the performance of the joints.

One aim of this work was to develop a simple test method and apparatus for testing a punched metal plate timber joints subjected to tension, compression, and moment forces, that aim has been achieved. The test methods presented were appropriated to determine the strength and stiffness of joints made with punched metal plate fasteners. The specimens were easy to manufacture and handle. The test apparatus was simple but effective; it applied equal force to both sides of the components and produced consistent results. The test specimens were prepared in accordance with British standard prEN1075:1997.

CHAPTER FOUR

INFLUENCE OF DEFORMATION / LOADING RATES ON THE BEHAVIOUR OF THE TEST SPECIMENS

4. INFLUENCE OF DEFORMATION / LOADING RATES ON THE BEHAVIOUR OF THE TEST SPECIMENS

4.1 INTRODUCTION

The semi-rigid behaviour of the punched metal plate timber joints (PMPTJ's) depends on several parameters, some of which are related to timber properties such as wood species, geometry of wood, moisture contents, and wood density. Others related to the plate properties such as plate size, plate thickness, number of bites, length of bites and plate direction. It is also believed that loading properties such as load rate, deformation rate, direction of load, type of load, duration of load would influence the strength/stiffness characteristics of the timber structure. In order to establish a testing procedure, the effects of application of different deformation and loading rates on the performance of the joints were examined. From literature review, it is evident that extensive studies of load-duration effects have been carried out. Very few, if any, studies have been made to study the effects of loading and deformation rates under short-term loading. The evaluation of the effects of loading and deformation rates are interesting to those dealing with test procedures and the design of the punched metal plate timber joints subjected to various loads.

This chapter describes a series of tests carried out on timber joints made with punched metal plate timber fasteners (PMPTF's) in which the load was applied parallel to the grain of the timber. The specimens were loaded to failure both in tension and in compression in order to determine the influences of deformation and loading rates on the strength and behaviour of the punched metal plate timber joints under short-term duration.

4.2 TESTING PROGRAM

Tests were carried out to determine the influence of deformation and loading rates on the strength characteristics of the punched metal plate timber joints subjected to tension and compression loading parallel to the grain. Testing programme for joints subjected to tension and compression loading at different deformation and loading rates are summarised in table 4.1 and 4.2 respectively. Minimum of 5 specimen joints at each deformation and loading rate were tested, totalling over 85 specimen joints.

Plate ref. number	Plate properties (mm)			Deformation rate (mm/min)	
	Length	Width	Thickness	Tension	Compression
B90212	120	30	1.2	1	1
B90212	120	30	1.2	2	3
B90212	120	30	1.2	3	5
B90212	120	30	1.2	4	–

Table 4.1. Testing programme for joints subjected to tension and compression loading at different deformation rate.

Plate ref. number	Plate properties (mm)			Load rate (N/min)	
	Length	Width	Thickness	Tension	Compression
B90212	120	30	1.2	500	500
B90212	120	30	1.2	1000	2000
B90212	120	30	1.2	1500	4000
B90212	120	30	1.2	2000	5000
B90212	120	30	1.2	2500	10000

Table 4.2. Testing programme for joints subjected to tension and compression loading at different loading rate.

4.3 LABORATORY WORK

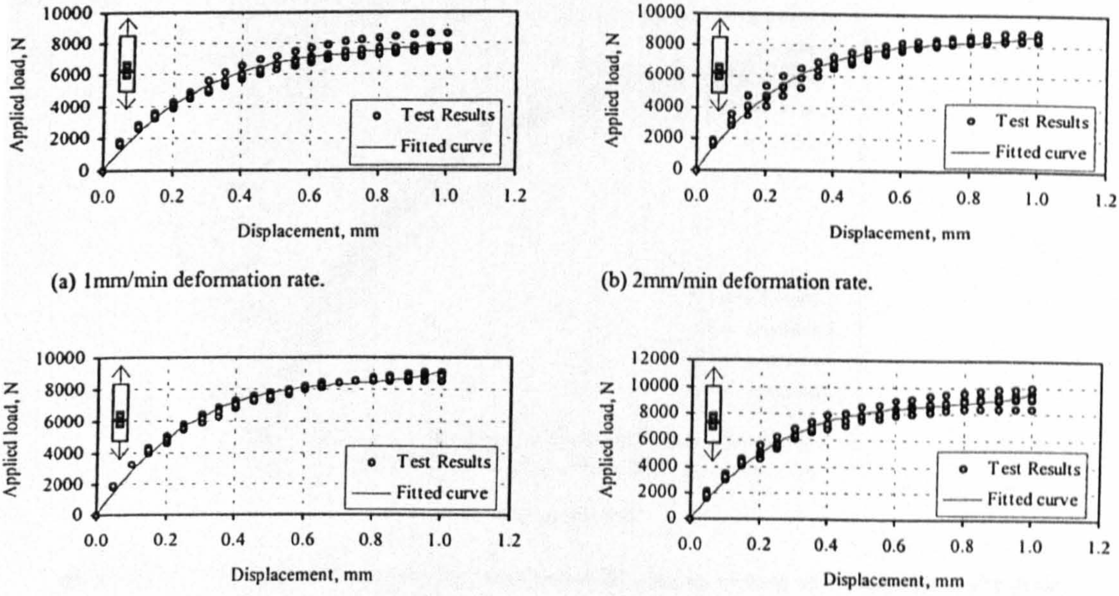
The punched metal plate type used in construction of testing specimens was (B90212-120mm×30mm×1.2mm) as supplied by MiTek industries. The specimens were loaded to failure in tension and compression. All joint specimens were manufactured using material as explained in chapter 3. The average moisture content at the time of testing was 12 % and the mean density was 475 kg/m^3.

The tension test samples were generally made of two pieces of timber dimensioned as 73 × 300 mm and 73 × 80 mm by 45 mm thickness. For compression tests, samples were made of two pieces of timber dimensioned as 73 × 170 mm by 45 mm thickness. The specimens were made according to the British standard pr EN 1075: 1997 as explained in chapter 3. Typical tension and compression test specimens are shown in Figures 3.2 and 3.3 respectively and test set-up is shown in Figure 3.3. The instrumentation and loading procedures were explained previously in chapter 3.

4.4 Effect of deformation rate

4.4.1 Tension tests

In Figure 4.1 typical non-linear load-displacement curves up to 1mm displacement with average curves for specimens at various deformation rates subjected to tensile loading parallel to the grain of timber are shown.



(a) 1mm/min deformation rate.

(b) 2mm/min deformation rate.

(c) 3mm/min deformation rate.

(d) 4mm/min deformation rate.

Figure 4.1 Load – displacement behaviour of joints loaded in tension parallel to the grain at different deformation rate.

The behaviour of the joints tested was assessed through their load-displacement relationships up to failure loads. The load-displacement behaviour of each joint specimen was examined and third order polynomial equations were fitted to define the curves. The fitted curves simulated the load-displacement behaviour of the connections with good accuracy. These equations were directed to pass through the point of origin to simulate the condition of zero deformation at zero loads.

A comparison of joints performance at different deformation rates up to 1mm displacement is presented in Figure 4.2. The failure load at 1mm displacement for each group of specimens is shown in Table 4.3.

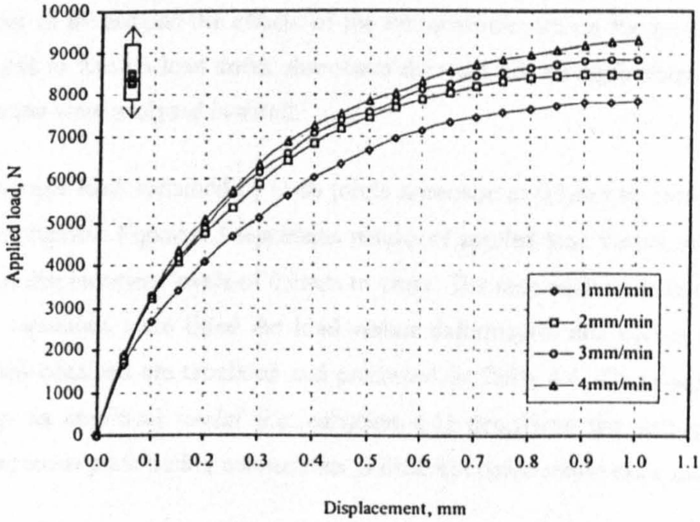


Figure 4.2 Comparison of joints performance subjected to tension force parallel to the grain at different deformation rate.

Plate ref. number	Deformation rate (mm/min)	Average load at 1mm displacement (N)
B90212	1	7830
B90212	2	8487
B90212	3	8818
B90212	4	9306

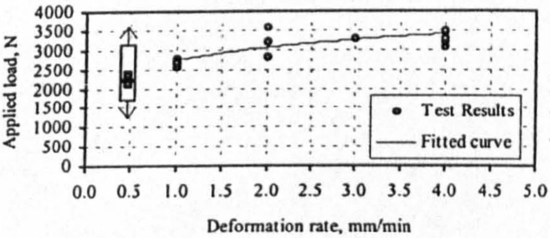
Table 4.3 The average load at 1mm displacement for joints subjected to tension force parallel to the grain at various deformation rate.

It was observed that the deformation rate had significant effects on the strength of the joints when loaded in tension. The strength of the joints increased with an increase in the deformation rate. The rate of increasing was increased as the deformation rate increased.

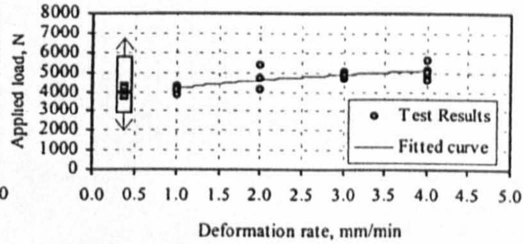
4.4.1.1 The strength characteristics of the joints

In order to investigate the effects of the deformation rate on the performance of the joints subjected to tension load under short-term duration, the strength characteristics of all tested specimens were analysed in detail.

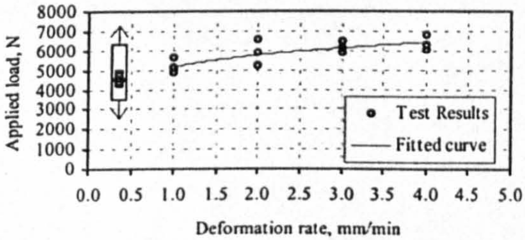
The average load sustained by each joints specimen at 0.1mm to 1mm displacement levels was determined. Figure 4.3 represents results of applied load versus deformation rate in the joints at displacement levels of 0.1mm to 1mm. The relationships were approximately linear. Power equations were fitted the load versus deformation rate curves to define them. The equations obtained are tabulated and presented in Table 4.4. These equations were used to develop an empirical model (i.e. equation 4.1) describing the strength characteristics of punched metal plate timber connections at different deformation rates under tensile loading.



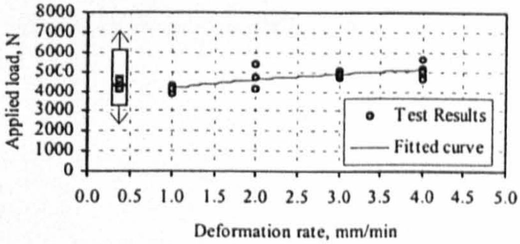
(a) Characteristics at 0.1mm displacement.



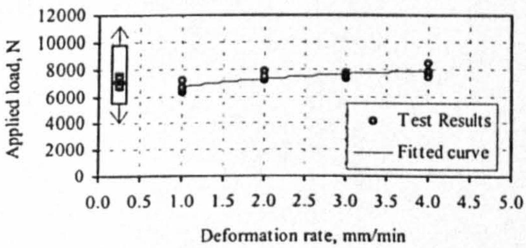
(b) Characteristics at 0.2mm displacement.



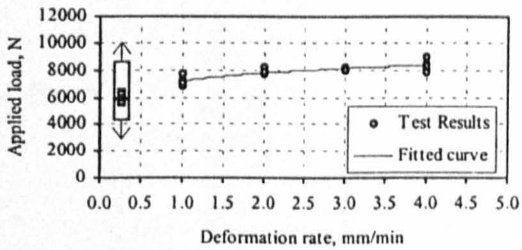
(c) Characteristics at 0.3mm displacement.



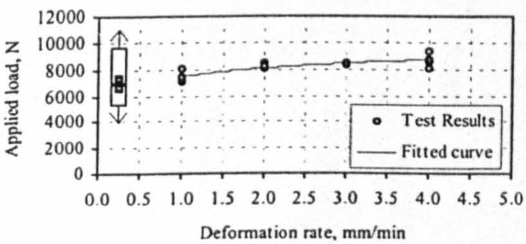
(d) Characteristics at 0.4mm displacement.



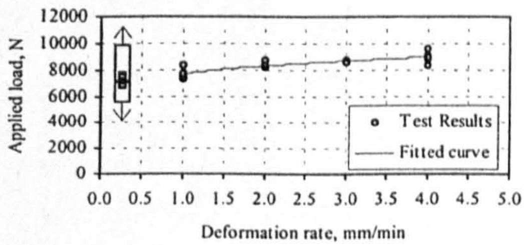
(e) Characteristics at 0.5mm displacement.



(f) Characteristics at 0.6mm displacement.

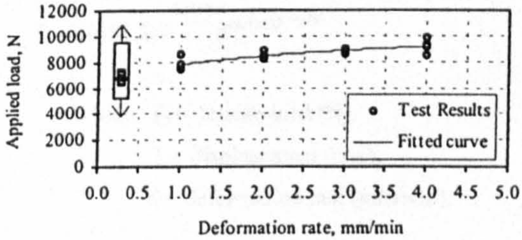


(g) Characteristics at 0.7mm displacement.

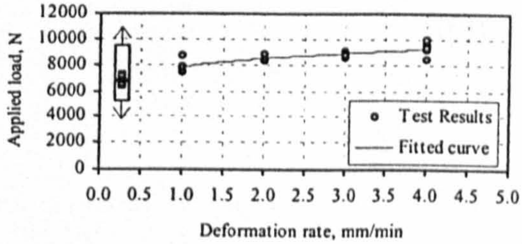


(h) Characteristics at 0.8mm displacement.

Figure 4.3 Load sustained in the joint versus deformation rate under tensile loading parallel to the grain.



(i) Characteristics at 0.9mm displacement.



(k) Characteristics at 1mm displacement.

Figure 4.3 cont.

Displacement (mm)	Tensile load, P_t (N)	Coefficient of correlation, R^2
0.1	$2744.4\ d^{0.1560}$	0.8772
0.2	$4150.9\ d^{0.1491}$	0.9475
0.3	$5169.5\ d^{0.1574}$	0.9698
0.4	$6101.9\ d^{0.1317}$	0.963
0.5	$6718.3\ d^{0.1153}$	0.9504
0.6	$7188\ d^{0.1116}$	0.9728
0.7	$7495.3\ d^{0.1094}$	0.9838
0.8	$7690.7\ d^{0.1104}$	0.9912
0.9	$7789.3\ d^{0.1147}$	0.9966
1	$7811.5\ d^{0.1201}$	0.9877

d = deformation rate (mm/min).

Table 4.4 The equations of the various curves in Figure 4.3.

From the equations in Table 4.4, an empirical model (i.e. equation 4.1) describing the tensile load sustain in the joints at different deformation rates was developed.

$$P_t = 8651.2\delta^{0.4612} d^{0.1101\delta^{-0.1736}} \tag{4.1}$$

where P_t = tensile load (N).

δ = displacement (mm).

d = deformation rate (mm/min).

In Figure 4.4, the effect of increases in the deformation rate on the performance and strength characteristics of the connections at displacement levels of 0.1mm to 1mm are shown. For all specimens tested the displacement at failure was about 1mm.

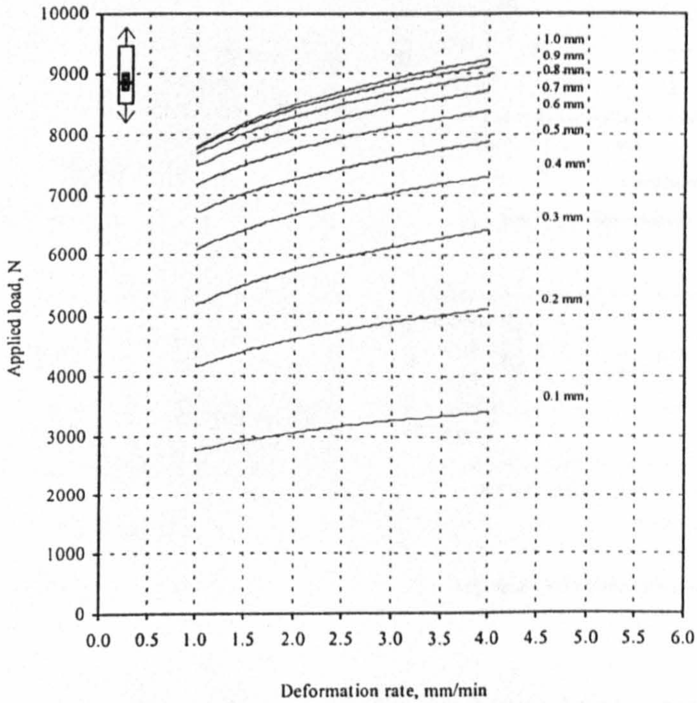
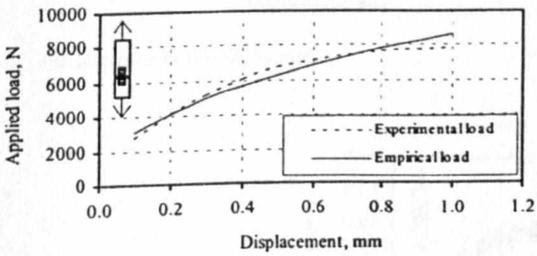


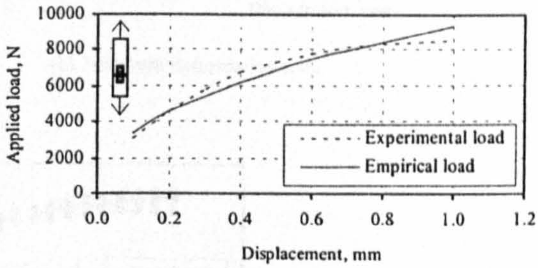
Figure 4.4 Load vs deformation rate in joints under tensile loading parallel to the grain.

It is clear that the performance and strength of the joints were dependent on the deformation rate at the joints when loaded in tension parallel to the grain. The strength of the joints increased with an increase of the deformation rate. The rate of increasing in strength was increased as the deformation rate increased. At high displacement (1mm), strength was high comparing with low displacement (0.1mm).

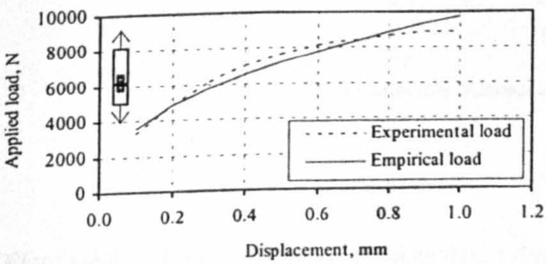
In Figure 4.5, a comparison of deformation rate versus displacement curves between experimental and empirical (i.e. equation 4.1) results for joints at different deformation rate are represented. The agreement between the empirical model and experimental observation was good.



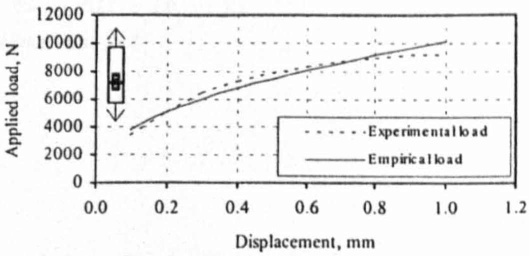
(a) 1mm/min deformation rate.



(b) 2mm/min deformation rate.



(c) 3mm/min deformation rate.

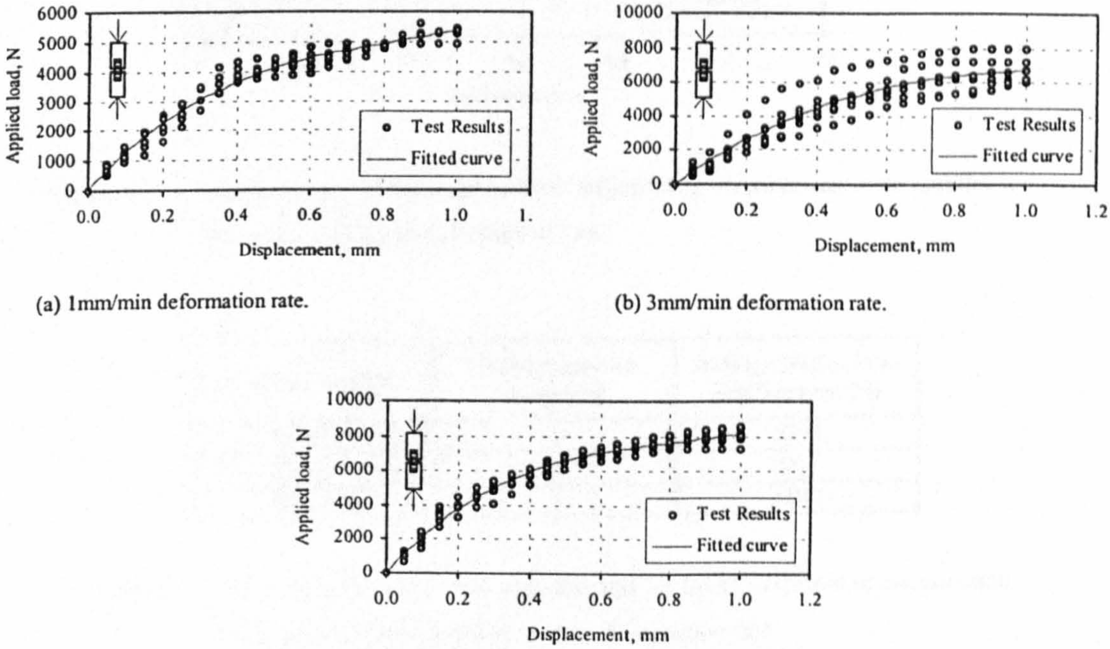


(d) 4mm/min deformation rate.

Figure 4.5 Comparison of deformation rate vs displacement curve between experimental and empirical (i.e. equation 4.1) results.

4.4.2 Compression tests

In Figure 4.6 typical non-linear load-displacement curves up to 1mm displacement with average curves for specimens at various deformation rates subjected to compression loading parallel to the grain of timber are shown.



(a) 1mm/min deformation rate.

(b) 3mm/min deformation rate.

(c) 5mm/min deformation rate.

Figure 4.6 Load – displacement behaviour of joints loaded in compression parallel to the grain at different deformation rate.

Similar method of analysis used in tension test was applied to compression test. A comparison of joints performance at different deformation rate up to 1mm displacement is presented in Figure 4.7. The failure load at 1mm displacement for each group of specimens is shown in Table 4.5.

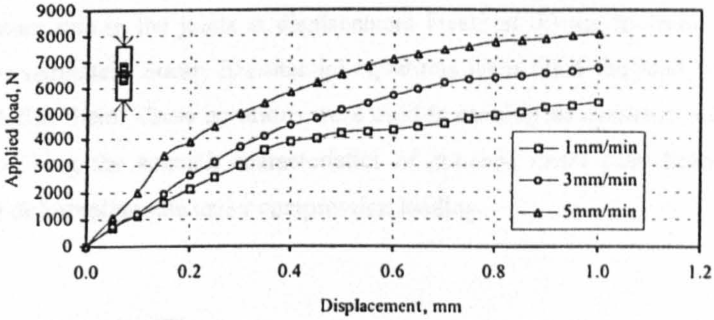


Figure 4.7 Comparison of joints performance subjected to compression force parallel to the grain at different deformation rate.

Plate ref. number	Deformation rate (mm/min)	Average load at 1mm displacement (N)
B90212	1	5399
B90212	3	6711
B90212	5	8040

Table 4.5 The average load at 1mm displacement for joints subjected to compression force parallel to the grain at various deformation rate.

It was observed that the deformation rates, similar to tensile loads, had significant effects on the strength of the joints when loaded in compression. The strength of the joints increased with an increase in the deformation rate. The rate of increasing was approximately linear.

4.4.2.1 The strength characteristics of the joints

In order to investigate the effects of the deformation rate on the performance of the joints subjected to compression load under short-term duration, the strength characteristics of all tested specimens were analysed in detail.

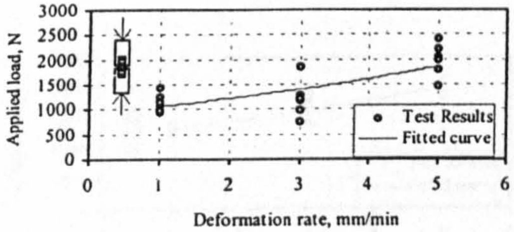
The average magnitude of the applied load sustained by each joint specimen at 0.1mm to 1mm displacement level was determined. Figure 4.8 represents results of applied load versus deformation rate in the joints at displacement levels of 0.1mm to 1mm. The relationships were approximately linear. Exponential equations were fitted the load versus deformation rate to define them. These equations were used to develop an empirical model (i.e. equation 4.2) describing the strength characteristics of punched metal plate timber connections at different deformation rate under compression loading.

$$P_c = 5491.9\delta^{0.7085} e^{0.1043\delta^{-0.1196d}} \tag{4.2}$$

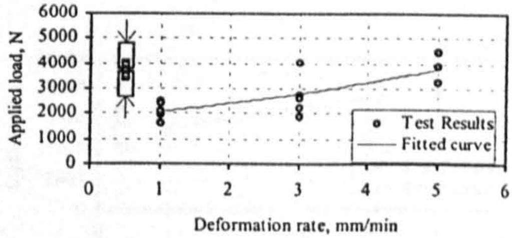
where P_c = compression load (N).

δ = displacement (mm).

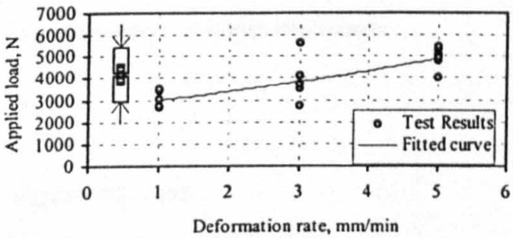
d = deformation rate (mm/min).



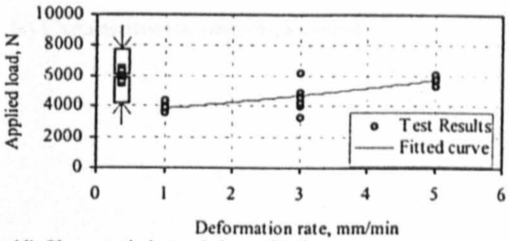
(a) Characteristics at 0.1mm displacement.



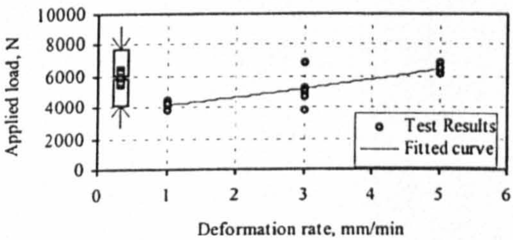
(b) Characteristics at 0.2mm displacement.



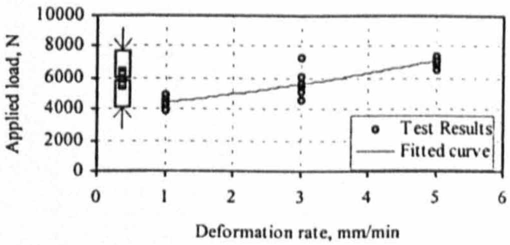
(c) Characteristics at 0.3mm displacement.



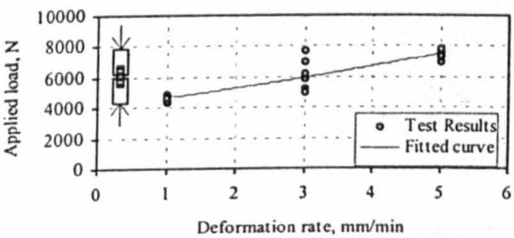
(d) Characteristics at 0.4mm displacement.



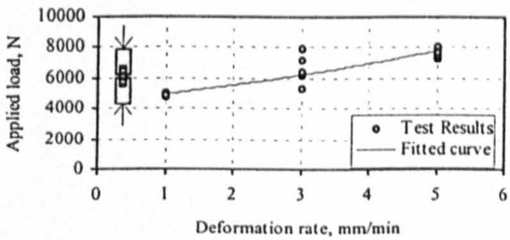
(e) Characteristics at 0.5mm displacement.



(f) Characteristics at 0.6mm displacement.

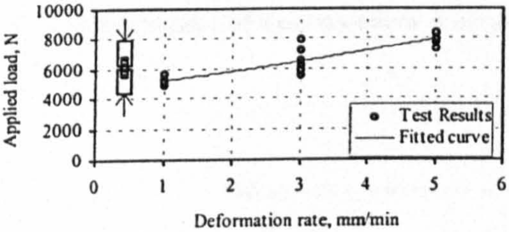


(g) Characteristics at 0.7mm displacement.

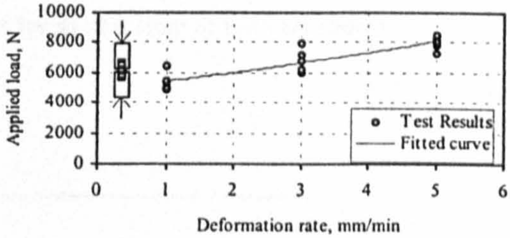


(h) Characteristics at 0.8mm displacement.

Figure 4.8 Load sustained in the joint versus deformation rate under compression loading parallel to the grain.



(i) Characteristics at 0.9mm displacement.



(k) Characteristics at 1mm displacement.

Figure 4.8 cont.

In Figure 4.9, the effect of increases in the deformation rate on the performance and strength characteristics of the connections at displacement levels of 0.1mm to 1mm are shown.

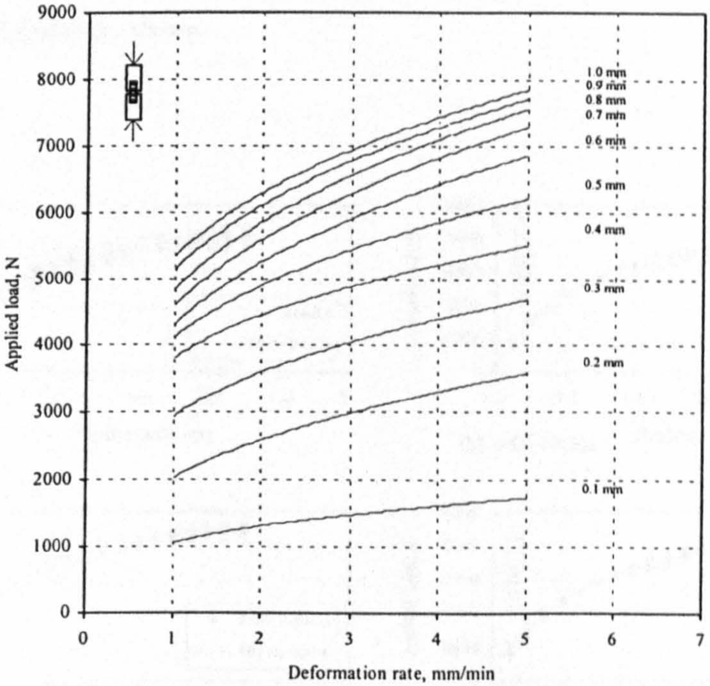


Figure 4.9 Load vs deformation rate in joints under compression loading parallel to the grain.

It is clear that the performance and strength of the joints were dependent on the deformation rate at the joints when loaded in compression parallel to the grain. The strength of the joints increased with an increase in the deformation rate. The rate of increasing in strength was increased as the deformation rate increased. At high displacement (1mm), the strength was high comparing with low displacement (0.1mm).

4.5 Effect of loading rate

4.5.1 Tension tests

In Figure 4.10 typical non-linear load-displacement curves up to 0.9mm displacement with average curves for specimens at various loading rate subjected to tensile loading parallel to the grain of timber are shown.

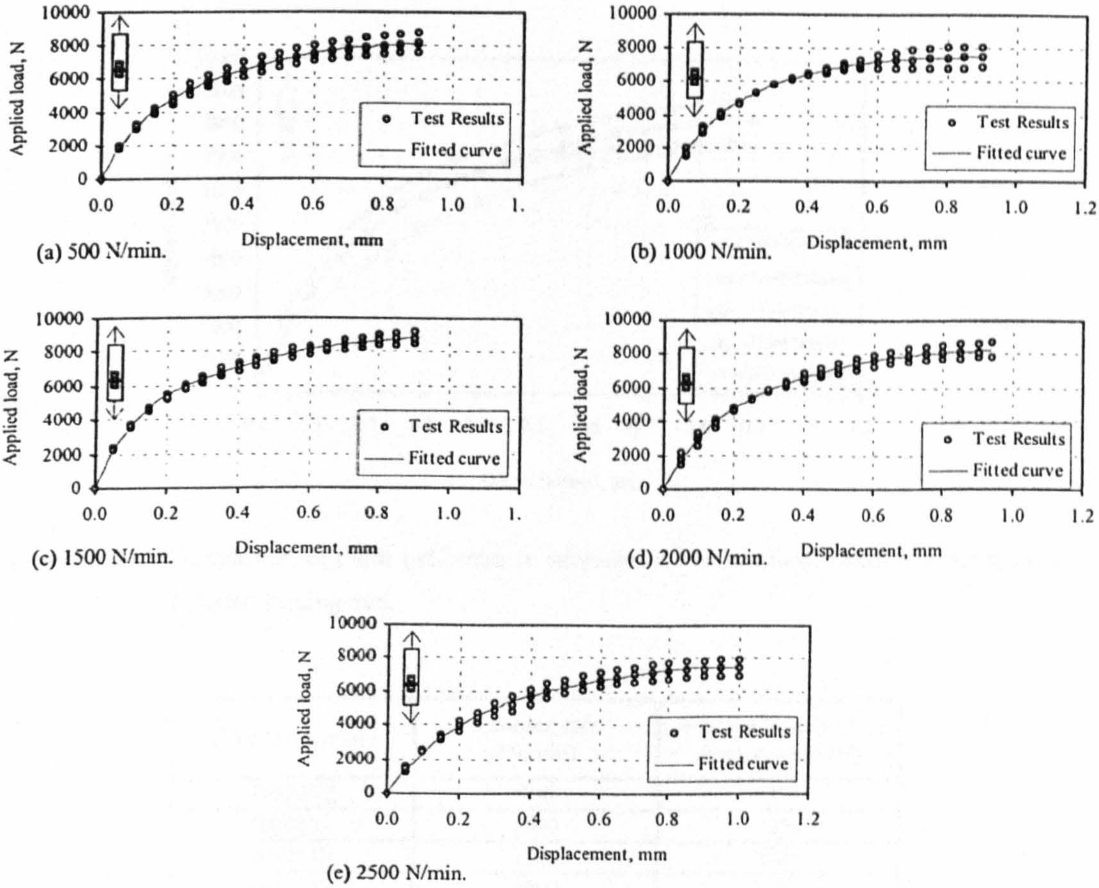


Figure 4.10 Load – displacement behaviour of joints loaded in tension parallel to the grain at different loading rate.

The behaviour of the joints tested was assessed through observation of the failed specimens and their load-displacement relation. The load-displacement behaviour of each joint specimen was examined and fifth order polynomial equations were fitted to define the curves. The fitted curves simulated the load-displacement behaviour of the connection with good accuracy. These equations were directed to pass through the point of origin to simulate the condition of zero deformation at zero loads.

A comparison of joints performance at different deformation rates up to 0.9mm displacement is presented in Figure 4.11. The failure load at 0.9mm displacement for each group of specimens is shown in Table 4.6.

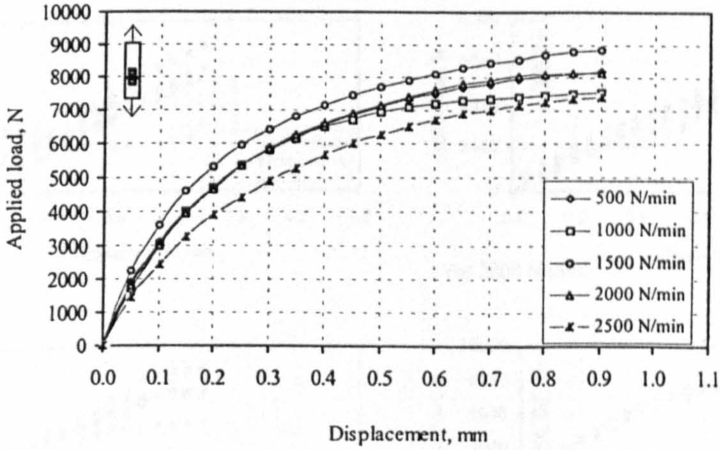


Figure 4.11 Comparison of joints performance subjected to tension force parallel to the grain at different loading rate.

Plate ref. number	Loading rate (N/min)	Average load at 1mm displacement (N)
B90212	500	8177
B90212	1000	7528
B90212	1500	8846
B90212	2000	8169
B90212	2500	7398

Table 4.6 The average load at 0.9mm displacement for joints subjected to tension force parallel to the grain at various loading rate.

From the results obtained, it was observed that the 500 N/min, 1000 N/min and 2000 N/min loading rates are almost identical but the 1500 N/min and 2500 N/min loading rates behaved in an unpredictable manner, the strength of the joints was high with 1500 N/min and low with 2500 N/min.

4.5.2 Compression tests

In Figure 4.12 typical non-linear load-displacement curves up to 0.9mm displacement with average curves for specimens at various loading rate subjected to compression loading parallel to the grain of timber are shown.

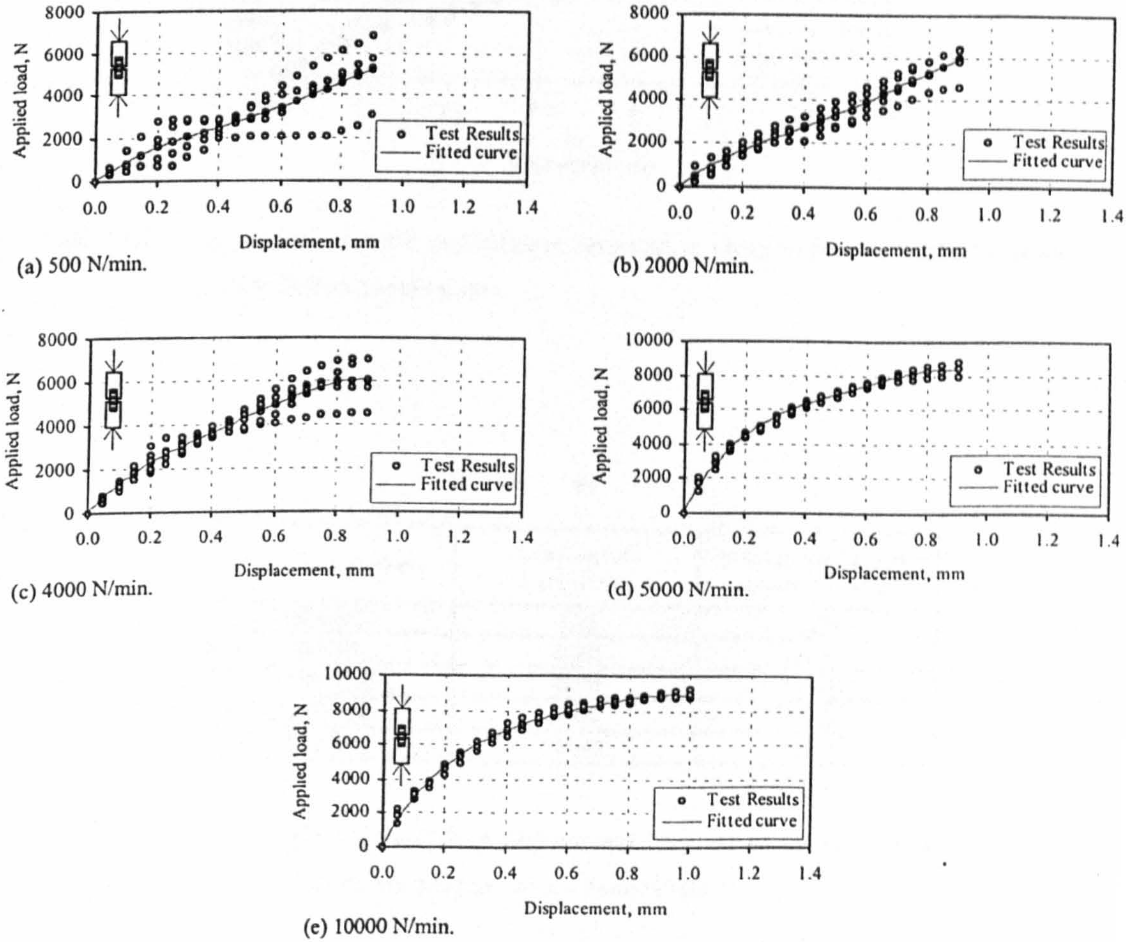


Figure 4.12 Load – displacement behaviour of joints loaded in compression parallel to the grain at different loading rate.

Similar method of analysis used in tension test was applied to compression test. A comparison of joints performance at different loading rate up to 0.9mm displacement is presented in Figure 4.13. The failure load at 0.9mm displacement for each group of specimens is shown in Table 4.7.

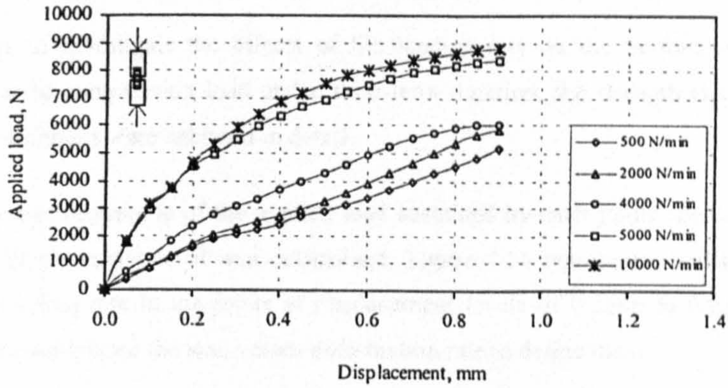


Figure 4.13 Comparison of joints performance subjected to compression force parallel to the grain at different loading rate.

Plate ref. number	Loading rate (N/min)	Average load at 1mm displacement (N)
B90212	500	5209
B90212	2000	5839
B90212	4000	6048
B90212	5000	8402
B90212	10000	8815

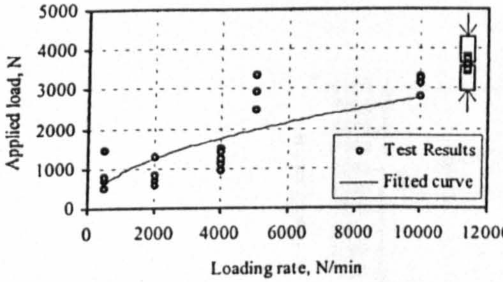
Table 4.7 The average load at 0.9mm displacement for joints subjected to compression force parallel to the grain at various loading rate.

It was observed that the loading rate had significant effects on the strength of the joints when loaded in compression. The strength of the joints increased with an increase in the loading rate.

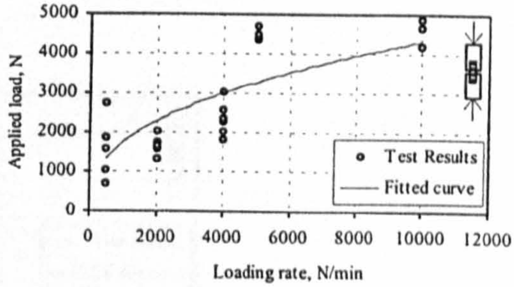
4.5.2.1 The strength characteristics of the joints

In order to investigate the effects of the loading rate on the performance of the joints subjected to compression load under short-term duration, the strength characteristics of all tested specimens were analysed in detail.

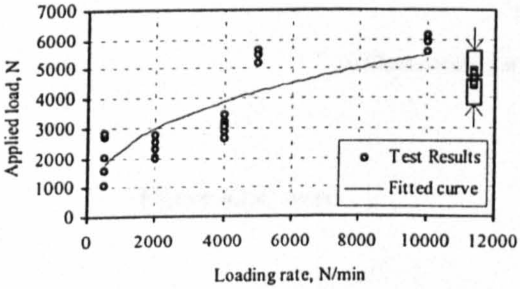
The average magnitude of the applied load sustained by each joints specimen at 0.1mm to 0.9mm displacement level was determined. Figure 4.14 represents results of applied load versus loading rate in the joints at displacement levels of 0.1mm to 0.9mm. Exponential equations were fitted the load versus deformation rate to define them.



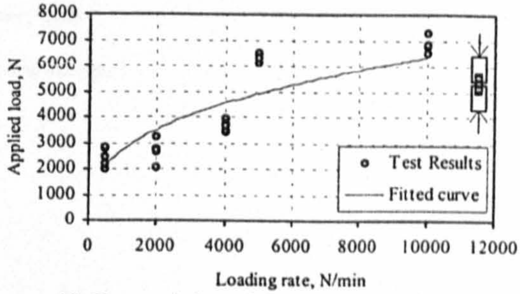
(a) Characteristics at 0.1mm displacement.



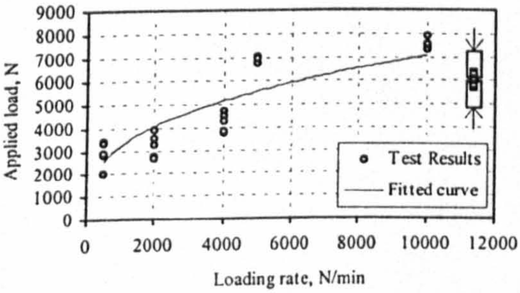
(b) Characteristics at 0.2mm displacement.



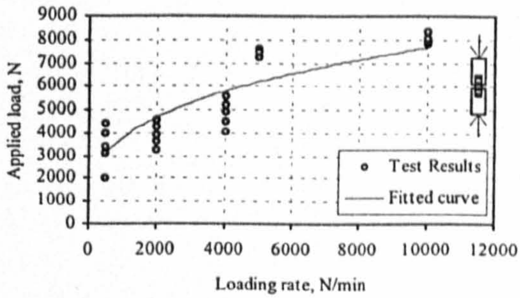
(c) Characteristics at 0.3mm displacement.



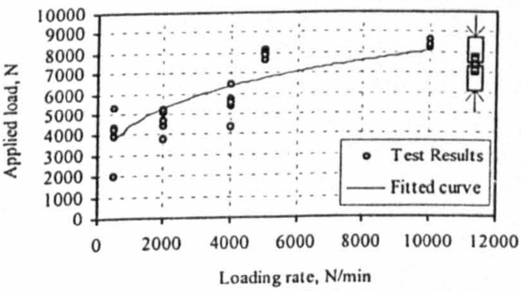
(d) Characteristics at 0.4mm displacement.



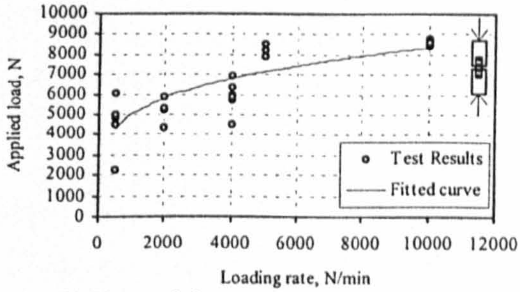
(e) Characteristics at 0.5mm displacement.



(f) Characteristics at 0.6mm displacement.

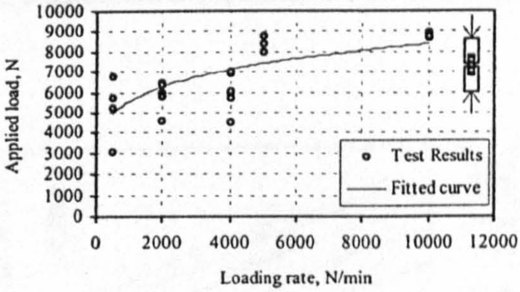


(g) Characteristics at 0.7mm displacement.



(h) Characteristics at 0.8mm displacement.

Figure 4.14 Load sustained in the joint versus loading rate under compression loading parallel to the grain.



(i) Characteristics at 0.9mm displacement.

Figure 4.14 cont.

In Figure 4.15, the effect of increases in the loading rate on the performance and strength characteristics of the connections at displacement levels from 0.1mm to 0.9mm are shown.

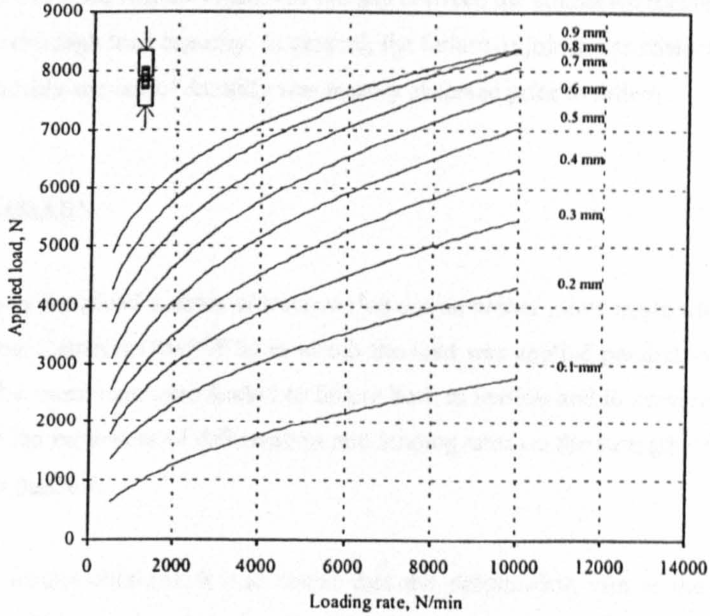


Figure 4.15 Load vs loading rate in joints under compression loading parallel to the grain.

It is clear that the performance and strength of the joints were dependent on the loading rate at the joints when loaded in compression parallel to the grain. The strength of the joints increased with an increase of the loading rate. At high displacement (0.9mm), the strength was high comparing with low displacement (0.1mm).

4.6 Failure modes

All joints studied behaved in a similar manner. They showed a non-linear response from beginning up to the failure load. In tension tests, as the load increased, plate started to peel away from the timber members at their upper end. This peeling progressed toward the centre of the joint until the plate withdrew completely (i.e. anchorage failure). In compression tests, there were three modes of failure. The most common mode of failure was anchorage failure (teeth withdrawal). As the load increased, plate started to peel away from the timber members at their lower end. This peeling progressed upward until the plate withdrew completely. The second failure mode was plate buckling, as the load increased the middle of the plate started buckling. The third was the closure of the gap between the connected member, this happened in joints with high load capacity. In general, the failure of joints was characterised as ductile. A considerable amount of ductility was usually observed prior to failure.

4.7 SUMMARY

This chapter described a series of tests carried out on timber joints made with punched metal plate timber fasteners (PMPTF's) in which the load was applied parallel to the grain of the timber. The specimens were loaded to failure both in tension and in compression in order to determine the influences of deformation and loading rates on the strength of the joints under short-term duration.

From the results obtained, it was found that the deformation rate at the joints having a significant effects on the strength and performance of the joints. Increasing the deformation rate would increase the strength of the joints. The rate of increasing in strength was increased as the deformation rate increased when loaded in tension and compression. Also it was found that the loading rate has significant effects when subjected to compression loading. Increasing the loading rate would increase the strength of the joints under compression loading. In order to establish a testing procedure and loading method, it was decided to use a deformation rate of 1mm/min in all tests because it gave more consistent results.

The failure of joints was characterised as ductile, a considerable amount of ductility was generally observed prior to failure. In the case of compression loads, there were three modes of failure, the most common mode of failure was anchorage failure (teeth withdrawal); as the load increased the toothed-plates started to peel away from the timber members. The second failure mode was plate buckling, as the load increased the middle of the plate started buckling. The third failure modes was the closure of the gap between the connected member, this happened when compression load applied at high load level. In the case of tensile loads the most common mode of failure was anchorage failure.

Empirical models describing the strength characteristics of joints at different deformation rates subjected to tension and compression loading were developed and compared well with the experimental results.

CHAPTER FIVE

LOAD-DISPLACEMENT CHARACTERISTICS OF PUNCHED METAL PLATE TIMBER JOINTS SUBJECTED TO TENSILE LOADS

5- LOAD-DISPLACEMENT CHARACTERISTICS OF PUNCHED METAL PLATE TIMBER JOINTS SUBJECTED TO TENSILE LOADS

5.1 INTRODUCTION

The load capacities of the punched metal-plate timber connections are established, in general, by empirical means as a result of destructive testing in accordance with relevant national standards. The basis of tests is tensile loading applied parallel and or perpendicular to the grain of the timber.

During the past decade, very few research studies have been carried out on the short-term behaviour of punched metal plate timber connections subjected to lateral loading. To-date, there is little information available on any parametric or comparative studies to determine the efficiency of such connections with regards to the level of rigidity they provide. Designers usually consider the effect of plate size on the joints. Having said that, the effects of the different characteristics of the metal plates on the structural performance of the joints have not been studied in detail.

This chapter describes details of experimental work investigating load-displacement characteristics of the punched metal plate timber connections under short duration loading, in which the effects of different factors such as number of bites, length of bites, grain directions and plate thickness were considered. This is to evaluate their efficiency for use in a variety of timber structures. It is anticipated in this chapter to determine the structural behaviour of punched metal plate timber connections when subjected to tensile loads with respect to their strength and displacement characteristics. Also, empirical models developed to simulate the load-displacement behaviour of the joints using different parameters.

5.2 TESTING PROGRAM

Tests were carried out to determine the influences of different variables such as number of bites, length of bites, grain directions and plate thickness on the performance of the punched metal plate timber joints subjected to tensile loading. Testing programme for different variables (number of bites, length of bites, grain directions, plate thickness) are summarised in table 5.1. Minimum of 5 specimens per joint type were tested, totalling over 70 specimen joints.

Plate ref. number	Plate properties (mm)			Bite properties		Grain direction
	Length	Width	Thickness	Number	Length (mm)	
M20/0310B	101	25	1	1	8	0
M20/0310B	101	25	1	2	8	0
M20/0310B	101	25	1	3	8	0
M20/0310B	101	25	1	4	8	0
M20/0310B	101	25	1	5	8	0
M20/0310B	101	25	1	6	8	0
M20/0310B	101	25	1	7	8	0
M20/0310B	101	25	1	8	8	0
M20/0310B	101	25	1	8	8	30
M20/0310B	101	25	1	8	8	60
M20/0310B	101	25	1	8	8	90
M14/1333	133	38	2	8	5	0
M14/1333	133	38	2	8	10	0
M14/1333	133	38	2	8	15	0

Table 5.1. Testing programme for joints subjected to tensile loading.

5.3 LABORATORY WORK

For testing the effects of the number of bites and grain directions the punched metal plate type used was M20/0310B-101mm×25mm×1mm and for the length of bites a small strip 130mm×38mm×2mm which was cut from plate number M14/1333 as supplied by MiTek industries. The specimens were loaded to failure in tension. All joint specimens were manufactured using material as explained in chapter 3. The average moisture content at the time of testing was 12 % and the mean density was 475 kg/m^3. The induced deformation rate during loading was 1mm/min.

The test samples were generally made of two pieces of timber dimensioned as 73 × 300 mm and 73 × 80 mm by 45 mm thickness. The specimens were made according to the British standard pr EN 1075: 1997 as explained in chapter 3. Typical tension test specimen is shown in Figure 3.1 and test set-up is shown in Figure 3.6. The instrumentation and loading procedures were as explained in chapter 3.

5.4 RESULTS AND DISCUSSION

The emphasis of the past research efforts on timber joints has focused on their strength and load carrying capacities. Very few studies have been made of the stiffness and ductility of the connections. This is probably due to the old allowable stress calculation method, which disregards the structural behaviour at the ultimate limit state. In this section the structural behaviour of joints with respect to their strength, stiffness and ductility are considered.

Timber and connections failure modes are different. The timber failure modes are often brittle where the connections failures are most probably ductile. The main source of ductility in timber structures is the mechanically fastened joints.

5.4.1 Effects of number of bites

Tests were carried out to determine the influences of number of bites on the performance of the punched metal plate timber joints subjected to tensile loads. The test samples were generally made of two pieces of timber dimensioned as 73mm×300mm and 73mm×80mm by 45mm thickness. The punched metal plate type used in construction of testing specimens was M20/0310B-101mm×25mm×1mm. The specimens were loaded to failure in tension. All joint specimens were manufactured using material as explained in chapter 3.

In Figure 5.1 typical load-displacement curves up to 0.6mm displacement with fitted curve (average curves) for specimens with various number of bites subjected to tensile loading are shown. All joints made of punched metal plates M20/0310B with equal length of bites (8mm) and the loads applied parallel to the grain of timber.

The behaviour of the joints tested was assessed through observation of the failed specimens and their load-displacement relationship. The load-displacement behaviour of each joint specimen was examined and second order polynomial equation was fitted to define the curves. The fitted curves simulated the load-displacement behaviour of the connection with good accuracy. These equations were directed to pass through the point of origin to simulate the condition of zero deformation at zero loads.

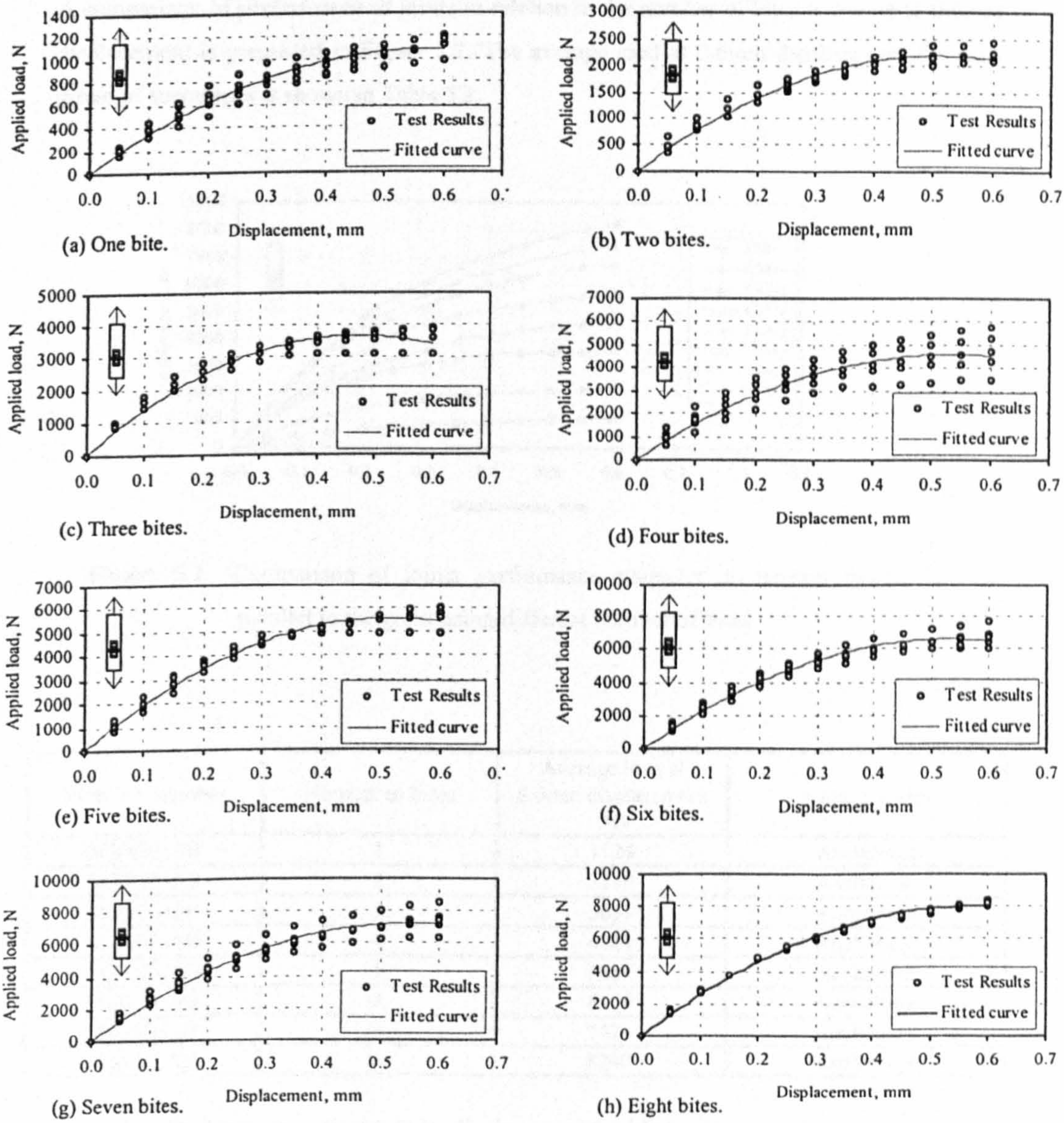


Figure 5.1 Load – displacement behaviour of joints with different number of bites loaded in tension parallel to the grain.

A comparison of performance of joints in relation to the number of bites tested up to 0.6mm displacement is presented in Figure 5.2. The average load at 0.6mm displacement for each group of specimens is shown in Table 5.2.

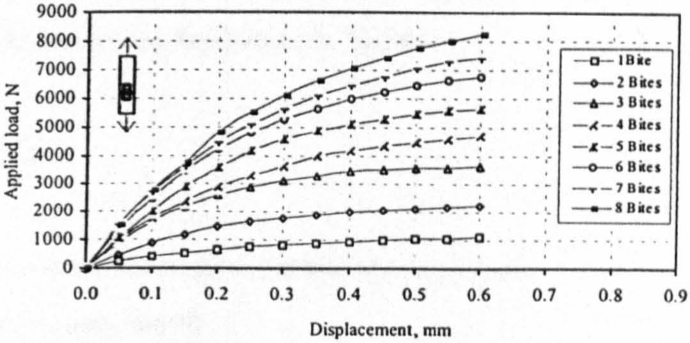


Figure 5.2 Comparison of joints performance subjected to tension force parallel to the grain using different number of bites.

Plate ref. number	Number of bites	Average load at 0.6mm displacement (N)	Failure modes
M20/0310B	1	1126	Anchorage
M20/0310B	2	2219	Anchorage
M20/0310B	3	3631	Anchorage
M20/0310B	4	4701	Anchorage
M20/0310B	5	5637	Anchorage
M20/0310B	6	6769	Anchorage
M20/0310B	7	7426	Anchorage
M20/0310B	8	8240	Anchorage

Table 5.2 The average load at 0.6mm displacement for joints with various number of bites subjected to tension force parallel to the grain.

It was observed that the number of bites had significant effects on the ultimate strength and stiffness and hence on the ductility of the joints when loaded in tension. The stiffness of the joints increased with an increase in the number of bites. The rate of increasing was approximately linear.

5.4.1.1 The stiffness characteristics of the joints

In order to investigate the effects of number of bites on the performance of the joints subjected to tension load under short-term duration, the stiffness characteristics of all tested specimens were analysed in detail. The stiffness of the joint (K_t) defined as the ratio between the applied load and the displacement in the joint.

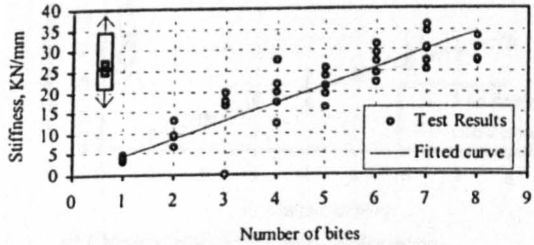
$$K_t = \frac{P_t}{\delta} \tag{5.1}$$

where K_t = stiffness of the joint under tensile loading (N/mm).

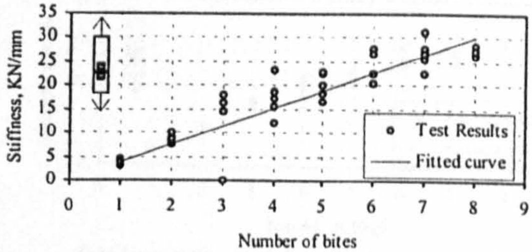
P_t = tensile load (N).

δ = displacement (mm).

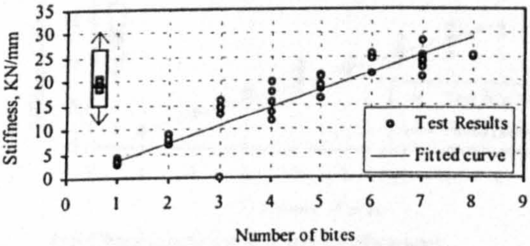
For all specimens tested the displacement at failure was about 0.6mm.The average magnitude of the stiffness sustained by each joints specimen at 0.05mm to 0.6mm displacement level was determined. Figure 5.3 represents results of stiffness versus number of bites in the joints at displacement levels of 0.05mm to 0.6mm. Linear equations were fitted the stiffness versus number of bites curves to define them. These equations were directed to pass through the point of origin to simulate the condition of zero stiffness at number of bites equals to zero. The equations obtained are tabulated and presented in Table 5.3. These equations were then analysed and an empirical model (i.e. equation 5.2) describing the stiffness of punched metal plate timber connections with different number of bites under tensile loading was developed.



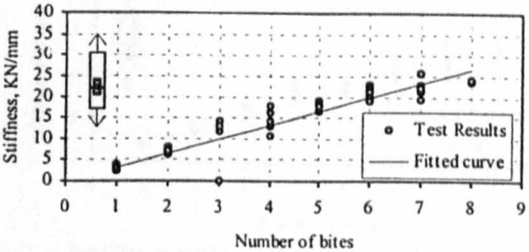
(a) Characteristics at 0.05mm displacement.



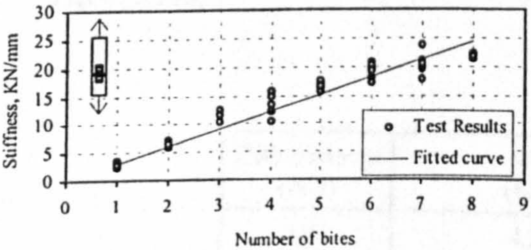
(b) Characteristics at 0.1mm displacement.



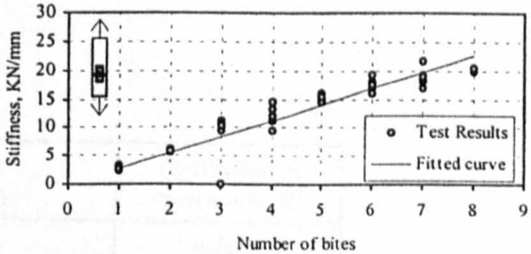
(c) Characteristics at 0.15mm displacement.



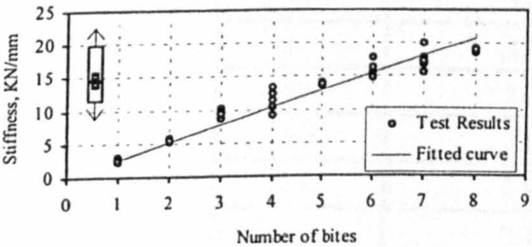
(d) Characteristics at 0.2mm displacement.



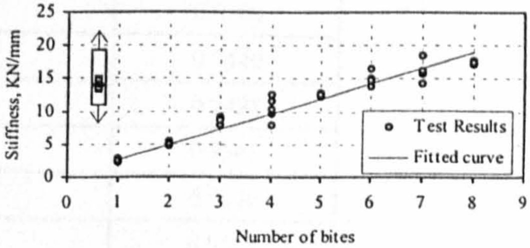
(e) Characteristics at 0.25mm displacement.



(f) Characteristics at 0.3mm displacement.

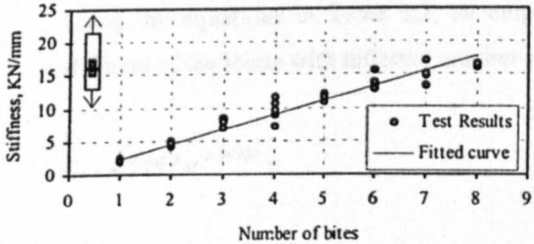


(g) Characteristics at 0.35mm displacement.

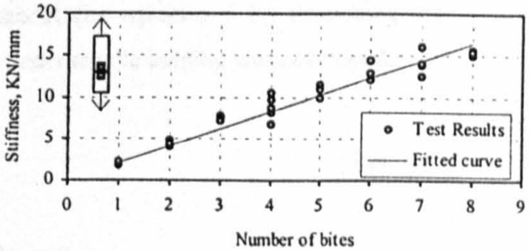


(h) Characteristics at 0.4mm displacement.

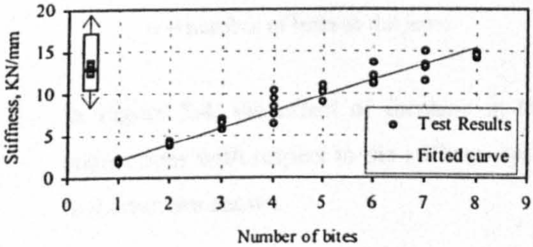
Figure 5.3 Stiffness sustained in the joint versus number of bites under tensile loading parallel to the grain.



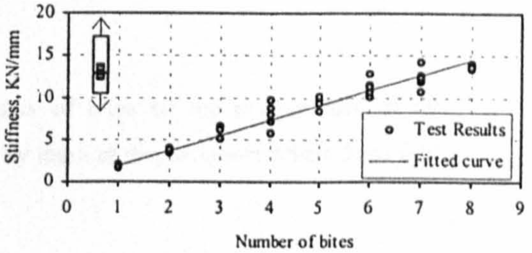
(i) Characteristics at 0.45mm displacement.



(k) Characteristics at 0.5mm displacement.



(m) Characteristics at 0.55mm displacement.



(n) Characteristics at 0.6mm displacement.

Figure 5.3 cont.

Displacement (mm)	Stiffness (KN/mm)	Coefficient of correlation, R^2
0.05	4.3291 n	0.9204
0.1	3.7725 n	0.9017
0.15	3.6222 n	0.9106
0.2	3.3343 n	0.9440
0.25	3.0469 n	0.9498
0.3	2.8059 n	0.9561
0.35	2.5915 n	0.9636
0.4	2.3937 n	0.9688
0.45	2.2193 n	0.9755
0.5	2.0665 n	0.9823
0.55	1.9359 n	0.9841
0.6	1.8134 n	0.9864

n = number of bites in the joints.

Table 5.3 The equations of the various curves in Figure 5.3.

Using the equations in Table 5.3, an empirical model (i.e equation 5.2) describing the stiffness of the joints with different number of bites under tensile loading was developed.

$$K_t = 4.5297\, e^{-1.5625\delta}\, n \tag{5.2}$$

where K_t = stiffness of the joint under tensile loading (kN/mm).

δ = displacement (mm).

n = number of bites in the joint.

In Figure 5.4, the effect of increase in the number of bites on the performance of the connections with respect to the stiffness sustained by them at displacement levels from 0.05 to 0.6mm are shown.

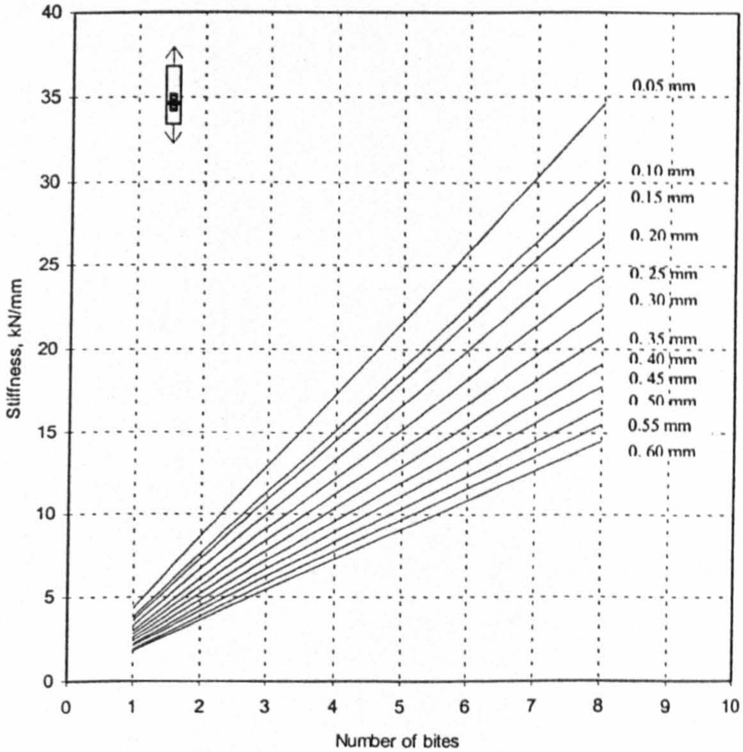
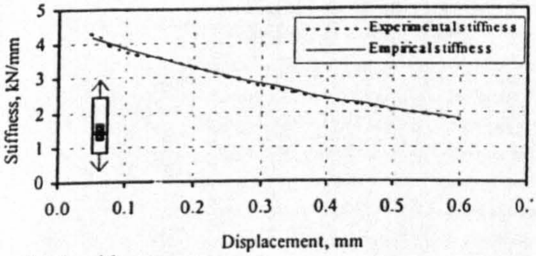


Figure 5.4 Stiffness vs number of bites in joints under tensile loading parallel to the grain.

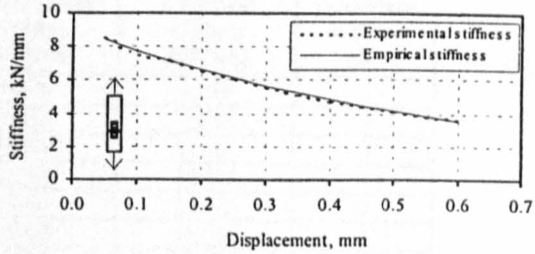
It is clear that the stiffness of the joints were dependent on the number of bites in the joints when loaded in tension parallel to the grain. The stiffness of the joints increased with an increase in the number of bites. The rate of increasing was approximately linear. At low displacement (0.05mm), stiffness was high comparing with high displacement (0.6mm). The rate of increasing in stiffness was reduced as displacement was increased.

In Figure 5.5, a comparison of stiffness versus displacement between experimental and empirical (i.e. equation 5.2) results, for joints with different number of bites are represented. There was a good agreement between the empirical model and experimental results.

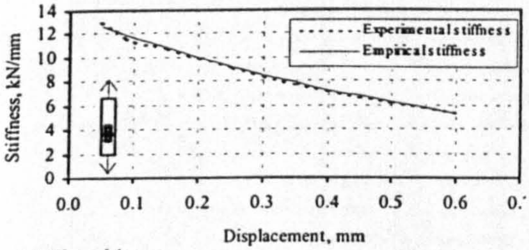
In Table 5.4 Comparison between the experimental and empirical (i.e. equation 5.2) stiffness at displacement levels from 0.05mm to 0.6mm for the various number of bites in the joints are shown.



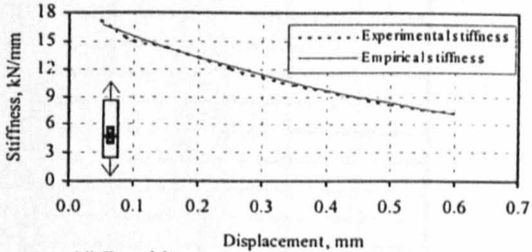
(a) One bite.



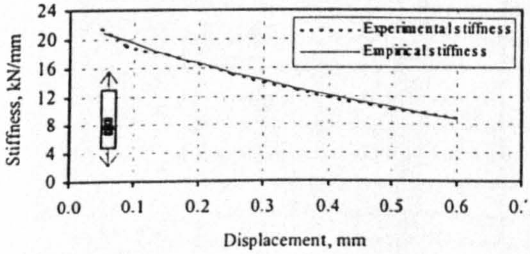
(b) Two bites.



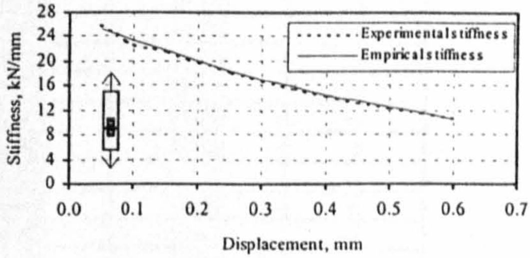
(c) Three bites.



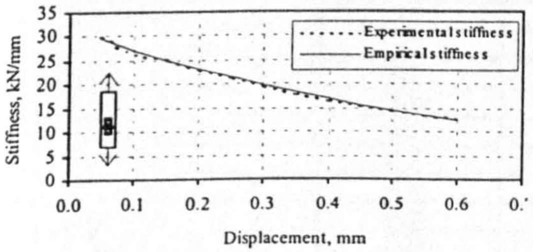
(d) Four bites.



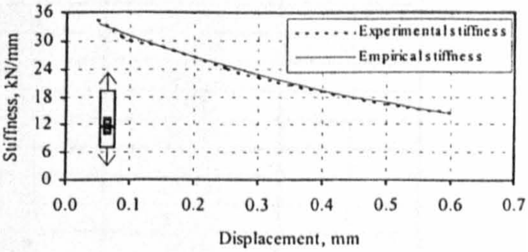
(e) Five bites.



(f) Six bites.



(g) Seven bites.



(h) Eight bites.

Figure 5.5 Comparison of stiffness vs displacement curve between experimental and empirical (i.e. equation 5.2) results.

Plate Number	Number of Bites	Displacement level (mm)	Experimental stiffness (kN/mm)	Empirical stiffness (kN/mm)	Percentage of Error (%)
M20/0310B	1	0.05	4.329	4.189	-3
M20/0310B	2	0.05	8.658	8.379	-3
M20/0310B	3	0.05	12.987	12.568	-3
M20/0310B	4	0.05	17.316	16.757	-3
M20/0310B	5	0.05	21.646	20.946	-3
M20/0310B	6	0.05	25.975	25.136	-3
M20/0310B	7	0.05	30.304	29.325	-3
M20/0310B	8	0.05	34.633	33.514	-3
M20/0310B	1	0.1	3.772	3.874	3
M20/0310B	2	0.1	7.545	7.749	3
M20/0310B	3	0.1	11.317	11.623	3
M20/0310B	4	0.1	15.090	15.498	3
M20/0310B	5	0.1	18.863	19.372	3
M20/0310B	6	0.1	22.635	23.247	3
M20/0310B	7	0.1	26.407	27.121	3
M20/0310B	8	0.1	30.180	30.996	3
M20/0310B	1	0.15	3.622	3.583	-1
M20/0310B	2	0.15	7.244	7.167	-1
M20/0310B	3	0.15	10.867	10.750	-1
M20/0310B	4	0.15	14.489	14.333	-1
M20/0310B	5	0.15	18.111	17.916	-1
M20/0310B	6	0.15	21.733	21.500	-1
M20/0310B	7	0.15	25.355	25.083	-1
M20/0310B	8	0.15	28.978	28.666	-1
M20/0310B	1	0.2	3.334	3.314	-1
M20/0310B	2	0.2	6.669	6.628	-1
M20/0310B	3	0.2	10.003	9.942	-1
M20/0310B	4	0.2	13.337	13.256	-1
M20/0310B	5	0.2	16.671	16.570	-1
M20/0310B	6	0.2	20.006	19.884	-1
M20/0310B	7	0.2	23.340	23.198	-1
M20/0310B	8	0.2	26.674	26.512	-1
M20/0310B	1	0.25	3.047	3.065	1
M20/0310B	2	0.25	6.094	6.130	1
M20/0310B	3	0.25	9.141	9.195	1
M20/0310B	4	0.25	12.188	12.260	1
M20/0310B	5	0.25	15.235	15.325	1
M20/0310B	6	0.25	18.281	18.390	1

Table 5.4 Comparison between experimental and empirical stiffness at displacement level from 0.05mm to 0.6mm for various number of bites in the joints.

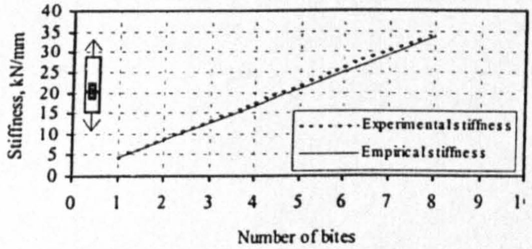
Plate Number	Number of Bites	Displacement level (mm)	Experimental stiffness (kN/mm)	Empirical stiffness (kN/mm)	Percentage of Error (%)
M20/0310B	7	0.25	21.328	21.455	1
M20/0310B	8	0.25	24.375	24.520	1
M20/0310B	1	0.3	2.806	2.835	1
M20/0310B	2	0.3	5.612	5.669	1
M20/0310B	3	0.3	8.418	8.504	1
M20/0310B	4	0.3	11.224	11.338	1
M20/0310B	5	0.3	14.029	14.173	1
M20/0310B	6	0.3	16.835	17.008	1
M20/0310B	7	0.3	19.641	19.842	1
M20/0310B	8	0.3	22.447	22.677	1
M20/0310B	1	0.35	2.591	2.622	1
M20/0310B	2	0.35	5.183	5.243	1
M20/0310B	3	0.35	7.774	7.865	1
M20/0310B	4	0.35	10.366	10.486	1
M20/0310B	5	0.35	12.957	13.108	1
M20/0310B	6	0.35	15.549	15.730	1
M20/0310B	7	0.35	18.140	18.351	1
M20/0310B	8	0.35	20.732	20.973	1
M20/0310B	1	0.4	2.394	2.425	1
M20/0310B	2	0.4	4.787	4.849	1
M20/0310B	3	0.4	7.181	7.274	1
M20/0310B	4	0.4	9.575	9.698	1
M20/0310B	5	0.4	11.968	12.123	1
M20/0310B	6	0.4	14.362	14.547	1
M20/0310B	7	0.4	16.756	16.972	1
M20/0310B	8	0.4	19.150	19.397	1
M20/0310B	1	0.45	2.219	2.242	1
M20/0310B	2	0.45	4.439	4.485	1
M20/0310B	3	0.45	6.658	6.727	1
M20/0310B	4	0.45	8.877	8.969	1
M20/0310B	5	0.45	11.097	11.212	1
M20/0310B	6	0.45	13.316	13.454	1
M20/0310B	7	0.45	15.535	15.697	1
M20/0310B	8	0.45	17.754	17.939	1
M20/0310B	1	0.5	2.067	2.074	0
M20/0310B	2	0.5	4.133	4.148	0
M20/0310B	3	0.5	6.200	6.222	0
M20/0310B	4	0.5	8.266	8.295	0
M20/0310B	5	0.5	10.332	10.369	0
M20/0310B	6	0.5	12.399	12.443	0
M20/0310B	7	0.5	14.466	14.517	0
M20/0310B	8	0.5	16.532	16.591	0
M20/0310B	1	0.55	1.936	1.918	-1
M20/0310B	2	0.55	3.872	3.836	-1
M20/0310B	3	0.55	5.808	5.754	-1
M20/0310B	4	0.55	7.744	7.672	-1
M20/0310B	5	0.55	9.679	9.590	-1
M20/0310B	6	0.55	11.615	11.508	-1

Table 5.4 cont.

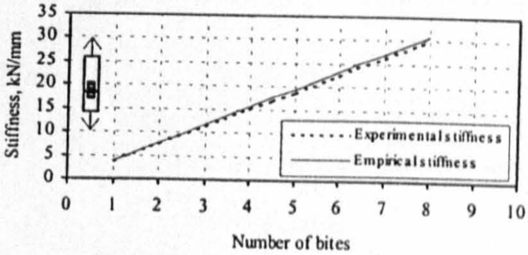
Plate Number	Number of Bites	Displacement level (mm)	Experimental stiffness (kN/mm)	Empirical stiffness (kN/mm)	Percentage of Error (%)
M20/0310B	7	0.55	13.551	13.426	-1
M20/0310B	8	0.55	15.487	15.344	-1
M20/0310B	1	0.6	1.813	1.774	-2
M20/0310B	2	0.6	3.627	3.548	-2
M20/0310B	3	0.6	5.440	5.322	-2
M20/0310B	4	0.6	7.254	7.095	-2
M20/0310B	5	0.6	9.067	8.869	-2
M20/0310B	6	0.6	10.880	10.643	-2
M20/0310B	7	0.6	12.694	12.417	-2
M20/0310B	8	0.6	14.507	14.191	-2

Table 5.4 cont.

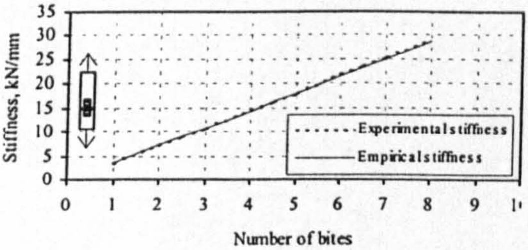
In Figure 5.6, a comparison of stiffness versus number of bites between experimental and empirical (i.e. equation 5.2) results for various joints with different number of bites at displacement levels from 0.05mm to 0.6mm are represented. There was a good agreement between the empirical model and experimental results.



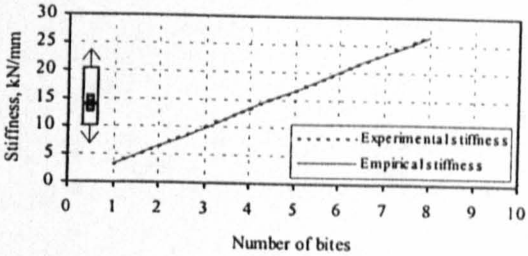
(a) Characteristics at 0.05mm displacement.



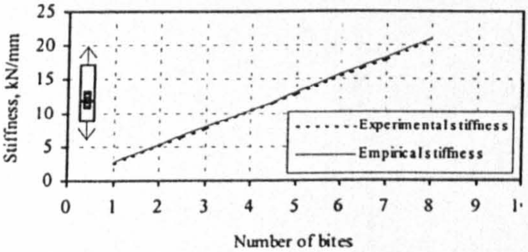
(b) Characteristics at 0.1mm displacement.



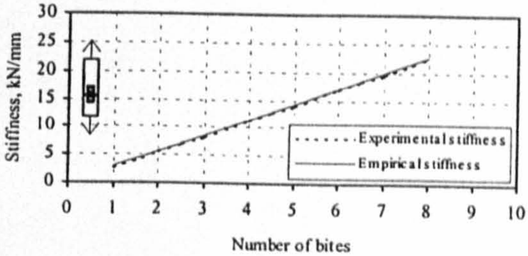
(c) Characteristics at 0.15mm displacement.



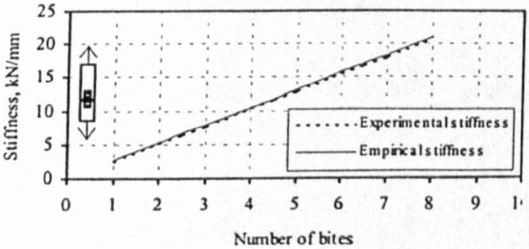
(d) Characteristics at 0.2mm displacement.



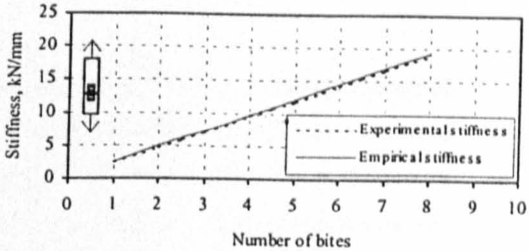
(e) Characteristics at 0.25mm displacement.



(f) Characteristics at 0.3mm displacement.

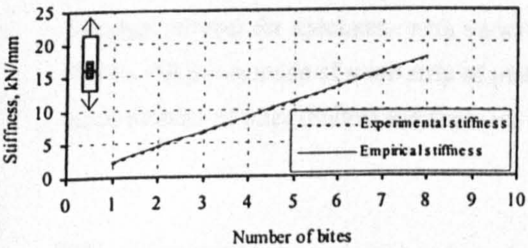


(g) Characteristics at 0.35mm displacement.

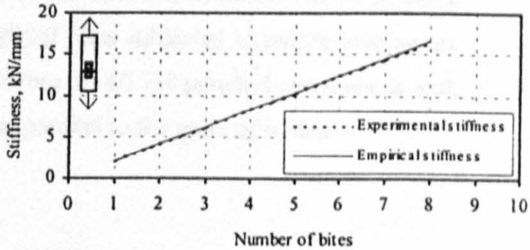


(h) Characteristics at 0.4mm displacement.

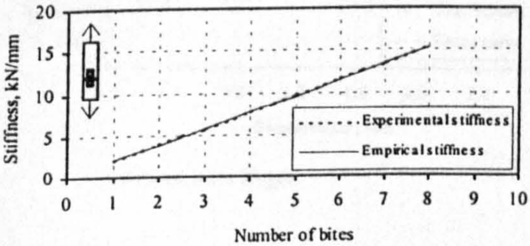
Figure 5.6 Comparison of stiffness vs number of bites between experimental and empirical (i.e. equation 5.2) results.



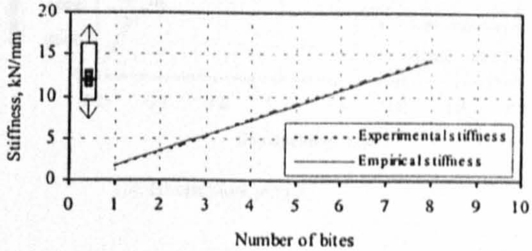
(i) Characteristics at 0.45mm displacement.



(k) Characteristics at 0.5mm displacement.



(m) Characteristics at 0.55mm displacement.



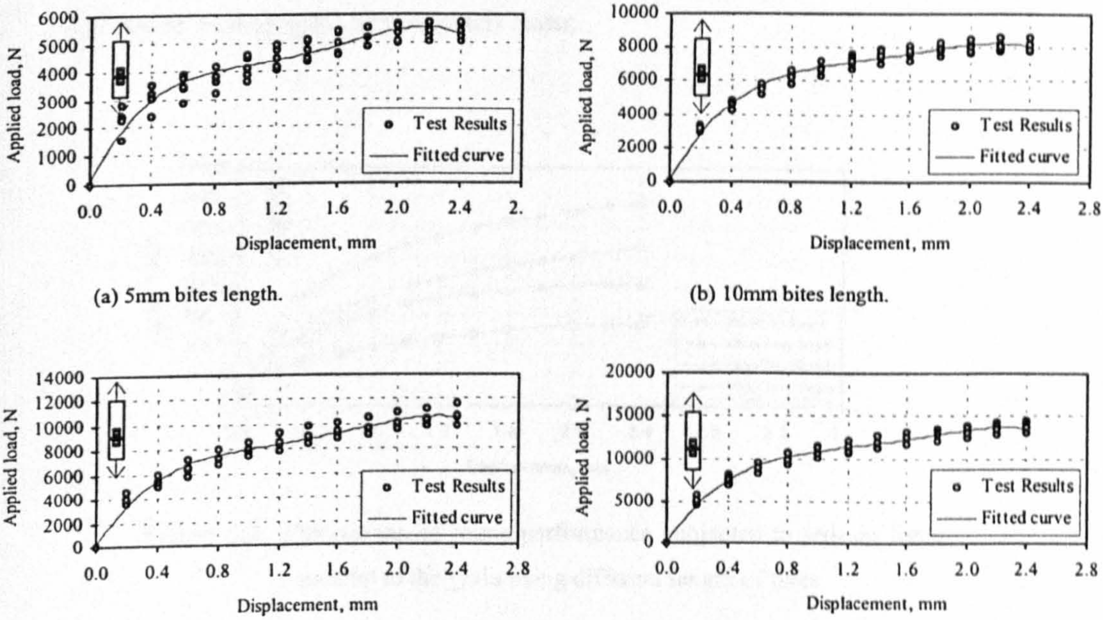
(n) Characteristics at 0.6mm displacement.

Figure 5.6 cont.

5.4.2 Effects of length of bites

Tests were carried out to determine the influences of length of bites on the performance of the punched metal plate timber joints subjected to tensile loads. The test samples were generally made of two pieces of timber dimensioned as 73mm×300mm and 73mm×80mm by 45mm thickness. The punched metal plate type used in construction of testing specimens was small strip of plates cut from M14/1333. The specimens were loaded to failure in tension. All joint specimens were manufactured using material as explained in chapter 3.

In Figure 5.7 typical load-displacement curves up to 0.24mm displacement with fitted curve (average curves) for specimens with various length of bites subjected to tensile loading are shown. All joints made of small strip of plates cut from M14/1333 punched metal plates with equal number of bites (8bites) and the loads applied parallel to the grain of timber.



(a) 5mm bites length.

(b) 10mm bites length.

(c) 15mm bites length.

(d) 20mm bites length.

Figure 5.7 Load – displacement behaviour of joints with different length of bites loaded in tension parallel to the grain.

The behaviour of the joints tested was assessed through observation of the failed specimens and their load-displacement relation. The load-displacement behaviour of each joint specimen was recorded and plotted. Fourth order polynomial equations was fitted to define the curves. The fitted curves simulated the load-displacement behaviour of the connection with good accuracy. These equations were directed to pass through the point of origin to simulate the condition of zero deformation at zero loads.

For all specimens tested the displacement at failure was about 2.4mm. A comparison of performance of joints in relation to the length of bites tested up to 2.4mm displacement is presented in Figure 5.8. The average load at 2.4mm displacement for each group of specimens is shown in Table 5.5. It was observed that the length of bites had significant effects on ultimate strength and stiffness and hence on the ductility of the joints when loaded in tension. The stiffness of the joints increased with an increase in the bites length. The rate of increasing was approximately linear.

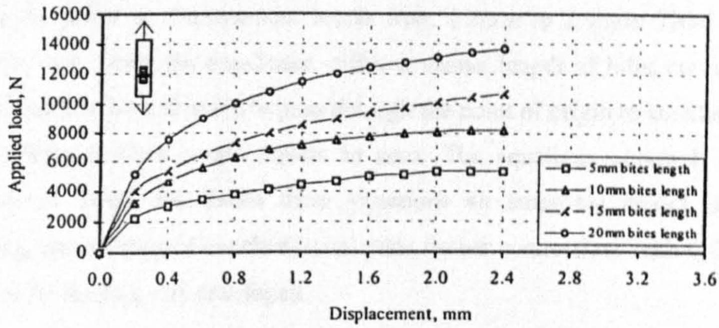


Figure 5.8 Comparison of joints performance subjected to tension force parallel to the grain using different length of bites.

Plate ref. number	Length of bites (mm)	Average load at 2.4mm displacement (N)
M14/1333	5	5409
M14/1333	10	8170
M14/1333	15	10657
M14/1333	20	13650

Table 5.5 The average load at 2.4mm displacement for joints with various bites length subjected to tension force parallel to the grain.

5.4.2.1 The stiffness characteristics of the joints

In order to investigate the effects of length of bites on the performance of the joints subjected to tension load parallel to the grain under short-term duration, the stiffness characteristics of all tested specimens were analysed in detail. The stiffness of the joint (K_t) defined as the ratio between the applied load and the displacement in the joint as described in equation 5.1.

The average magnitude of the stiffness sustained by each joints specimen at 0.2mm to 2.4mm displacement level was determined. Figure 5.9 represents results of stiffness versus length of bites in the joints at displacement levels from 0.2mm to 2.4mm. Third order polynomial equations were fitted the non-linear stiffness versus length of bites curves to define them. These equations were directed to pass through the point of origin to simulate the condition of zero stiffness at bites length equals to zero. The equations obtained are tabulated and presented in Table 5.6. From these equations an empirical model (i.e. equation 5.3) describing the stiffness of punched metal plate timber connections with different bites length under tensile loading was developed.

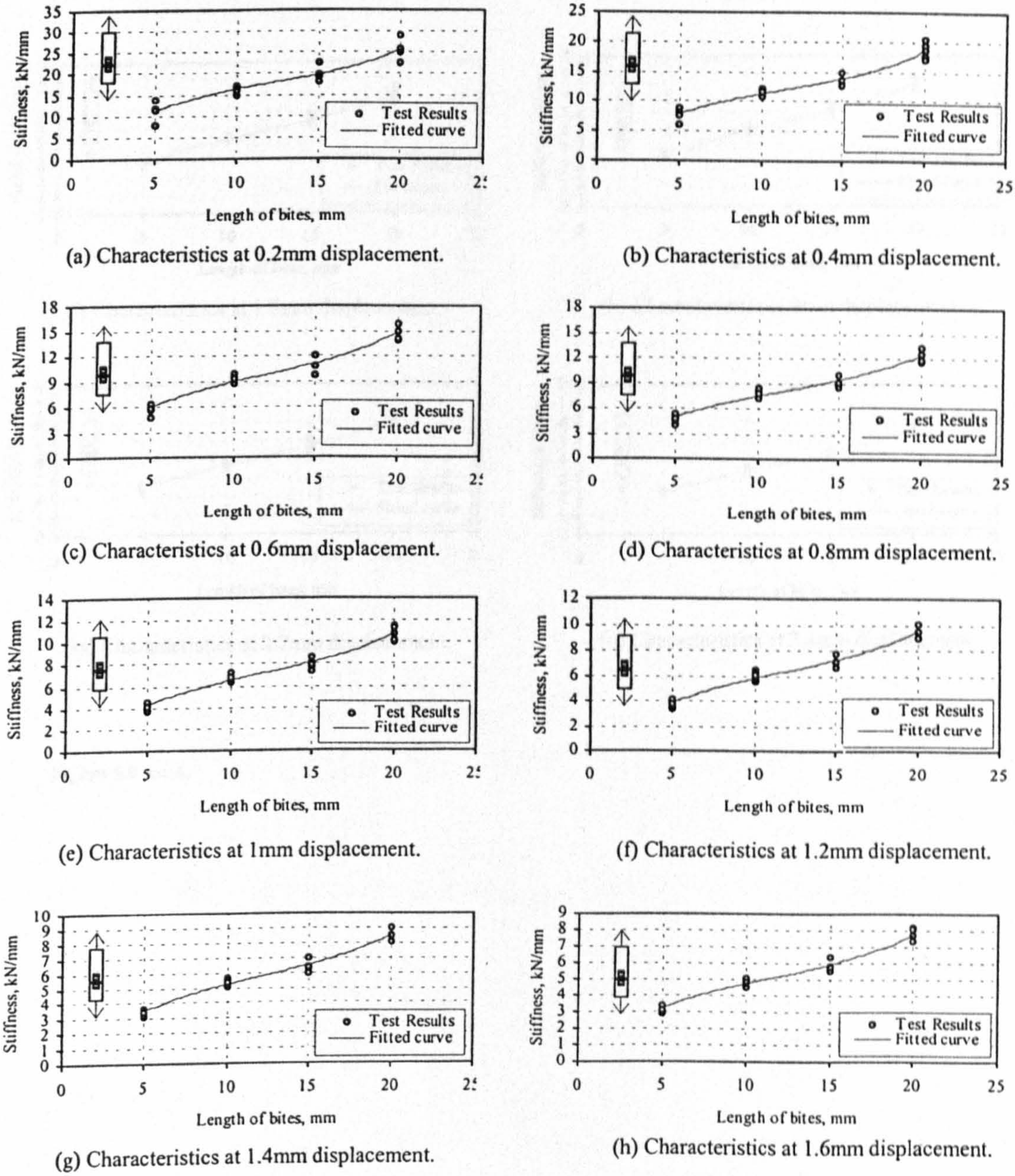
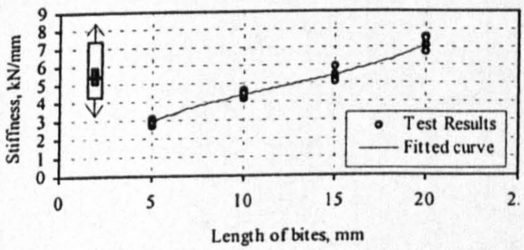
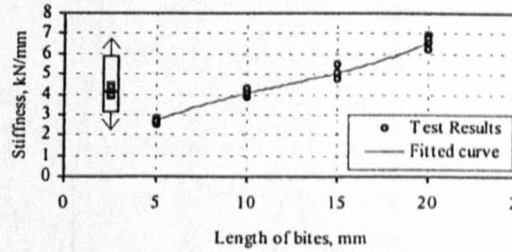


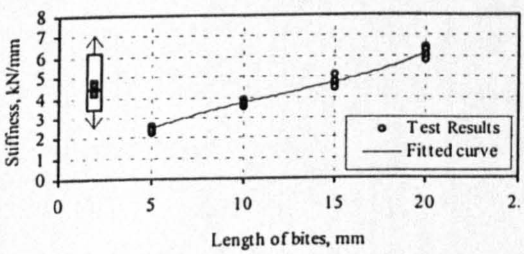
Figure 5.9 Stiffness sustained in the joint versus length of bites under tensile loading parallel to the grain.



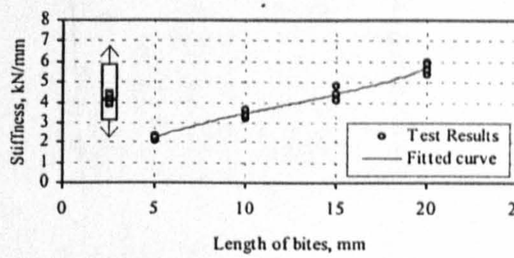
(i) Characteristics at 1.8mm displacement.



(k) Characteristics at 2mm displacement.



(m) Characteristics at 2.2mm displacement.



(n) Characteristics at 2.4mm displacement.

Figure 5.9 cont.

Displacement (mm)	Stiffness (KN/mm)	Coefficient of correlation, R^2
0.2	$0.0056\, l^3 - 0.2011\, l^2 + 3.0836\, l$	0.9990
0.4	$0.0044\, l^3 - 0.1524\, l^2 + 2.2109\, l$	0.9961
0.6	$0.0031\, l^3 - 0.1093\, l^2 + 1.6712\, l$	0.9933
0.8	$0.0024\, l^3 - 0.0838\, l^2 + 1.3502\, l$	0.9927
1.0	$0.002\, l^3 - 0.0717\, l^2 + 1.1679\, l$	0.9941
1.2	$0.0018\, l^3 - 0.0651\, l^2 + 1.0516\, l$	0.9960
1.4	$0.0016\, l^3 - 0.0592\, l^2 + 0.9522\, l$	0.9970
1.6	$0.0015\, l^3 - 0.0542\, l^2 + 0.8689\, l$	0.9988
1.8	$0.0013\, l^3 - 0.0487\, l^2 + 0.7908\, l$	0.9998
2.0	$0.0012\, l^3 - 0.0432\, l^2 + 0.7177\, l$	1
2.2	$0.001\, l^3 - 0.0375\, l^2 + 0.647\, l$	0.9996
2.4	$0.0009\, l^3 - 0.0326\, l^2 + 0.584\, l$	0.9990

l = length of bites in the joints (mm).

Table 5.6 The equations of the various curves in Figure 5.9.

Using the equations in Table 5.6, an empirical model (i.e equation 5.3) describing the stiffness of the joints with different length of bites under tensile loading was developed.

$$K_t = 0.002\, \delta^{-0.7467}\, l^3 - 0.0714\, \delta^{-0.7263}\, l^2 + 1.1483\, \delta^{-0.6671}\, l \qquad (5.3)$$

where K_t = stiffness of the joint under tensile loading (kN/mm).

δ = displacement (mm).

l = length of bites in the joint(mm).

In Figure 5.10, the effect of increase in the bites length on the performance of the connections with respect to the stiffness sustained by them at displacement levels from 0.2mm to 2.4mm are shown.

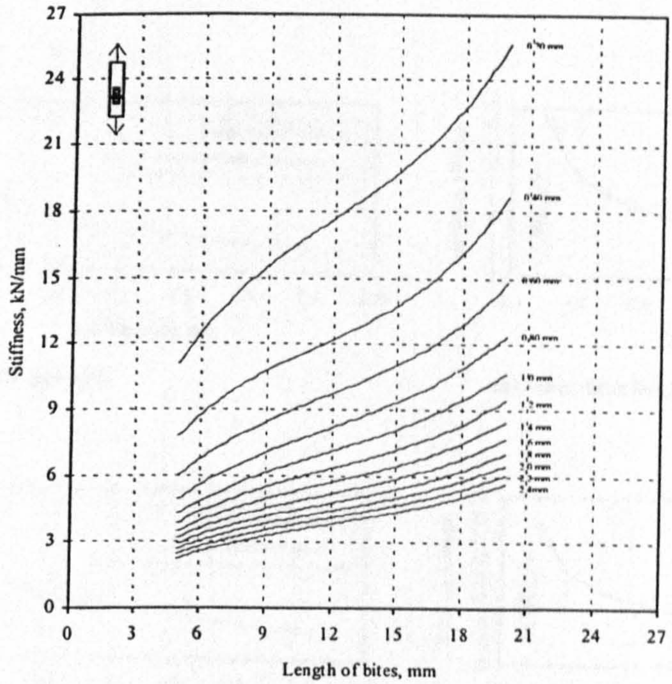
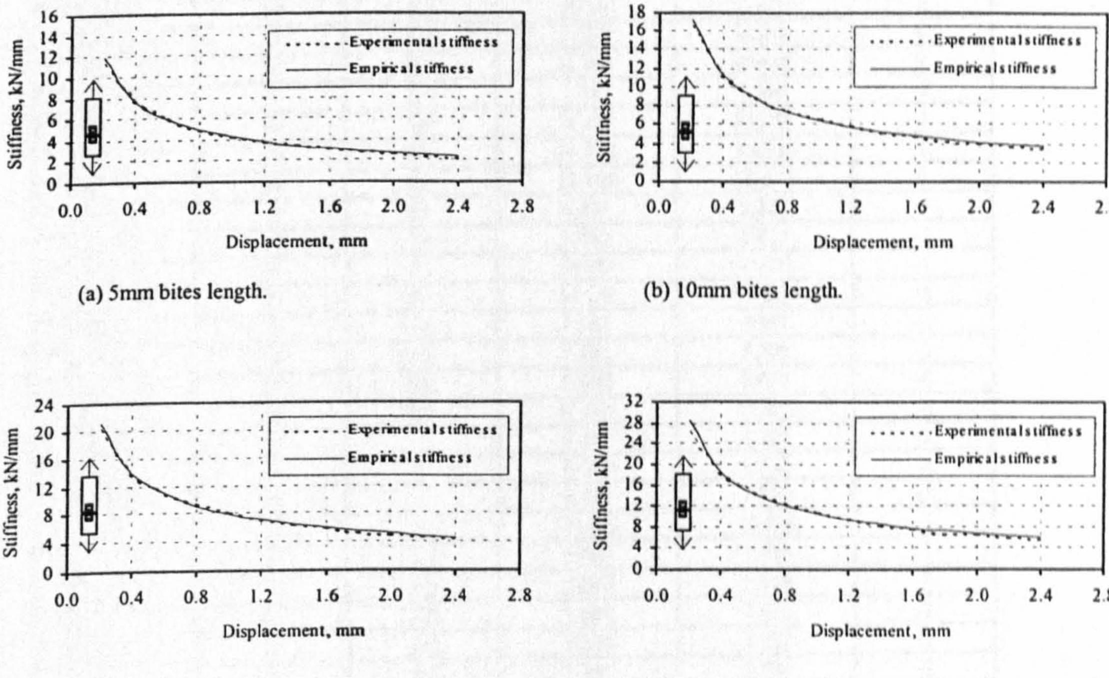


Figure 5.10 Stiffness vs length of bites in joints under tensile loading parallel to the grain.

It is clear that the stiffness of the joints were dependent on the length of bites in the joints when loaded in tension parallel to the grain. The stiffness of the joints increased with an increase in the bites length. The rate of increase in stiffness increased as the length of bites increased above approximately 60% of the maximum length of bites available in a tested punched metal plate. At low displacement levels, stiffness was high compared with at high displacement levels. The rate of increasing in stiffness was reduced as displacement was increased.

In Figure 5.11, a comparison of stiffness versus displacement relationships between experimental and the developed empirical results for joints with different bites length are represented. There was a good agreement between the empirical model and experimental results.



(a) 5mm bites length.

(b) 10mm bites length.

(c) 15mm bites length.

(d) 20mm bites length.

Figure 5.11 Comparison of stiffness vs displacement curve between experimental and empirical (i.e. equation 5.3) results.

In Table 5.7 Comparison between the experimental and empirical (i.e. equation 5.3) stiffness at displacement levels 0.2mm to 2.4mm for the various bites length in the joints are shown.

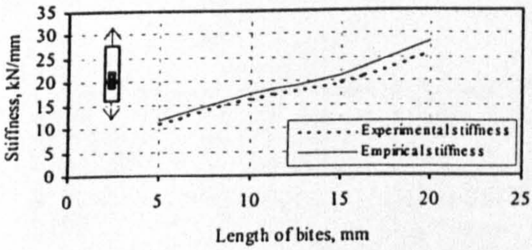
Plate Number	Bites length (mm)	Displacement level (mm)	Experimental stiffness (kN/mm)	Empirical stiffness (kN/mm)	Percentage of Error (%)
M14/1333	5	0.2	11.091	11.886	7
M14/1333	10	0.2	16.326	17.271	6
M14/1333	15	0.2	19.907	21.144	6
M14/1333	20	0.2	26.032	28.494	9
M14/1333	5	0.4	7.795	7.603	-2
M14/1333	10	0.4	11.269	11.234	0
M14/1333	15	0.4	13.724	13.866	1
M14/1333	20	0.4	18.458	18.473	0
M14/1333	5	0.6	6.011	5.852	-3
M14/1333	10	0.6	8.882	8.727	-2
M14/1333	15	0.6	10.938	10.821	-1
M14/1333	20	0.6	14.504	14.332	-1
M14/1333	5	0.8	4.956	4.859	-2
M14/1333	10	0.8	7.522	7.293	-3
M14/1333	15	0.8	9.498	9.072	-4
M14/1333	20	0.8	12.684	11.968	-6
M14/1333	5	1	4.297	4.207	-2
M14/1333	10	1	6.509	6.343	-3
M14/1333	15	1	8.136	7.910	-3
M14/1333	20	1	10.678	10.406	-3
M14/1333	5	1.2	3.856	3.739	-3
M14/1333	10	1.2	5.806	5.659	-3
M14/1333	15	1.2	7.201	7.070	-2
M14/1333	20	1.2	9.392	9.282	-1
M14/1333	5	1.4	3.481	3.384	-3
M14/1333	10	1.4	5.202	5.138	-1
M14/1333	15	1.4	6.363	6.430	1
M14/1333	20	1.4	8.164	8.426	3
M14/1333	5	1.6	3.177	3.103	-2
M14/1333	10	1.6	4.769	4.725	-1
M14/1333	15	1.6	5.901	5.922	0
M14/1333	20	1.6	7.698	7.749	1
M14/1333	5	1.8	2.899	2.876	-1
M14/1333	10	1.8	4.338	4.389	1
M14/1333	15	1.8	5.292	5.507	4
M14/1333	20	1.8	6.736	7.196	7
M14/1333	5	2	2.658	2.686	1
M14/1333	10	2	4.057	4.108	1
M14/1333	15	2	5.095	5.160	1
M14/1333	20	2	6.674	6.736	1
M14/1333	5	2.2	2.423	2.525	4
M14/1333	10	2.2	3.720	3.869	4
M14/1333	15	2.2	4.643	4.865	5
M14/1333	20	2.2	5.940	6.344	7

Table 5.7 Comparison between experimental and empirical stiffness at displacement level from 0.2mm to 2.4mm for various bites length in the joints.

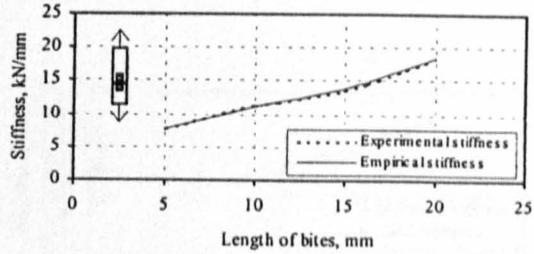
Plate Number	Bites length (mm)	Displacement level (mm)	Experimental stiffness (kN/mm)	Empirical stiffness (kN/mm)	Percentage of Error (%)
M14/1333	5	2.4	2.218	2.387	8
M14/1333	10	2.4	3.480	3.663	5
M14/1333	15	2.4	4.463	4.610	3
M14/1333	20	2.4	5.840	6.007	3

Table 5.7 cont.

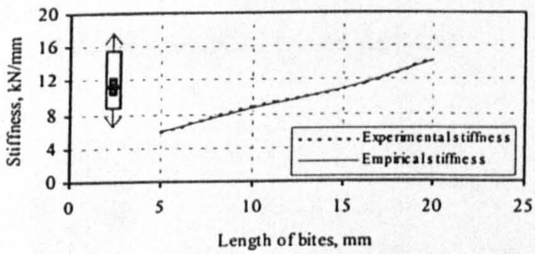
In Figure 5.12, a comparison of stiffness versus length of bites between experimental and empirical (i.e. equation 5.3) results for various joints with different length of bites at displacement levels from 0.2mm to 2.4mm are represented. There was a good agreement between the empirical model and experimental results.



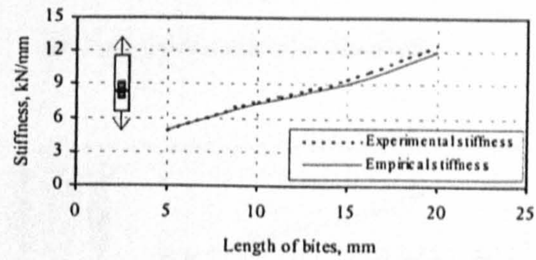
(a) Characteristics at 0.2mm displacement.



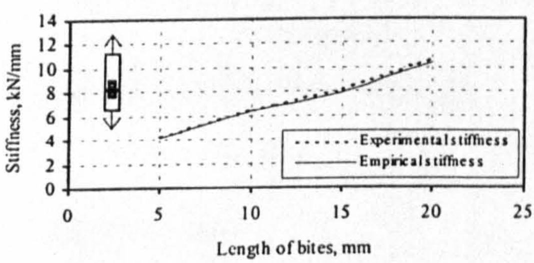
(b) Characteristics at 0.4mm displacement.



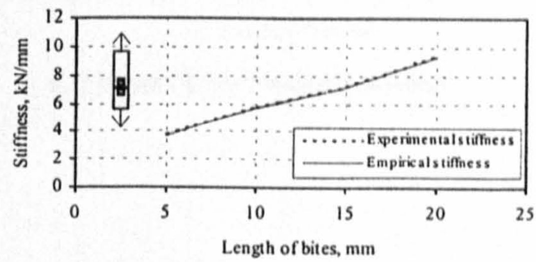
(c) Characteristics at 0.6mm displacement.



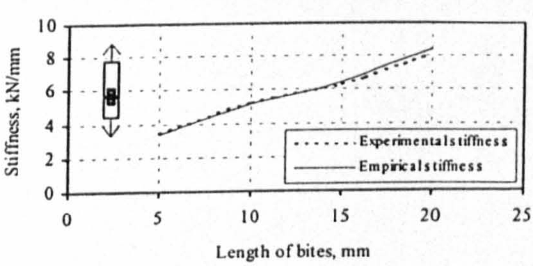
(d) Characteristics at 0.8mm displacement.



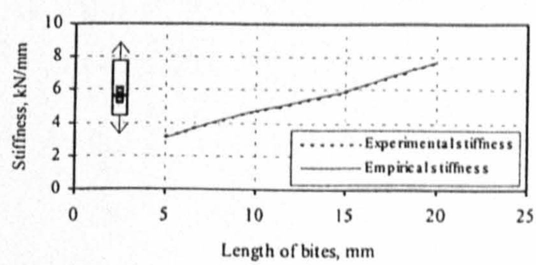
(e) Characteristics at 1mm displacement.



(f) Characteristics at 1.2mm displacement.

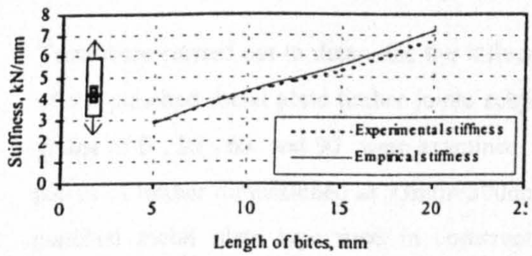


(g) Characteristics at 1.4mm displacement.

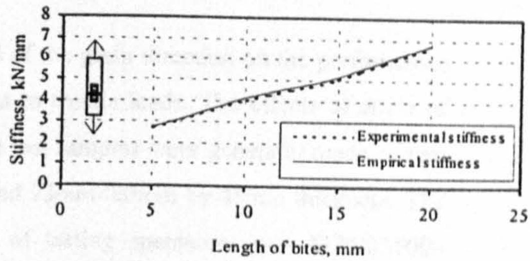


(h) Characteristics at 1.6mm displacement.

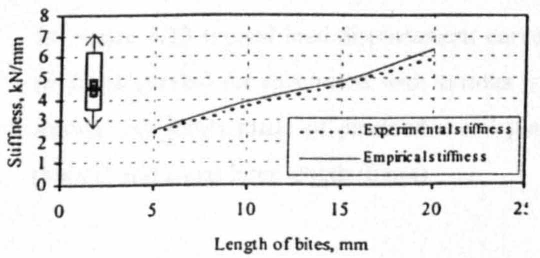
Figure 5.12 Comparison of stiffness vs length of bites between experimental and empirical (i.e. equation 5.3) results.



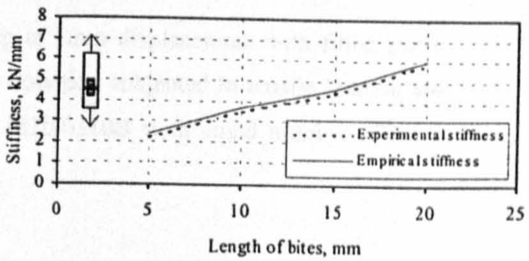
(i) Characteristics at 1.8mm displacement.



(k) Characteristics at 2mm displacement.



(m) Characteristics at 2.2mm displacement.



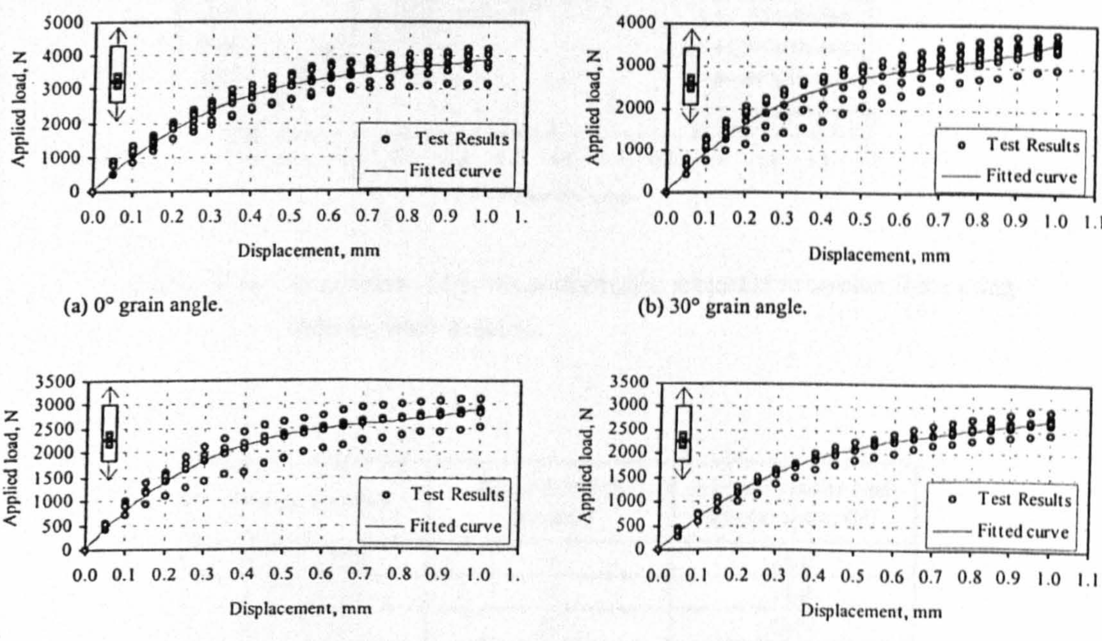
(n) Characteristics at 2.4mm displacement.

Figure 5.12 cont.

5.4.3 Effects of grain direction

Tests were carried out to determine the influences of the grain direction on the performance of the punched metal plate timber joints subjected to tensile loads. The effects of angle of grains of 0 , 30 , 60 and 90 were examined. The test samples were generally made of two pieces of timber dimensioned as 73mm×300mm and 73mm×80mm by 45mm thickness. The punched metal plate type used in construction of testing specimens was M20/0310B-101mm×25mm×1mm. The specimens were loaded to failure in tension. All joint specimens were manufactured using material as explained in chapter 3.

In Figure 5.13 typical load-displacement curves up to 1mm displacement with fitted curve (average curves) for specimens with various grain direction subjected to tensile loading are shown. All joints made of punched metal plates M20/0310B with equal number of bites (8bites) and equal bites length (8mm).



(a) 0° grain angle.

(b) 30° grain angle.

(c) 60° grain angle.

(d) 90° grain angle.

Figure 5.13 Load – displacement behaviour of joints under tension loading with different grain direction.

The behaviour of the joints tested was assessed through observation of the failed specimens and their load-displacement relation. The load-displacement behaviour of each joint specimen was recorded and plotted. Third order polynomial equations was fitted to define the curves. The fitted curves simulated the load-displacement behaviour of the connection with good accuracy. These equations were directed to pass through the point of origin to simulate the condition of zero deformation at zero loads.

A comparison of joints performance in relation to the grain direction tested up to 1mm displacement is presented in Figure 5.14. The average load at 1mm displacement for each group of specimens is shown in Table 5.8.

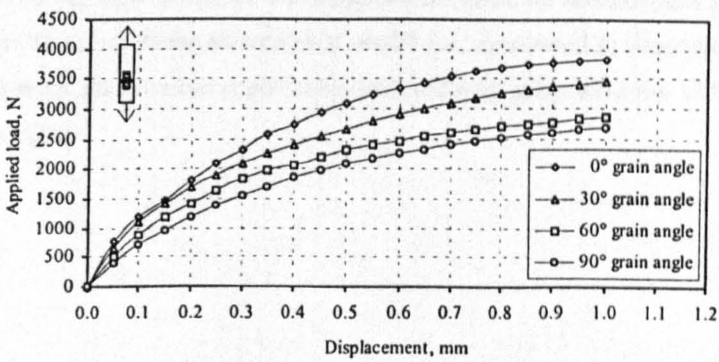


Figure 5.14 Comparison of joints performance subjected to tension force using different grain direction.

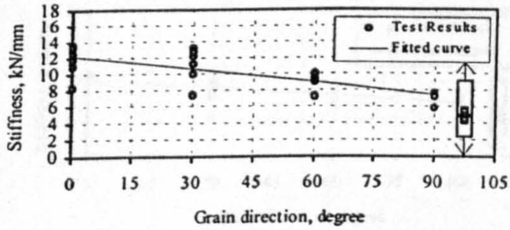
Plate ref. number	Grain direction (degree)	Average load at 1mm displacement (N)
M20/0310B	0	3827
M20/0310B	30	3446
M20/0310B	60	2852
M20/0310B	90	2691

Table 5.8 The average load at 1mm displacement for joints with various grain direction subjected to tension force.

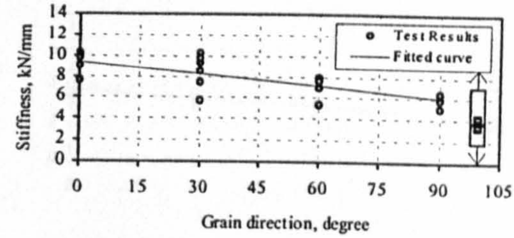
5.4.3.1 The stiffness characteristics of the joints

In order to investigate the effects of the grain direction on the performance of the joints subjected to tension load under short-term duration, the stiffness characteristics of all tested specimens were analysed. The stiffness of the joint (K_t) defined as the ratio between the applied load and the displacement in the joint as described in equation 5.1.

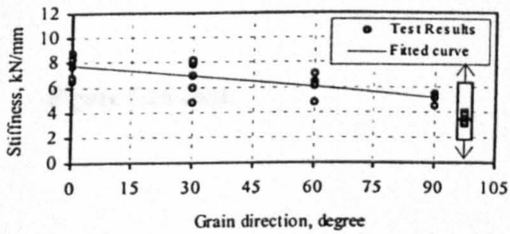
For all specimens tested the displacement at failure was about 1mm. The average magnitude of the stiffness sustained by each joints specimen at 0.1mm to 1mm displacement level was determined. Figure 5.15 represents results of stiffness versus grain direction in the joints at displacement levels of 0.1mm to 1mm. The relationship between stiffness and the grain direction was approximately linear. Linear equations were fitted the stiffness versus grain direction curves to define them. The equations obtained are tabulated and presented in Table 5.9. From these equations an empirical model (i.e. equation 5.4) describing the stiffness of punched metal plate timber connections with different grain direction under tensile loading was developed.



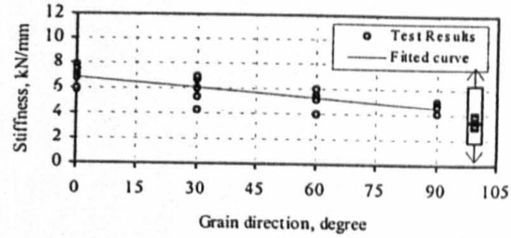
(a) Characteristics at 0.1mm displacement.



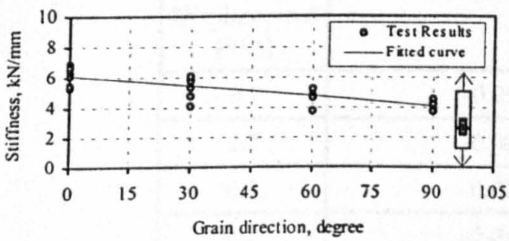
(b) Characteristics at 0.2mm displacement.



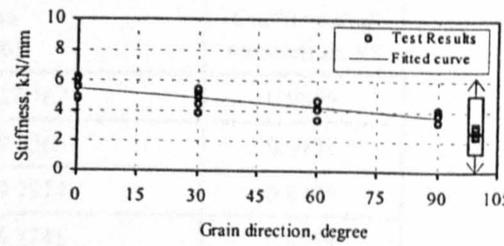
(c) Characteristics at 0.3mm displacement.



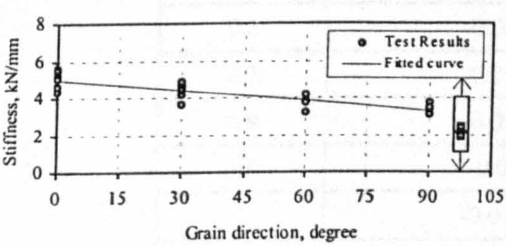
(d) Characteristics at 0.4mm displacement.



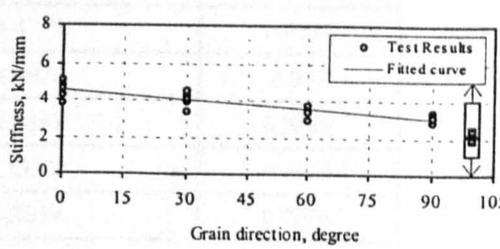
(e) Characteristics at 0.5mm displacement.



(f) Characteristics at 0.6mm displacement.

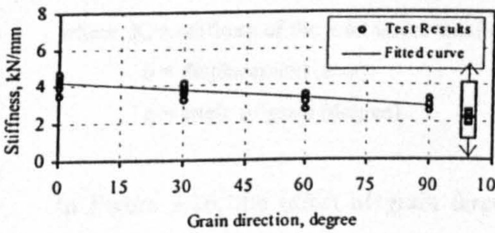


(g) Characteristics at 0.7mm displacement.

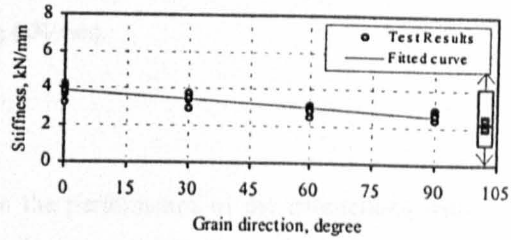


(h) Characteristics at 0.8mm displacement.

Figure 5.15 Stiffness sustained in the joint versus grain directions under tensile loading.



(i) Characteristics at 0.7mm displacement.



(k) Characteristics at 0.7mm displacement.

Figure 5.15 cont.

Displacement (mm)	Stiffness (KN/mm)	Coefficient of correlation, R^2
0.1	-0.0538 g + 12.167	0.9605
0.2	-0.0359 g + 9.2562	0.9737
0.3	-0.0283 g + 7.7974	0.9995
0.4	-0.0244 g + 6.7741	0.9859
0.5	-0.0221 g + 6.0647	0.9836
0.6	-0.0203 g + 5.4779	0.9781
0.7	-0.0187 g + 4.9974	0.977
0.8	-0.0168 g + 4.5542	0.9689
0.9	-0.015 g + 4.1523	0.9653
1	-0.0133 g + 3.8039	0.9604

g = angle of grain (degree).

Table 5.9 The equations of the various curves in Figure 5.15.

Using the equations in Table 5.9, an empirical model (i.e equation 5.4) describing the stiffness of the joints with different grain direction under tensile loading was developed.

$$K_t = 0.0145\,\delta^{-0.5739} g + 4.102\,\delta^{-0.5004} \qquad (5.4)$$

where K_t = stiffness of the joint under tensile loading (kN/mm).

δ = displacement (mm).

g = angle of grain (degree).

In Figure 5.16, the effect of grain direction on the performance of the connections with respect to the stiffness sustained by them at displacement levels from 0.1mm to 1mm are shown.

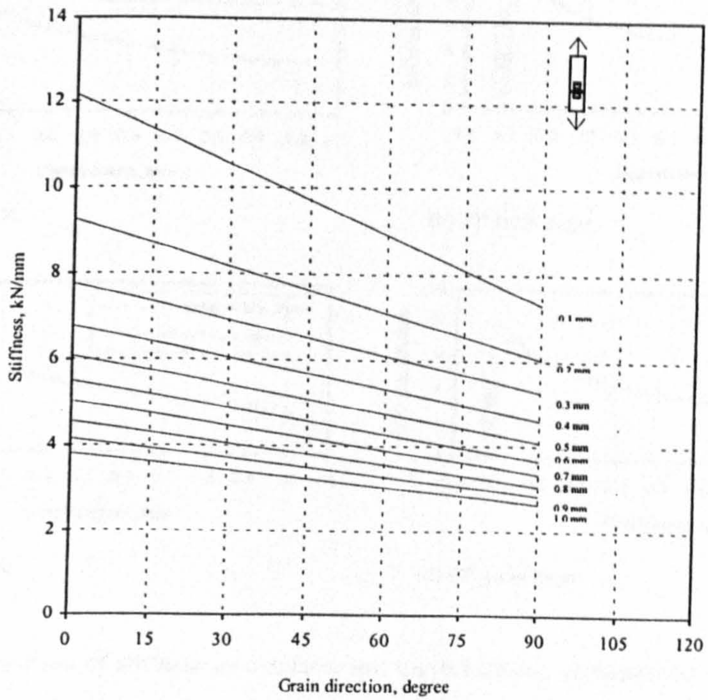
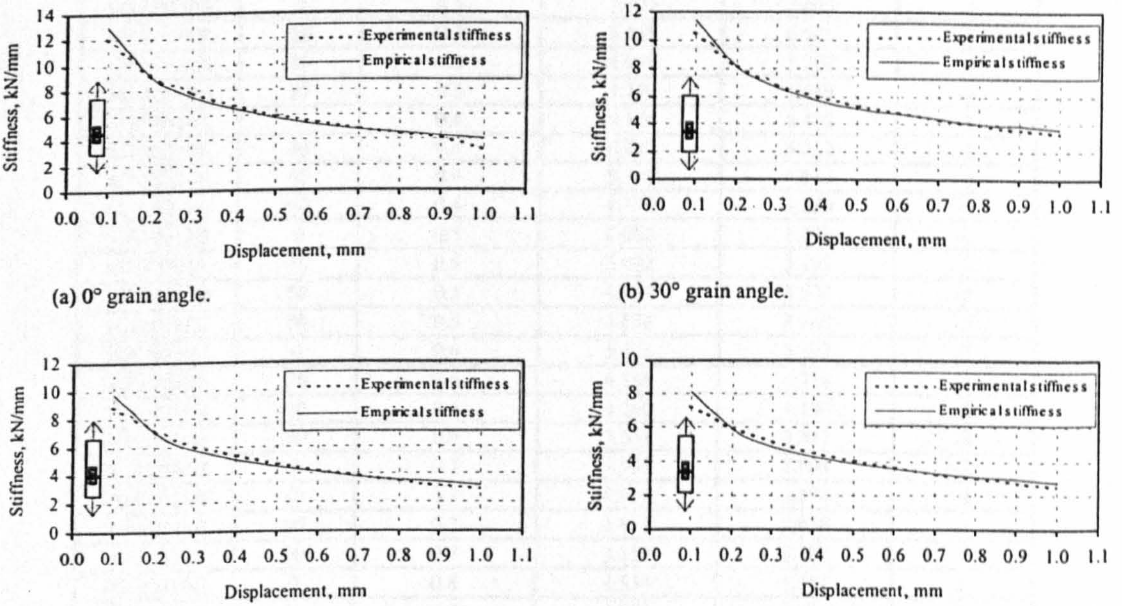


Figure 5.16 Stiffness vs grain direction in joints under tensile loading.

It is clear that the stiffness of the joints were dependent on the grain direction in the joints under tensile loading. The stiffness of the joints decreased with an increase in the angle of grain. The rate of decrease in stiffness increased as the angle of grain increased. At low displacement (0.1mm), stiffness was high comparing with high displacement (1mm). The rate of increasing in stiffness was reduced as displacement was increased.

In Figure 5.17, a comparison of stiffness versus displacement curves between experimental and empirical (i.e. equation 5.4) results for joints with different grain direction are represented. There was a good agreement between the empirical model and experimental results.



(a) 0° grain angle.

(b) 30° grain angle.

(c) 60° grain angle.

(d) 90° grain angle.

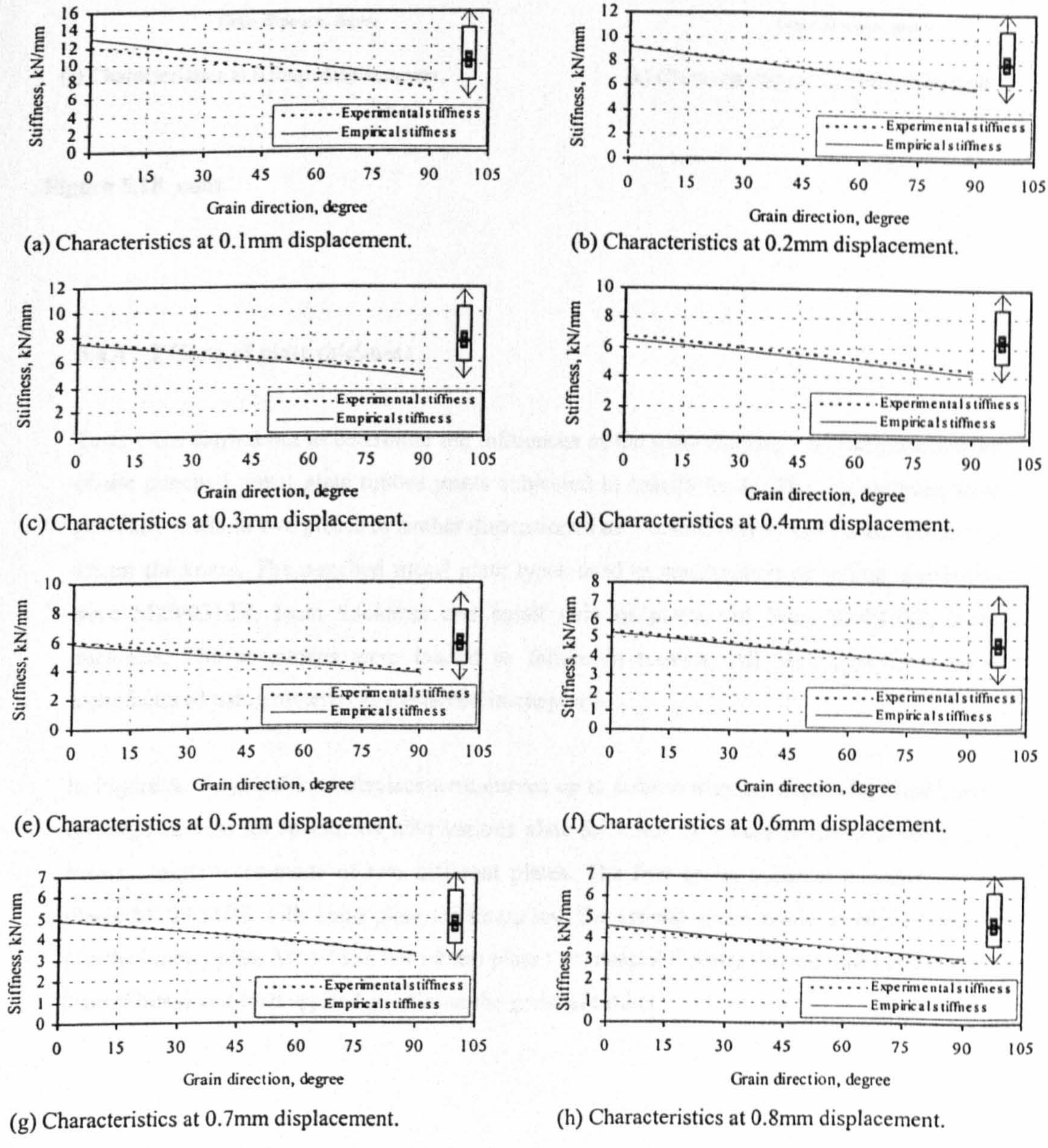
Figure 5.17 Comparison of stiffness vs displacement curve between experimental and empirical (i.e. equation 5.4) results.

In Table 5.10 Comparison between the experimental and empirical (i.e. equation 5.4) stiffness at displacement levels from 0.1mm to 1mm for the various grain direction in the joints are shown.

Plate Number	Grain direction (degree)	Displacement level (mm)	Experimental stiffness (kN/mm)	Empirical stiffness (kN/mm)	Percentage of Error (%)
M20/0310B	0	0.1	12.167	12.984	7
M20/0310B	30	0.1	10.553	11.353	8
M20/0310B	60	0.1	8.939	9.722	9
M20/0310B	90	0.1	7.325	8.091	10
M20/0310B	0	0.2	9.256	9.178	-1
M20/0310B	30	0.2	8.179	8.083	-1
M20/0310B	60	0.2	7.102	6.987	-2
M20/0310B	90	0.2	6.025	5.892	-2
M20/0310B	0	0.3	7.797	7.493	-4
M20/0310B	30	0.3	6.948	6.625	-5
M20/0310B	60	0.3	6.099	5.757	-6
M20/0310B	90	0.3	5.250	4.889	-7
M20/0310B	0	0.4	6.774	6.488	-4
M20/0310B	30	0.4	6.042	5.752	-5
M20/0310B	60	0.4	5.310	5.016	-6
M20/0310B	90	0.4	4.578	4.280	-7
M20/0310B	0	0.5	6.065	5.803	-4
M20/0310B	30	0.5	5.402	5.155	-5
M20/0310B	60	0.5	4.739	4.508	-5
M20/0310B	90	0.5	4.076	3.860	-5
M20/0310B	0	0.6	5.478	5.297	-3
M20/0310B	30	0.6	4.869	4.714	-3
M20/0310B	60	0.6	4.260	4.130	-3
M20/0310B	90	0.6	3.651	3.547	-3
M20/0310B	0	0.7	4.997	4.904	-2
M20/0310B	30	0.7	4.436	4.370	-1
M20/0310B	60	0.7	3.875	3.836	-1
M20/0310B	90	0.7	3.314	3.302	0
M20/0310B	0	0.8	4.554	4.587	1
M20/0310B	30	0.8	4.050	4.092	1
M20/0310B	60	0.8	3.546	3.598	1
M20/0310B	90	0.8	3.042	3.103	2
M20/0310B	0	0.9	4.152	4.324	4
M20/0310B	30	0.9	3.702	3.862	4
M20/0310B	60	0.9	3.252	3.400	5
M20/0310B	90	0.9	2.802	2.938	5
M20/0310B	0	1	3.804	4.102	8
M20/0310B	30	1	3.405	3.667	8
M20/0310B	60	1	3.006	3.232	8
M20/0310B	90	1	2.607	2.797	7

Table 5.10 Comparison between experimental and empirical stiffness at displacement level from 0.1mm to 1mm for various grain direction in the joints.

In Figure 5.18, a comparison of stiffness versus grain direction curves between experimental and empirical (i.e. equation 5.4) results for various joints with different grain direction at displacement levels of 0.1mm to 1mm are presented. There was a good agreement between the empirical model and experimental results.



(a) Characteristics at 0.1mm displacement.

(b) Characteristics at 0.2mm displacement.

(c) Characteristics at 0.3mm displacement.

(d) Characteristics at 0.4mm displacement.

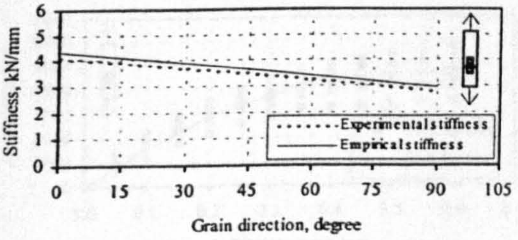
(e) Characteristics at 0.5mm displacement.

(f) Characteristics at 0.6mm displacement.

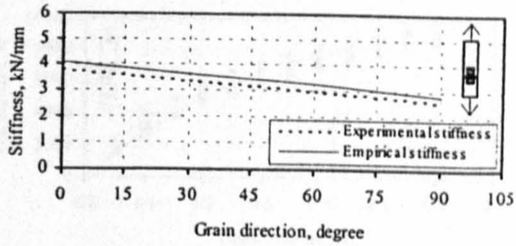
(g) Characteristics at 0.7mm displacement.

(h) Characteristics at 0.8mm displacement.

Figure 5.18 Comparison of stiffness vs grain direction between experimental and empirical (i.e. equation 5.4) results.



(i) Characteristics at 0.9mm displacement.



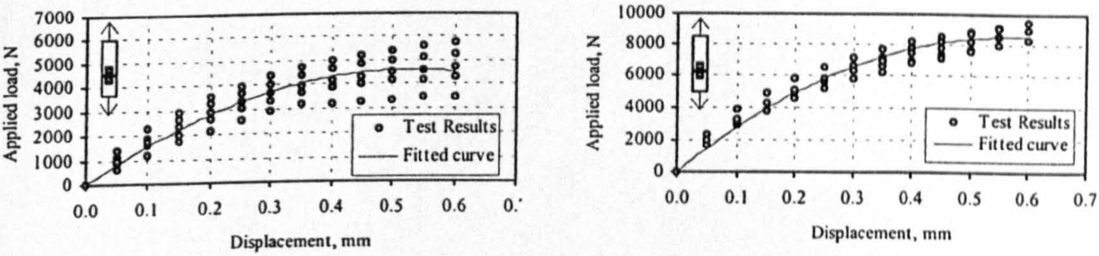
(k) Characteristics at 1mm displacement.

Figure 5.18 cont.

5.4.4 Effects of plate thickness

Tests were carried out to determine the influences of the plate thickness on the performance of the punched metal plate timber joints subjected to tensile loads. The test samples were generally made of two pieces of timber dimensioned as 73mm×300mm and 73mm×80mm by 45mm thickness. The punched metal plate types used in construction of testing specimens were M20/0310B, 1mm thickness and small strip of plates cut from M14/1333, 2mm thickness. The specimens were loaded to failure in tension. All joint specimens were manufactured using material as explained in chapter 3.

In Figure 5.19 typical load-displacement curves up to 0.6mm displacement with fitted curve (average curves) for specimens with various plate thickness subjected to tensile loading are shown. Joints were made of two different plates. The first group made of punched metal plates M20/0310B with 1mm plate thickness and the second group made of small strip of punched metal plate M14/1333 with 2mm plate thickness. All plates having equal number of bites (8bites) and load applied parallel to the grain of timber.



(a) 1mm plate thickness.

(b) 2mm plate thickness.

Figure 5.19 Load – displacement behaviour of joints with different plate thickness loaded in tension parallel to the grain.

The behaviour of the joints tested was assessed through observation of the failed specimens and their load-displacement relation. The load-displacement behaviour of each joint specimen was recorded and plotted. Second order polynomial equations were fitted to define the curves. The fitted curves simulated the load-displacement behaviour of the connection with good accuracy. These equations were directed to pass through the point of origin to simulate the condition of zero deformation at zero loads.

A comparison of performance of joints in relation to the plate thickness tested up to 0.6mm displacement is presented in Figure 5.20. The average load at 0.6mm displacement for each group of specimens is shown in Table 5.11. It was observed that the plate thickness had significant effects on ultimate strength and stiffness and hence on the ductility of the joints when loaded in tension. The ultimate load capacity of the joints increased with an increase in the plate thickness.

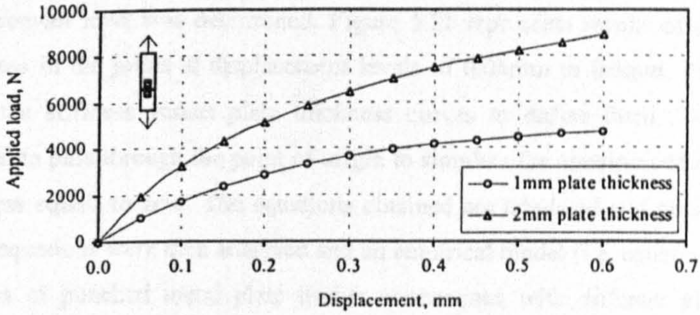


Figure 5.20 Comparison of joints performance subjected to tension force parallel to the grain using different plate thickness.

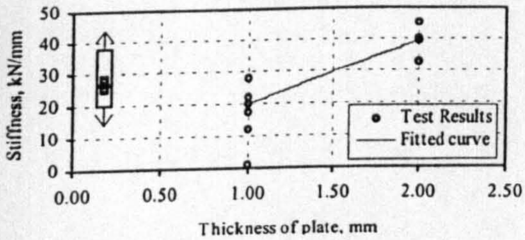
Plate ref. number	Plate thickness (mm)	Average load at 0.6mm displacement (N)	Failure modes
M20/0310B	1	4701	Anchorage
M14/1333	2	8915	Anchorage

Table 5.11 The average load at 0.6mm displacement for joints with various plate thickness subjected to tension force parallel to the grain.

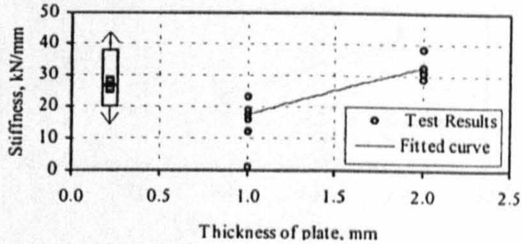
5.4.4.1 The stiffness characteristics of the joints

In order to investigate the effects of plate thickness on the performance of the joints subjected to tension load parallel to the grain under short-term duration, the stiffness characteristics of all tested specimens were analysed in detail. The stiffness of the joint (K_t) defined as the ratio between the applied load and the displacement in the joint as described in equation 5.1.

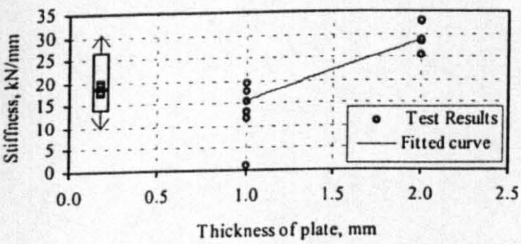
For all specimens tested the displacement at failure was about 0.6mm. The average magnitude of the stiffness sustained by each joints specimen at 0.05mm to 0.6mm displacement level was determined. Figure 5.21 represents results of stiffness versus plate thickness in the joints at displacement levels of 0.05mm to 0.6mm. Power equations were fitted the stiffness versus plate thickness curves to define them. These equations were directed to pass through the point of origin to simulate the condition of zero stiffness at plate thickness equals to zero. The equations obtained are tabulated and presented in Table 5.12. These equations were then analysed and an empirical model (i.e. equation 5.5) describing the stiffness of punched metal plate timber connections with different plate thickness under tensile loading was developed.



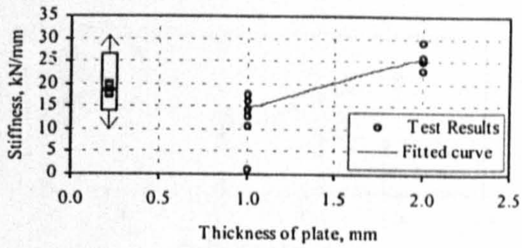
(a) Characteristics at 0.05mm displacement.



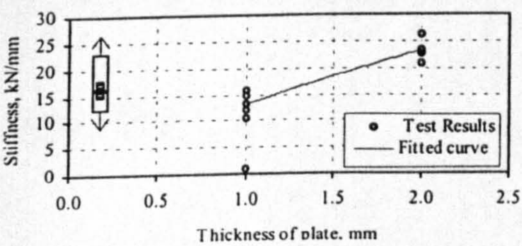
(b) Characteristics at 0.1mm displacement.



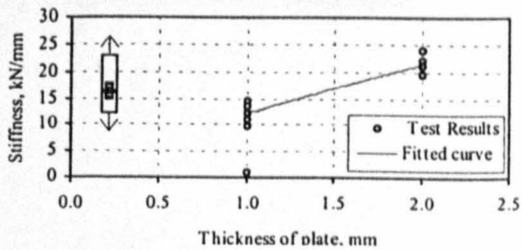
(c) Characteristics at 0.15mm displacement.



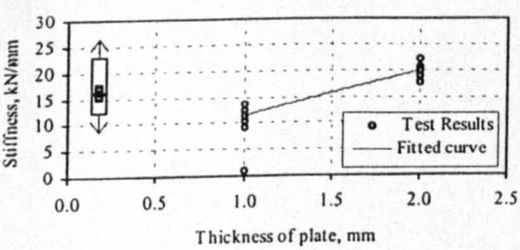
(d) Characteristics at 0.2mm displacement.



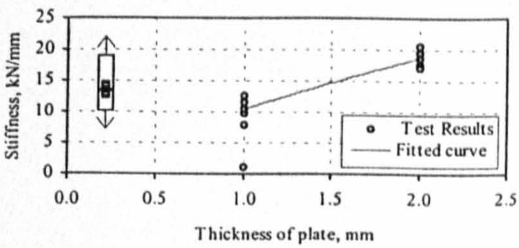
(e) Characteristics at 0.25mm displacement.



(f) Characteristics at 0.3mm displacement.

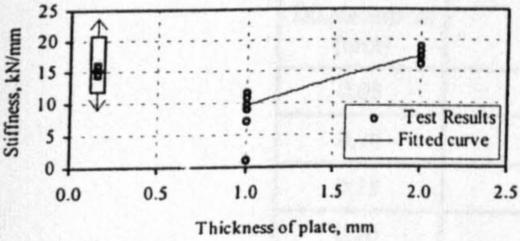


(g) Characteristics at 0.35mm displacement.

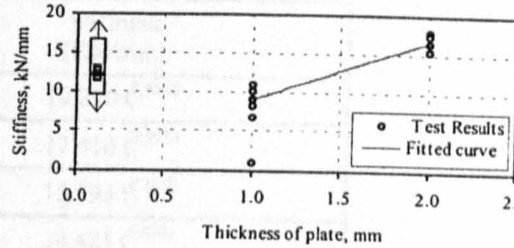


(h) Characteristics at 0.4mm displacement.

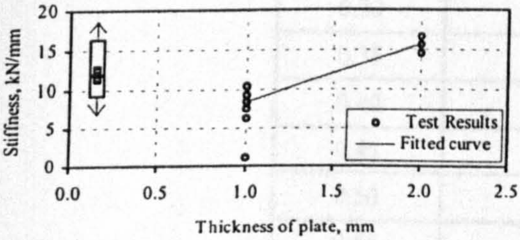
Figure 5.21 Stiffness sustained in the joint versus plate thickness under tensile loading parallel to the grain.



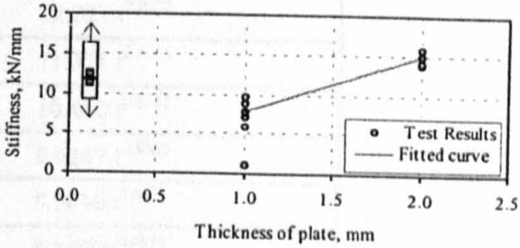
(i) Characteristics at 0.45mm displacement.



(k) Characteristics at 0.5mm displacement.



(m) Characteristics at 0.55mm displacement.



(n) Characteristics at 0.6mm displacement.

Figure 5.21 cont.

Displacement (mm)	Stiffness (KN/mm)
0.05	$19.820\ t^{0.9890}$
0.10	$17.410\ t^{0.9076}$
0.15	$15.593\ t^{0.8818}$
0.20	$14.425\ t^{0.8301}$
0.25	$13.248\ t^{0.8143}$
0.30	$12.223\ t^{0.8021}$
0.35	$11.371\ t^{0.8055}$
0.40	$10.460\ t^{0.8362}$
0.45	$9.6267\ t^{0.8562}$
0.50	$8.9660\ t^{0.8771}$
0.55	$8.3582\ t^{0.8981}$
0.60	$7.8350\ t^{0.9233}$

t = thickness of the plate (mm).

Table 5.12 The equations of the various curves in Figure 5.21.

Using the equations in Table 5.12, an empirical model (i.e equation 5.5) describing the stiffness of the joints with different plate thickness under tensile loading was developed.

$$K_t = 20.375e^{-1.6427\delta}t^{1.9261\delta^2-1.2968\delta+1.0291} \qquad (5.5)$$

where K_t = stiffness of the joint under tensile loading (kN/mm).

δ = displacement (mm).

t = thickness of plate(mm).

In Figure 5.22, the effect of increase in the plate thickness on the performance of the connections with respect to the stiffness sustained by them at displacement levels of 0.05mm to 0.6mm are shown.

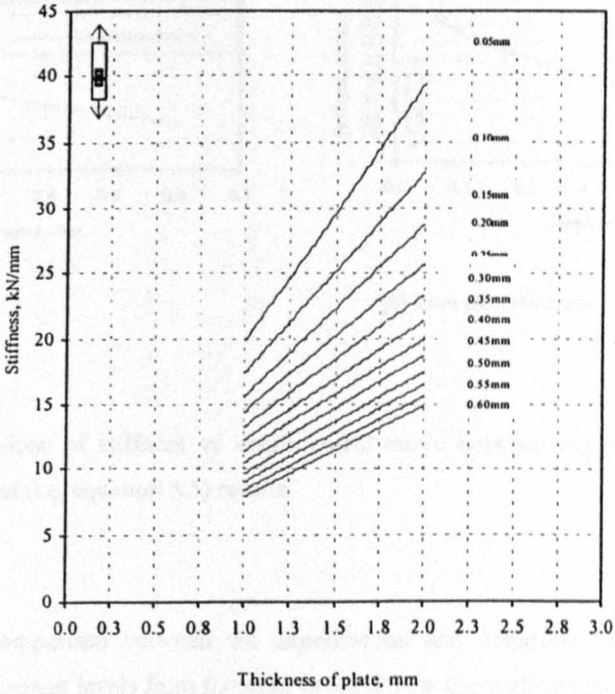
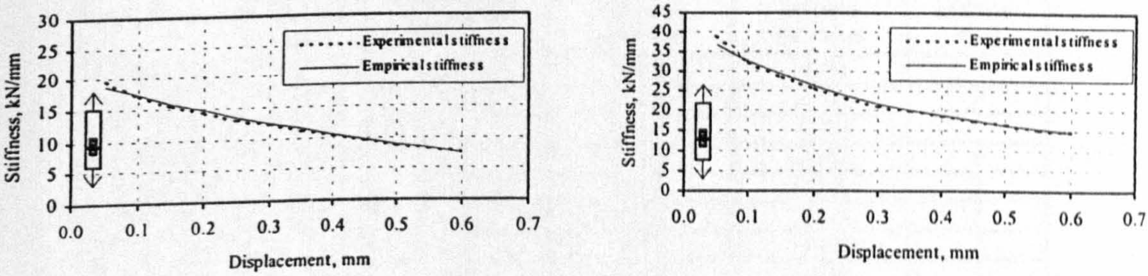


Figure 5.22 Stiffness vs thickness of plate in joints under tensile loading parallel to the grain.

It is clear that the stiffness of the joints were dependent on the thickness of plate in the joints when loaded in tension parallel to the grain. The stiffness of the joints increased with an increase in the plate thickness. At low displacement (0.05mm), stiffness was high comparing with high displacement (0.6mm). The rate of increasing in stiffness was reduced as displacement was increased.

In Figure 5.23, a comparison of stiffness versus displacement curves between experimental and empirical (i.e. equation 5.5) results for joints with different plate thickness are represented. There was a good agreement between the empirical model and experimental results.



(a) 1mm plate thickness.

(b) 2mm plate thickness.

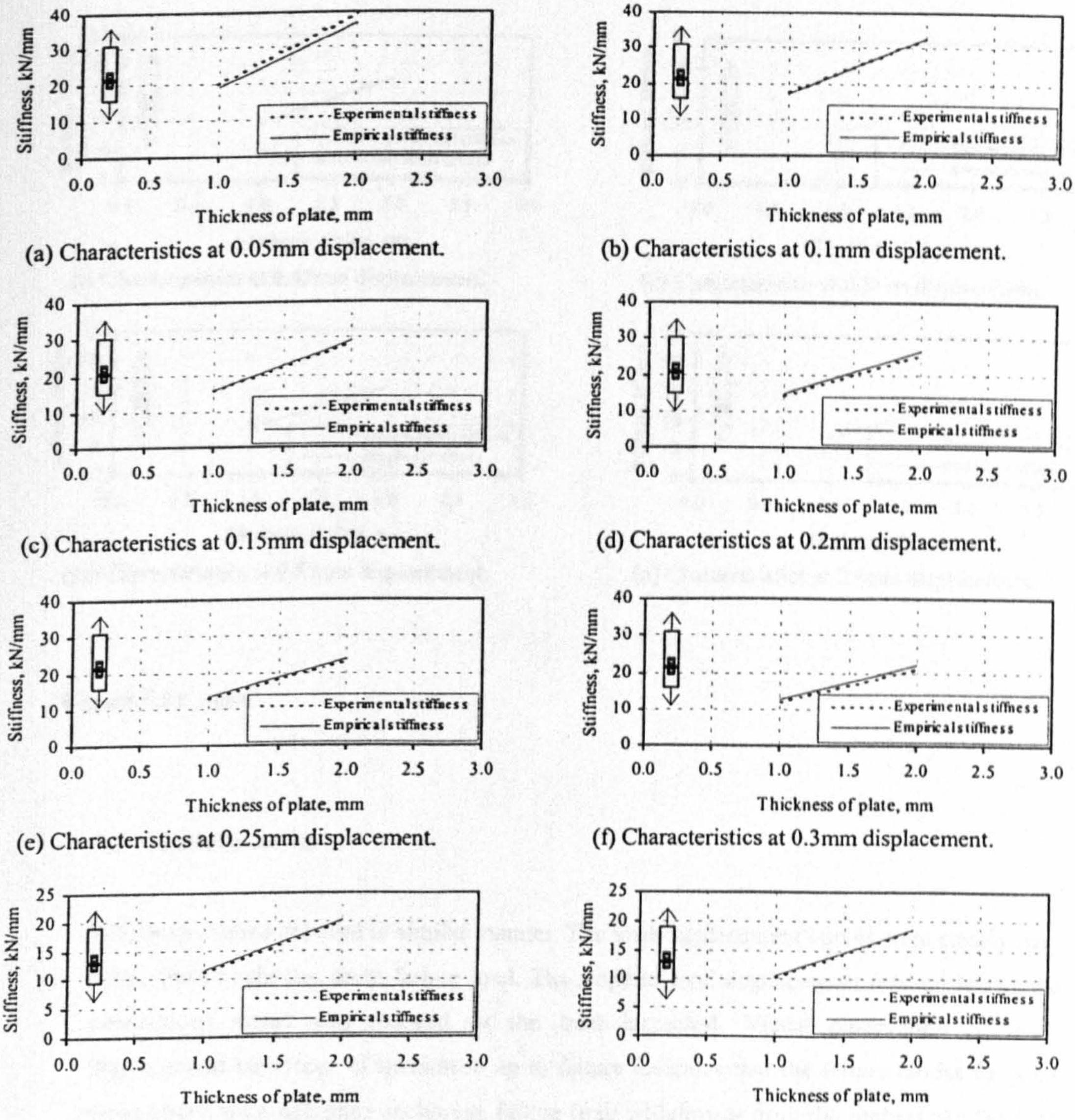
Figure 5.23 Comparison of stiffness vs displacement curve between experimental and empirical (i.e. equation 5.5) results.

In Table 5.13 Comparison between the experimental and empirical (i.e. equation 5.5) stiffness at displacement levels from 0.05mm to 0.6mm for the various plate thickness in the joints are shown.

Plate Number	Plate thickness (mm)	Displacement level (mm)	Experimental stiffness (kN/mm)	Empirical stiffness (kN/mm)	Percentage of Error (%)
M20/0310B	1	0.05	19.820	18.768	-5
M14/1333	2	0.05	39.339	36.741	-7
M20/0310B	1	0.1	17.410	17.288	-1
M14/1333	2	0.1	32.660	32.682	0
M20/0310B	1	0.15	15.593	15.925	2
M14/1333	2	0.15	28.733	29.266	2
M20/0310B	1	0.2	14.425	14.669	2
M14/1333	2	0.2	25.645	26.383	3
M20/0310B	1	0.25	13.248	13.513	2
M14/1333	2	0.25	23.296	23.943	3
M20/0310B	1	0.3	12.223	12.447	2
M14/1333	2	0.3	21.312	21.874	3
M20/0310B	1	0.35	11.371	11.466	1
M14/1333	2	0.35	19.874	20.118	1
M20/0310B	1	0.4	10.460	10.562	1
M14/1333	2	0.4	18.675	18.627	0
M20/0310B	1	0.45	9.627	9.729	1
M14/1333	2	0.45	17.427	17.362	0
M20/0310B	1	0.5	8.966	8.962	0
M14/1333	2	0.5	16.468	16.291	-1
M20/0310B	1	0.55	8.358	8.255	-1
M14/1333	2	0.55	15.576	15.388	-1
M20/0310B	1	0.6	7.835	7.604	-3
M14/1333	2	0.6	14.859	14.633	-2

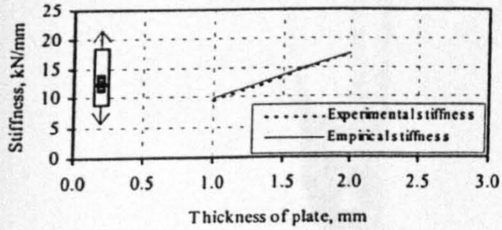
Table 5.13 Comparison between experimental and empirical stiffness at displacement level from 0.05mm to 0.6mm for various plate thickness in the joints.

In Figure 5.24, a comparison of stiffness versus thickness of plate curves between experimental and empirical (i.e. equation 5.5) results for various joints with different plate thickness at displacement levels from 0.05mm to 0.6mm are represented. There was a good agreement between the empirical model and experimental results.

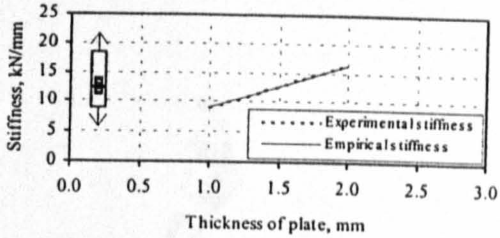


(a) Characteristics at 0.05mm displacement.
(b) Characteristics at 0.1mm displacement.
(c) Characteristics at 0.15mm displacement.
(d) Characteristics at 0.2mm displacement.
(e) Characteristics at 0.25mm displacement.
(f) Characteristics at 0.3mm displacement.
(g) Characteristics at 0.35mm displacement.
(h) Characteristics at 0.4mm displacement.

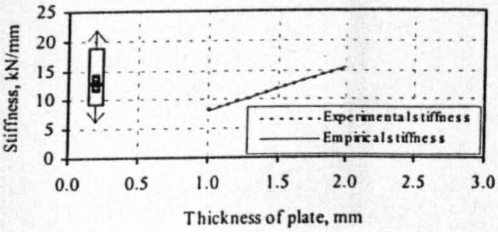
Figure 5.24 Comparison of stiffness vs thickness of plate between experimental and empirical (i.e. equation 5.5) results.



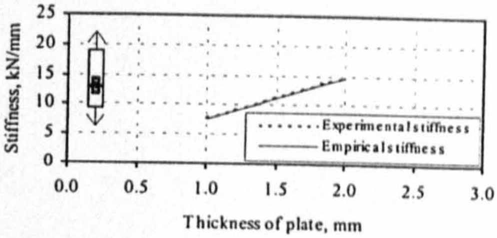
(i) Characteristics at 0.45mm displacement.



(k) Characteristics at 0.5mm displacement.



(m) Characteristics at 0.55mm displacement.



(n) Characteristics at 0.6mm displacement.

Figure 5.24 cont.

5.5 Failure modes

All joints studied behaved in similar manner. The load-displacement curves were clearly non-linear from beginning up to failure load. The slope of load-displacement relationship of the connections tested was reduced as the load increased. Visual observation of load-displacement behaviour of specimens up to failure indicates that the failure modes for joint types tested were nail plate anchorage failure (nail withdrawal from the timber). As the load increased, plate started to peel away from the timber members at their upper end. This peeling progressed downward until the plate withdrew completely. The failure of joints was characterised as ductile. A great deal of plastic deformation (ductility) was noted before failure. Typical anchorage failure of joints is shown in Figure 5.25.

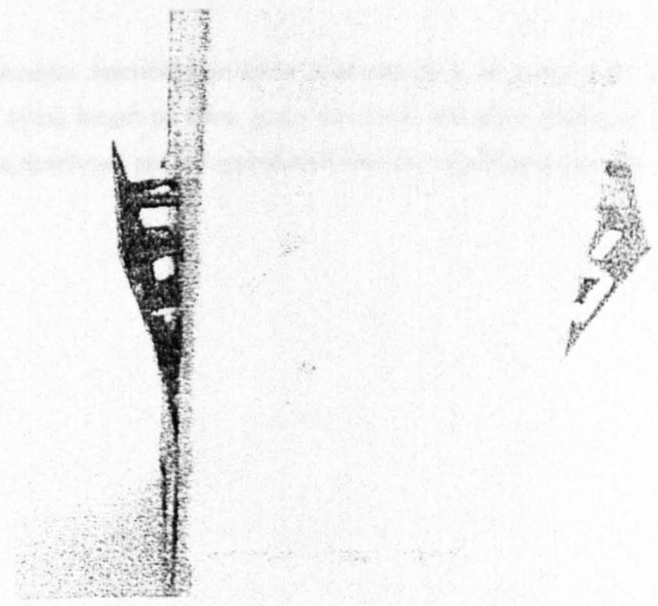


Figure 5.25 Typical failures of joint when loaded in tension parallel to the grains.

5.6 SUMMARY

In this chapter details of experimental work carried out to study the load-displacement characteristics of the punched metal plate timber connections, using joints with different parameters such as number of bites, length of bites, grain direction and thickness of the plate. The specimens tested were subjected to tensile loading.

From the results obtained, it was found that the number of bites, length of bites, the grain direction and the plate thickness in the joints have a significant effects on the load-displacement characteristics of the joints. Increasing number of bites, length of bites, thickness of plate and decreasing angle of grain direction would increase the strength and stiffness of the joints. The failure of joints was characterised as ductile, a considerable amount of ductility was generally observed prior to failure. The most common mode of failure was anchorage failure (teeth withdrawal); as the load increased the toothed-plates started to peel away from the timber members.

Empirical models describing stiffness characteristics of joints with different parameters (number of bites, length of bites, grain direction, and plate thickness) subjected to tensile loading were developed and compared well with the experimental results.

CHAPTER SIX

LOAD-DISPLACEMENT CHARACTERISTICS OF PUNCHED METAL PLATE TIMBER JOINTS SUBJECTED TO COMPRESSION LOADS

6. LOAD-DISPLACEMENT CHARACTERISTICS OF PUNCHED METAL PLATE TIMBER JOINTS SUBJECTED TO COMPRESSION LOADS

6.1 INTRODUCTION

This chapter describes details of experimental work investigating load-displacement characteristics of the punched metal plate timber connections under short duration loading, in which the effects of different factors such as number of bites, length of bites, grain directions and plate thickness were considered. This is to evaluate their efficiency for use in a variety of timber structures. It is anticipated in this chapter to determine the structural behaviour of punched metal plate timber connections when subjected to compression loads with respect to their strength and displacement characteristics. Also, empirical models are developed to simulate the load-displacement behaviour of the joints using different parameters.

6.2 TESTING PROGRAM

Tests were carried out to determine the influences of different variables such as number of bites, length of bites, grain directions and plate thickness on the performance of the punched metal plate timber joints subjected to compression loading. Testing programme for different variables (number of bites, length of bites, grain directions, plate thickness) are summarised in table 6.1. Minimum of 5 specimens per joint type were tested, totalling over 70 specimen joints.

Plate ref. number	Plate properties (mm)			Bite properties		Grain direction
	Length	Width	Thickness	Number	Length (mm)	
M20/0310B	101	25	1	1	8	0
M20/0310B	101	25	1	2	8	0
M20/0310B	101	25	1	3	8	0
M20/0310B	101	25	1	4	8	0
M20/0310B	101	25	1	5	8	0
M20/0310B	101	25	1	6	8	0
M20/0310B	101	25	1	7	8	0
M20/0310B	101	25	1	8	8	0
M20/0310B	101	25	1	8	8	30
M20/0310B	101	25	1	8	8	60
M20/0310B	101	25	1	8	8	90
M14/1333	133	38	2	8	5	0
M14/1333	133	38	2	8	10	0
M14/1333	133	38	2	8	15	0

Table 6.1. Testing programme for joints subjected to compression loading.

6.3 LABORATORY WORK

For testing the effects of the number of bites and grain directions the punched metal plate type used was M20/0310B-101mm×25mm×1mm and for the length of bites a small strip 130mm×38mm×2mm which was cut from plate number M14/1333 as supplied by MiTek industries. The specimens were loaded to failure in compression. All joint specimens were manufactured using material as explained in chapter 3. The average moisture content at the time of testing was 12 % and the mean density was 475 kg/m^3. The induced deformation rate during loading was 1mm/min.

The test samples were generally made of two pieces of timber dimensioned as 73 × 170 mm and 73 × 67 mm by 45 mm thickness. The specimens were made according to the British standard pr EN 1075: 1997 as explained in chapter 3. Typical compression test specimen is shown in Figure 3.2 and test set-up is shown in Figure 3.6. The instrumentation and loading procedures were as explained in chapter 3.

6.4 RESULTS AND DISCUSSION

6.4.1 Effects of number of bites

Tests were carried out to determine the influences of number of bites on the performance of the punched metal plate timber joints subjected to compression loads. The test samples were generally made of two pieces of timber dimensioned as 73mm×170mm and 73 × 67 by 45mm thickness. The punched metal plate type used in construction of testing specimens was M20/0310B-101mm×25mm×1mm. The specimens were loaded to failure in compression. All joint specimens were manufactured using material as explained in chapter 3.

In Figure 6.1 typical load-displacement curves up to 0.6mm displacement with fitted curve (average curves) for specimens with various number of bites subjected to compression loading are shown. All joints made of punched metal plates M20/0310B with equal length of bites (8mm) and the loads applied parallel to the grain of timber.

The behaviour of the joints tested was assessed through observation of the failed specimens and their load-displacement relation. The load-displacement behaviour of each joint specimen was examined and third order polynomial equations was fitted to define the curves. The fitted curves simulated the load-displacement behaviour of the connection with good accuracy. These equations were directed to pass through the point of origin to simulate the condition of zero deformation at zero loads.

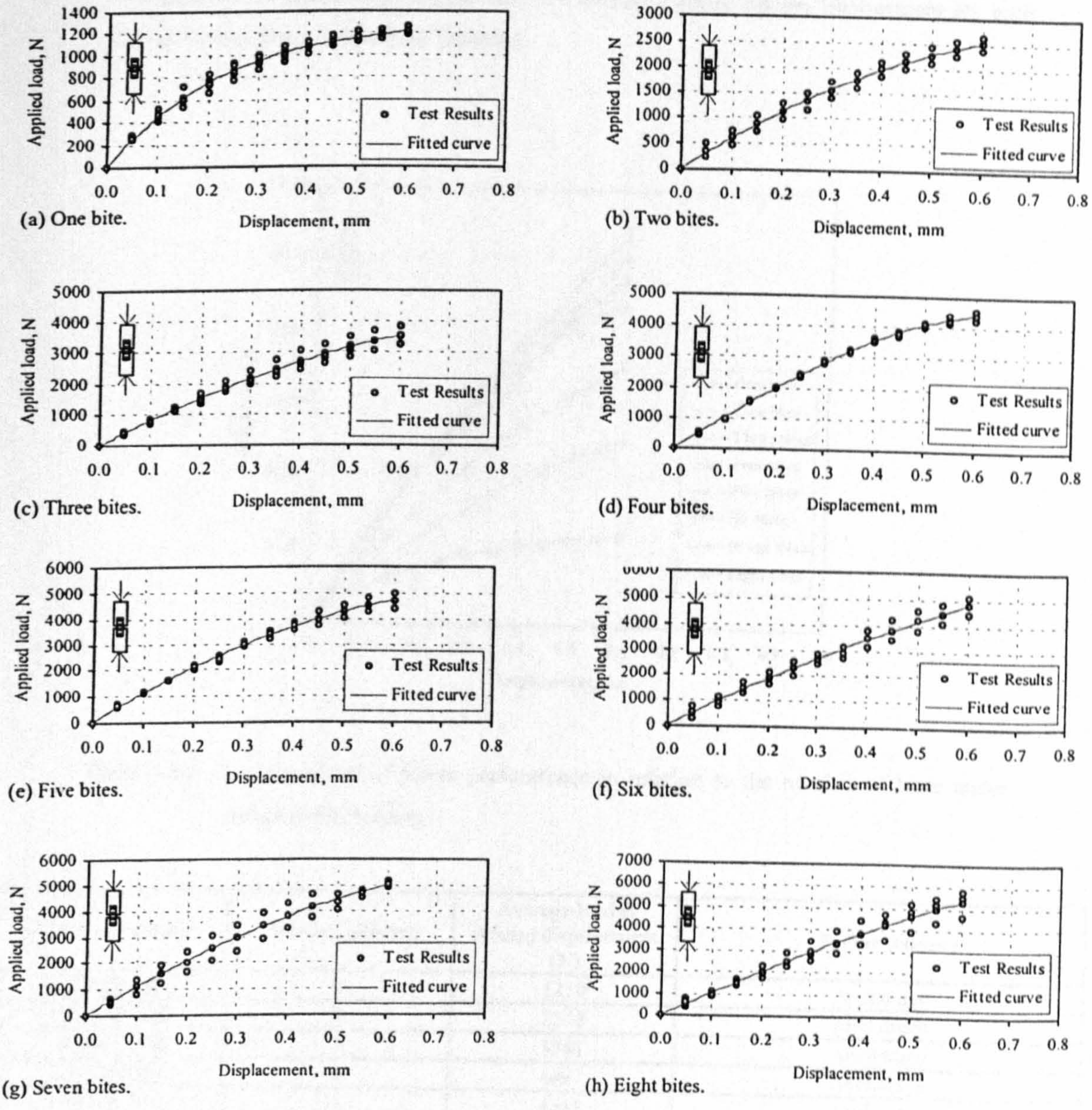


Figure 6.1 Load – displacement behaviour of joints with different number of bites loaded in compression parallel to the grain.

A comparison of performance of joints in relation to the number of bites tested up to 0.6mm displacement is presented in Figure 6.2. The average load at 0.6mm displacement for each group of specimens is shown in Table 6.2.

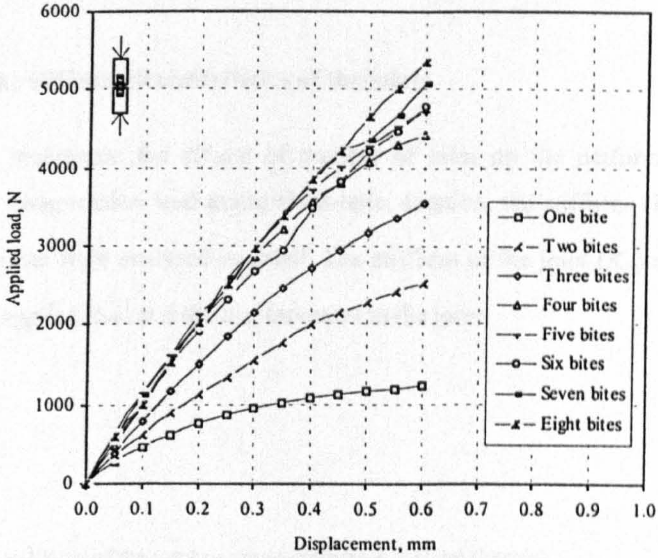


Figure 6.2 A comparison of joints performance in relation to the number of bites under compression loading.

Plate ref. number	Number of bites	Average load at 0.6mm displacement (N)	Failure modes
M20/0310B	1	1250	Anchorage
M20/0310B	2	2528	Anchorage
M20/0310B	3	3541	Anchorage
M20/0310B	4	4497	Anchorage
M20/0310B	5	4511	Anchorage
M20/0310B	6	4596	Closure of the gap
M20/0310B	7	4675	Closure of the gap-Plate buckling-Timber
M20/0310B	8	4864	Closure of the gap-Plate buckling-Timber

Table 6.2 The average load at 0.6mm displacement for joints with various number of bites subjected to compression force parallel to the grain.

It was observed that the number of bites had significant effects on the strength and stiffness and hence on the ductility of the joints when loaded in compression. The stiffness of the joints increased with an increase in the number of bites. The rate of increasing reduced as the number of bites increased above 50% of the total number of bites available in a standard toothed-plate size.

6.4.1.1 The stiffness characteristics of the joints

In order to investigate the effects of number of bites on the performance of the joints subjected to compression load under short-term duration, the stiffness characteristics of all tested specimens were analysed in detail. The stiffness of the joint (K_C) defined as the ratio between the applied load and the displacement in the joint.

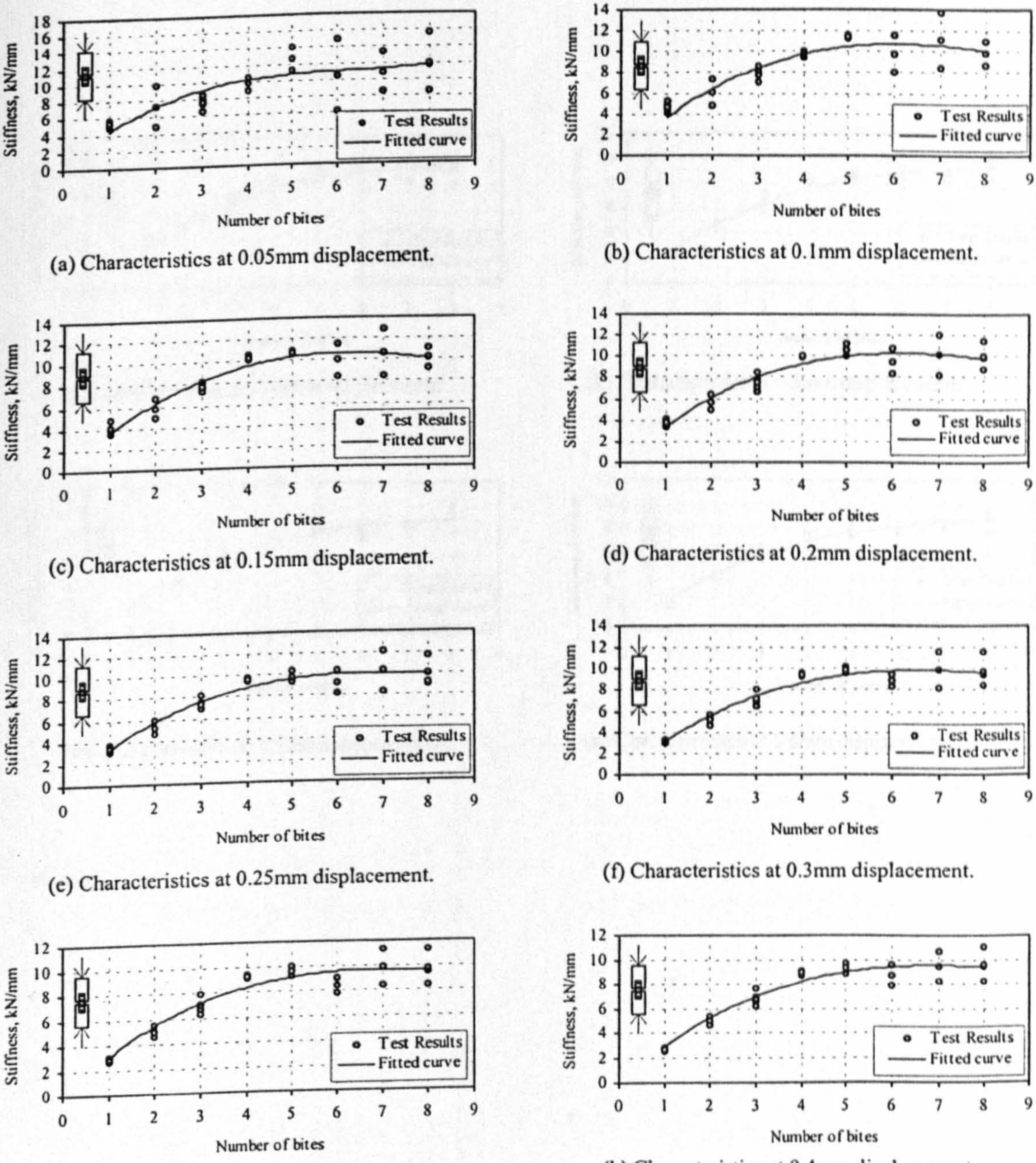
$$K_c = \frac{P_c}{\delta} \qquad (6.1)$$

where K_c = stiffness of the joint under compression loading (N/mm).

P_c = compression load (N).

δ = displacement (mm).

For all specimens tested the displacement at failure was about 0.6mm. The average magnitude of the stiffness sustained by each joints specimen at 0.05mm to 0.6mm displacement levels was determined. Figure 6.3 represents results of stiffness versus number of bites in the joints at displacement levels of 0.05mm to 0.6mm. The relationships were non-linear. Third order polynomial equations were fitted the stiffness versus number of bites curves to define them. These equations were directed to pass through the point of origin to simulate the condition of zero stiffness at number of bites equals to zero. The equations obtained are tabulated and presented in Table 6.3. These equations were then analysed and an empirical model (i.e. equation 6.2) describing the stiffness of punched metal plate timber connections with different number of bites under compression loading was developed.



(a) Characteristics at 0.05mm displacement.

(b) Characteristics at 0.1mm displacement.

(c) Characteristics at 0.15mm displacement.

(d) Characteristics at 0.2mm displacement.

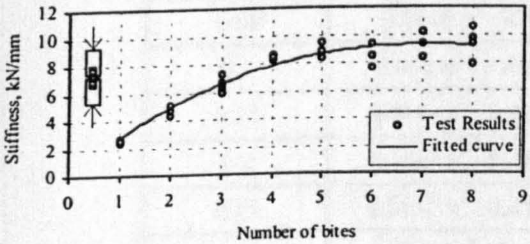
(e) Characteristics at 0.25mm displacement.

(f) Characteristics at 0.3mm displacement.

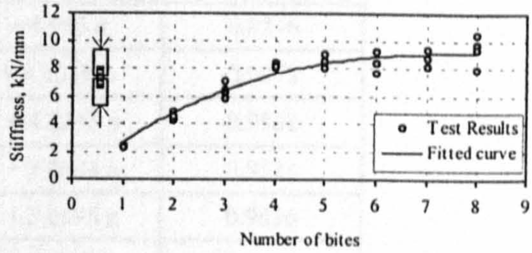
(g) Characteristics at 0.35mm displacement.

(h) Characteristics at 0.4mm displacement.

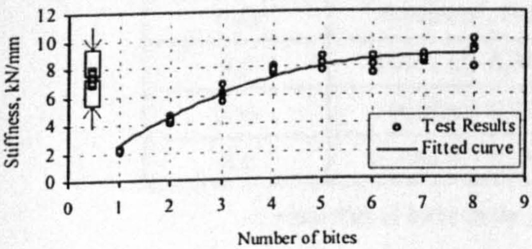
Figure 6.3 Stiffness sustained in the joint versus number of bites under compression loading parallel to the grain.



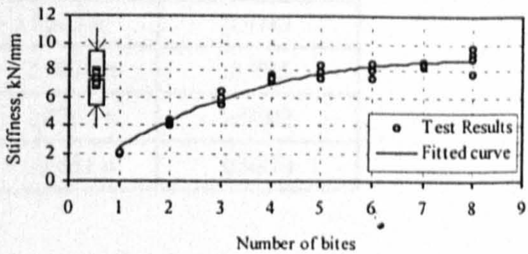
(i) Characteristics at 0.45mm displacement.



(k) Characteristics at 0.5mm displacement.



(m) Characteristics at 0.55mm displacement.



(n) Characteristics at 0.6mm displacement.

Figure 6.3 cont.

Displacement (mm)	Stiffness (kN/mm)	Coefficient of correlation, R^2
0.05	$0.0416\ n^3 - 0.769\ n^2 + 4.966\ n$	0.8346
0.1	$0.016\ n^3 - 0.4866\ n^2 + 4.1318\ n$	0.9073
0.15	$0.0148\ n^3 - 0.4634\ n^2 + 4.0233\ n$	0.9562
0.2	$0.0143\ n^3 - 0.4432\ n^2 + 3.8601\ n$	0.9524
0.25	$0.0157\ n^3 - 0.4313\ n^2 + 3.6895\ n$	0.9636
0.3	$0.0127\ n^3 - 0.3938\ n^2 + 3.542\ n$	0.9548
0.35	$0.0143\ n^3 - 0.3958\ n^2 + 3.4433\ n$	0.9447
0.4	$0.0101\ n^3 - 0.3396\ n^2 + 3.2453\ n$	0.9707
0.45	$0.0089\ n^3 - 0.31\ n^2 + 3.0603\ n$	0.9781
0.5	$0.0101\ n^3 - 0.3107\ n^2 + 2.9679\ n$	0.978
0.55	$0.0098\ n^3 - 0.2935\ n^2 + 2.8291\ n$	0.9802
0.6	$0.0081\ n^3 - 0.2593\ n^2 + 2.6451\ n$	0.9876

n = number of bites in the joints.

Table 6.3 The equations of the various curves in Figure 6.3.

Using the equations in Table 6.3, an empirical model (i.e equation 6.2) describing the stiffness of the joints with different number of bites under compression loading was developed.

$$K_C = 0.0066\ \delta^{-0.5231}\ n^3 - 0.2381\ \delta^{-0.3734}\ n^2 + 2.5611\ \delta^{-0.2307}\ n \qquad (6.2)$$

where K_c = stiffness of the joint under compression loading (kN/mm).

δ = displacement (mm).

n = number of bites in the joint.

In Figure 6.4, the effect of increase in the number of bites on the performance of the connections with respect to the stiffness sustained by them at displacement levels from 0.05 to 0.6mm are shown.

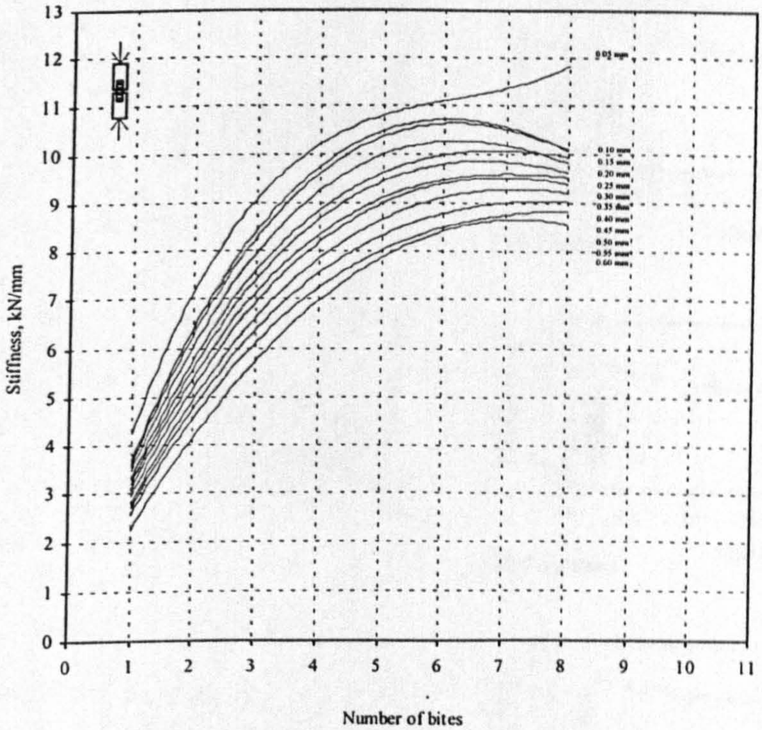


Figure 6.4 Stiffness vs number of bites in joints under compression loading parallel to the grain.

It is clear that the stiffness of the joints were dependent on the number of bites in the joints when loaded in compression parallel to the grain. The stiffness of the joints increased with an increase in the number of bites. The rate of increasing reduced as the number of bites increased above approximately 50% of the total number of bites available in a standard punched metal plate size. At low displacement (0.05mm), stiffness was high comparing with high displacement (0.6mm). The rate of increasing in stiffness was reduced as displacement was increased.

In Figure 6.5, a comparison of stiffness versus displacement curves between experimental and empirical (i.e. equation 6.2) results for joints with different number of bites are represented. There was a good agreement between the empirical model and experimental results.

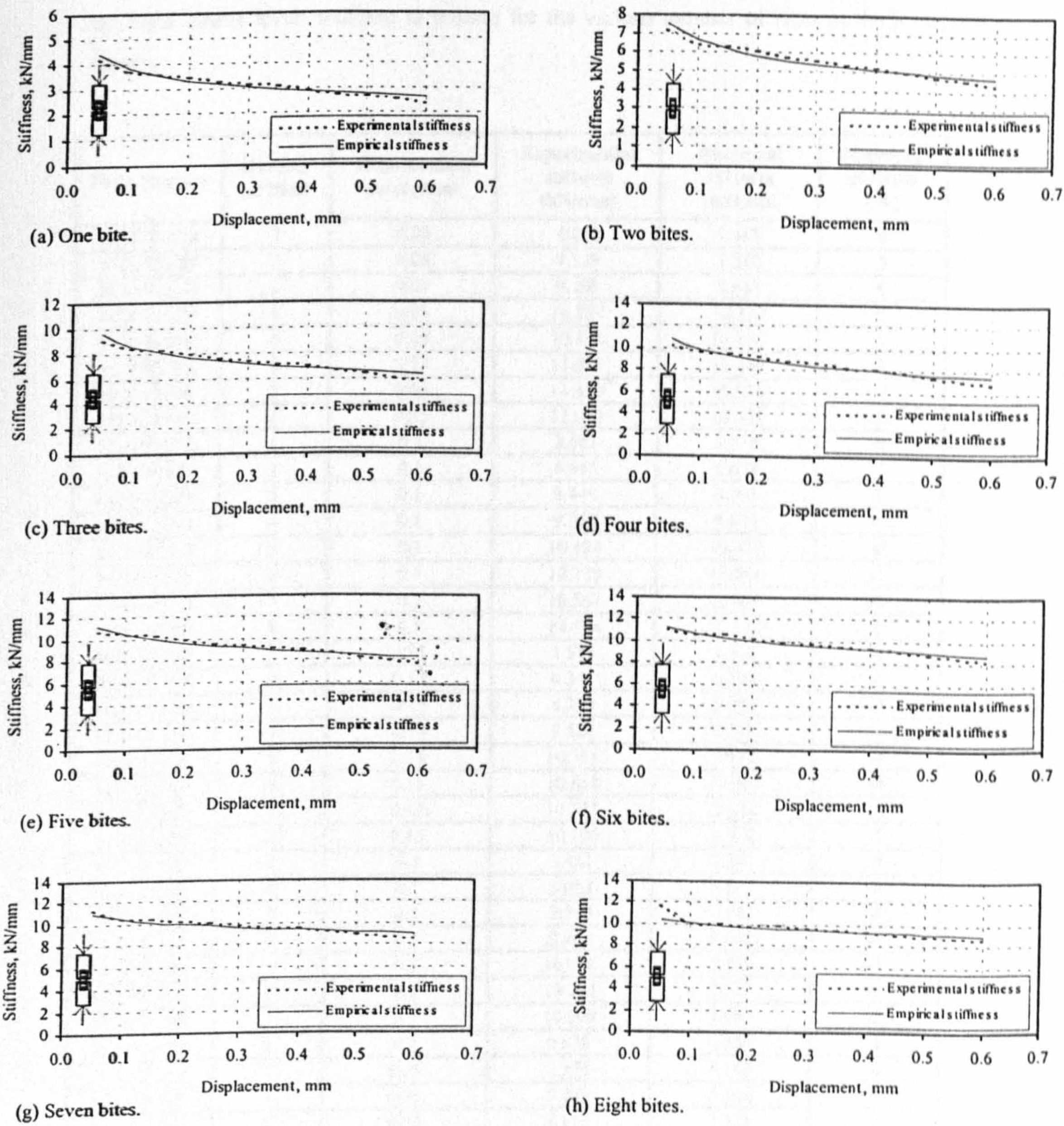


Figure 6.5 Comparison of stiffness vs displacement curve between experimental and empirical (i.e. equation 6.2) results.

In Table 6.4 Comparison between the experimental and empirical (i.e. equation 6.2) stiffness at displacement levels 0.05mm to 0.6mm for the various number of bites in the joints are shown.

Plate Number	Number of Bites	Displacement level (mm)	Experimental stiffness (kN/mm)	Empirical stiffness (kN/mm)	Percentage of Error (%)
M20/0310B	1	0.05	4.239	4.415	4
M20/0310B	2	0.05	7.189	7.562	5
M20/0310B	3	0.05	9.100	9.631	6
M20/0310B	4	0.05	10.222	10.812	6
M20/0310B	5	0.05	10.805	11.295	5
M20/0310B	6	0.05	11.098	11.269	2
M20/0310B	7	0.05	11.350	10.925	-4
M20/0310B	8	0.05	11.800	10.451	-11
M20/0310B	1	0.1	3.661	3.816	4
M20/0310B	2	0.1	6.445	6.639	3
M20/0310B	3	0.1	8.448	8.601	2
M20/0310B	4	0.1	9.766	9.834	1
M20/0310B	5	0.1	10.494	10.470	0
M20/0310B	6	0.1	10.729	10.641	-1
M20/0310B	7	0.1	10.567	10.480	-1
M20/0310B	8	0.1	10.104	10.118	0
M20/0310B	1	0.15	3.575	3.502	-2
M20/0310B	2	0.15	6.311	6.143	-3
M20/0310B	3	0.15	8.299	8.031	-3
M20/0310B	4	0.15	9.626	9.273	-4
M20/0310B	5	0.15	10.381	9.975	-4
M20/0310B	6	0.15	10.654	10.244	-4
M20/0310B	7	0.15	10.533	10.186	-3
M20/0310B	8	0.15	10.106	9.910	-2
M20/0310B	1	0.2	3.431	3.294	-4
M20/0310B	2	0.2	6.062	5.811	-4
M20/0310B	3	0.2	7.978	7.643	-4
M20/0310B	4	0.2	9.264	8.882	-4
M20/0310B	5	0.2	10.008	9.621	-4
M20/0310B	6	0.2	10.294	9.951	-3
M20/0310B	7	0.2	10.209	9.963	-2
M20/0310B	8	0.2	9.838	9.750	-1
M20/0310B	1	0.25	3.274	3.140	-4
M20/0310B	2	0.25	5.779	5.563	-4
M20/0310B	3	0.25	7.611	7.351	-3
M20/0310B	4	0.25	8.862	8.585	-3
M20/0310B	5	0.25	9.627	9.347	-3
M20/0310B	6	0.25	10.001	9.718	-3

Table 6.4 Comparison between experimental and empirical stiffness at displacement level of 0.05mm to 0.6mm for various number of bites in the joints.

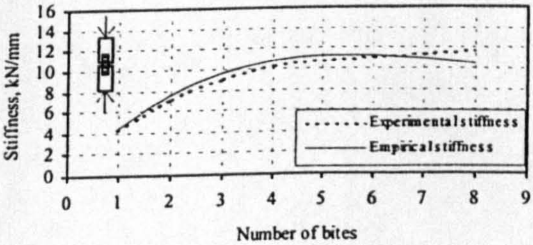
Plate Number	Number of Bites	Displacement level (mm)	Experimental stiffness (kN/mm)	Empirical stiffness (kN/mm)	Percentage of Error (%)
M20/0310B	7	0.25	10.078	9.781	-3
M20/0310B	8	0.25	9.951	9.618	-3
M20/0310B	1	0.3	3.161	3.020	-4
M20/0310B	2	0.3	5.610	5.368	-4
M20/0310B	3	0.3	7.425	7.118	-4
M20/0310B	4	0.3	8.680	8.345	-4
M20/0310B	5	0.3	9.453	9.123	-3
M20/0310B	6	0.3	9.818	9.526	-3
M20/0310B	7	0.3	9.854	9.628	-2
M20/0310B	8	0.3	9.635	9.504	-1
M20/0310B	1	0.35	3.062	2.922	-5
M20/0310B	2	0.35	5.418	5.208	-4
M20/0310B	3	0.35	7.154	6.926	-3
M20/0310B	4	0.35	8.356	8.145	-3
M20/0310B	5	0.35	9.109	8.934	-2
M20/0310B	6	0.35	9.500	9.361	-1
M20/0310B	7	0.35	9.614	9.495	-1
M20/0310B	8	0.35	9.537	9.404	-1
M20/0310B	1	0.4	2.916	2.839	-3
M20/0310B	2	0.4	5.213	5.072	-3
M20/0310B	3	0.4	6.952	6.763	-3
M20/0310B	4	0.4	8.194	7.974	-3
M20/0310B	5	0.4	8.999	8.771	-3
M20/0310B	6	0.4	9.428	9.218	-2
M20/0310B	7	0.4	9.541	9.377	-2
M20/0310B	8	0.4	9.399	9.314	-1
M20/0310B	1	0.45	2.759	2.768	0
M20/0310B	2	0.45	4.952	4.955	0
M20/0310B	3	0.45	6.631	6.621	0
M20/0310B	4	0.45	7.851	7.825	0
M20/0310B	5	0.45	8.664	8.628	0
M20/0310B	6	0.45	9.124	9.090	0
M20/0310B	7	0.45	9.285	9.272	0
M20/0310B	8	0.45	9.199	9.232	0
M20/0310B	1	0.5	2.667	2.706	1
M20/0310B	2	0.5	4.774	4.853	2
M20/0310B	3	0.5	6.380	6.496	2
M20/0310B	4	0.5	7.547	7.693	2
M20/0310B	5	0.5	8.335	8.501	2
M20/0310B	6	0.5	8.804	8.976	2
M20/0310B	7	0.5	9.015	9.176	2
M20/0310B	8	0.5	9.030	9.158	1
M20/0310B	1	0.55	2.545	2.651	4
M20/0310B	2	0.55	4.563	4.761	4
M20/0310B	3	0.55	6.110	6.384	4
M20/0310B	4	0.55	7.248	7.574	4
M20/0310B	5	0.55	8.033	8.386	4
M20/0310B	6	0.55	8.525	8.873	4

Table 6.4 cont.

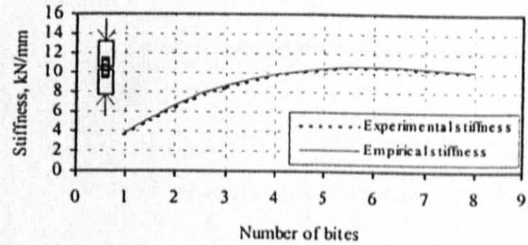
Plate Number	Number of Bites	Displacement level (mm)	Experimental stiffness (kN/mm)	Empirical stiffness (kN/mm)	Percentage of Error (%)
M20/0310B	7	0.55	8.784	9.089	3
M20/0310B	8	0.55	8.866	9.089	3
M20/0310B	1	0.6	2.394	2.602	9
M20/0310B	2	0.6	4.318	4.679	8
M20/0310B	3	0.6	5.820	6.284	8
M20/0310B	4	0.6	6.950	7.467	7
M20/0310B	5	0.6	7.755	8.281	7
M20/0310B	6	0.6	8.285	8.778	6
M20/0310B	7	0.6	8.588	9.009	5
M20/0310B	8	0.6	8.713	9.025	4

Table 6.4 cont.

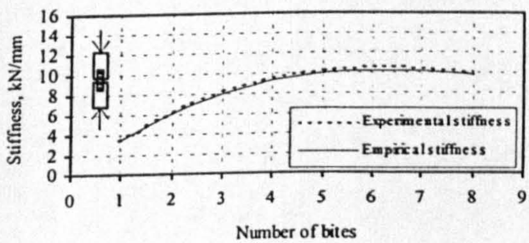
In Figure 6.6, a comparison of stiffness versus number of bites between experimental and empirical (i.e. equation 6.2) results for various joints with different number of bites at displacement levels of 0.05mm to 0.6mm are represented. There was a good agreement between the empirical model and experimental results.



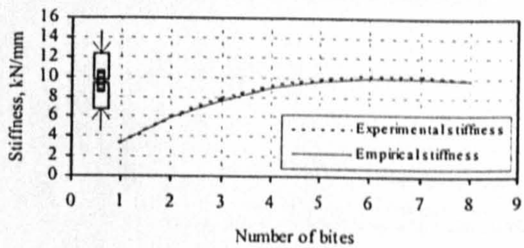
(a) Characteristics at 0.05mm displacement.



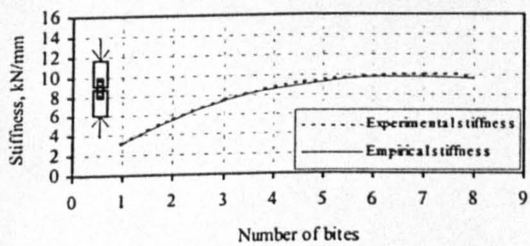
(b) Characteristics at 0.1mm displacement.



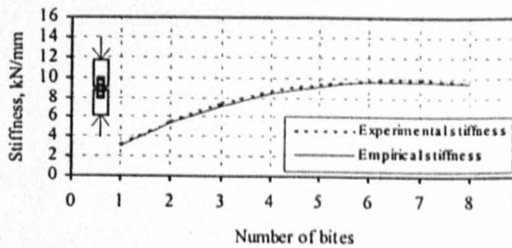
(c) Characteristics at 0.15mm displacement.



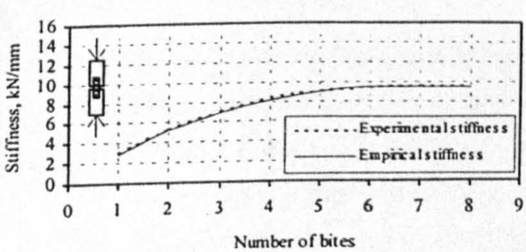
(d) Characteristics at 0.2mm displacement.



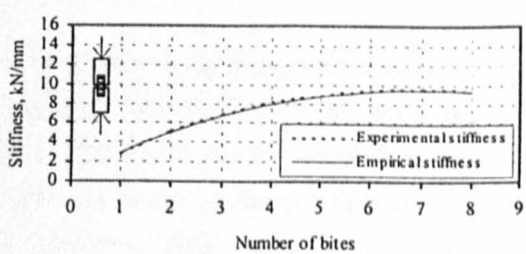
(e) Characteristics at 0.25mm displacement.



(f) Characteristics at 0.3mm displacement.

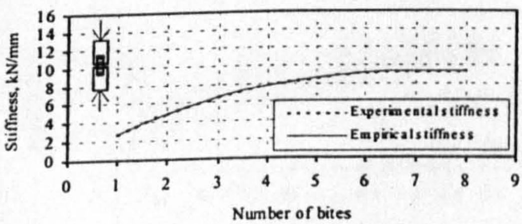


(g) Characteristics at 0.35mm displacement.

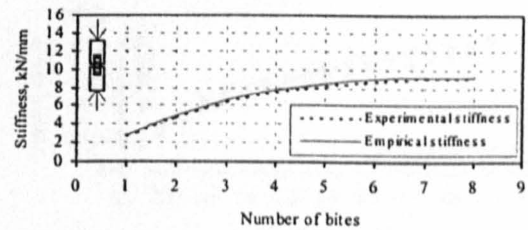


(h) Characteristics at 0.4mm displacement.

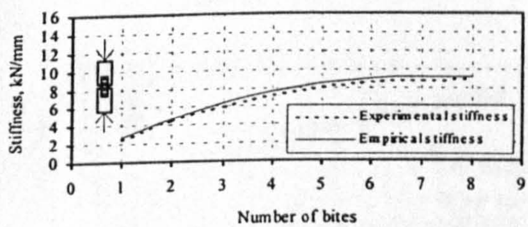
Figure 6.6 Comparison of stiffness vs number of bites between experimental and empirical (i.e. equation 6.2) results.



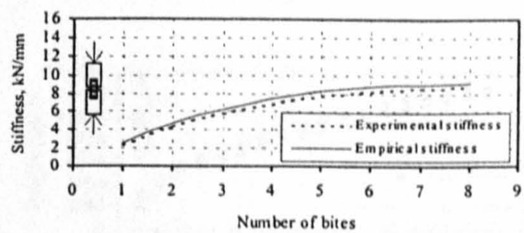
(i) Characteristics at 0.45mm displacement.



(k) Characteristics at 0.5mm displacement.



(m) Characteristics at 0.55mm displacement.



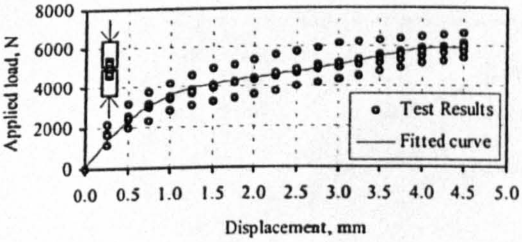
(n) Characteristics at 0.6mm displacement.

Figure 6.6 cont.

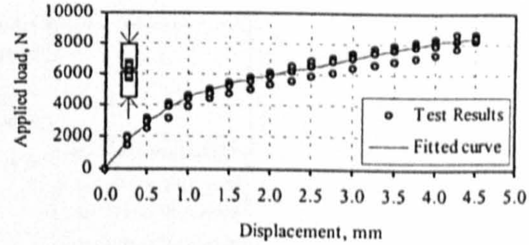
6.4.2 Effects of length of bites

Tests were carried out to determine the influences of length of bites on the performance of the punched metal plate timber joints subjected to compression loads. The test samples were generally made of two pieces of timber dimensioned as 73mm×170mm and 73mm×67mm by 45mm thickness. The punched metal plate type used in construction of testing specimens was small strip of plates cut from M14/1333. The specimens were loaded to failure in compression. All joint specimens were manufactured using material as explained in chapter 3.

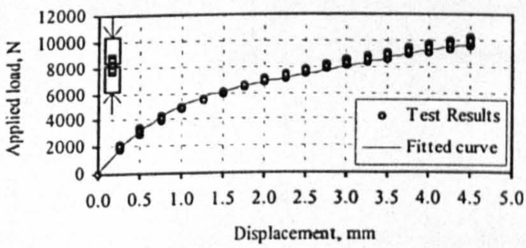
In Figure 6.7 typical load-displacement curves up to 4.5mm displacement with fitted curve (average curves) for specimens with various length of bites subjected to compression loading are shown. All joints made of small strip of M14/1333 punched metal plates with equal number of bites (8bites) and the loads applied parallel to the grain of timber.



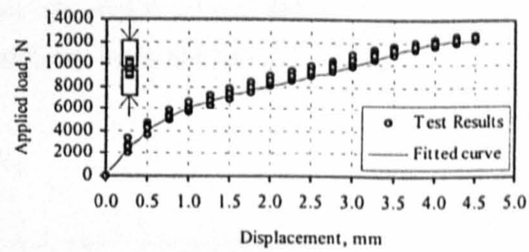
(a) 5mm bites length.



(b) 10mm bites length.



(c) 15mm bites length.



(d) 20mm bites length.

Figure 6.7 Load – displacement behaviour of joints with different bites length loaded in compression parallel to the grain.

The behaviour of the joints tested was assessed through observation of the failed specimens and their load-displacement relation. The load-displacement behaviour of each joint specimen was examined and fourth order polynomial equations was fitted to define the curves. The fitted curves simulated the load-displacement behaviour of the connection with good accuracy. These equations were directed to pass through the point of origin to simulate the condition of zero deformation at zero loads.

A comparison of joints performance in relation to the length of bites tested up to 4.5mm displacement is presented in Figure 6.8. The average load at 4.5mm displacement for each group of specimens is shown in Table 6.5.

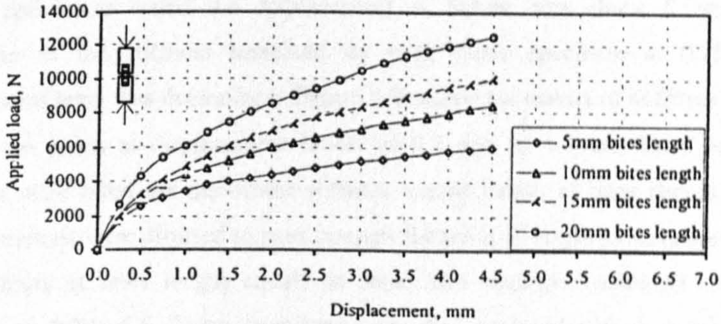


Figure 6.8 Comparison of joints performance subjected to compression force parallel to the grain using different length of bites.

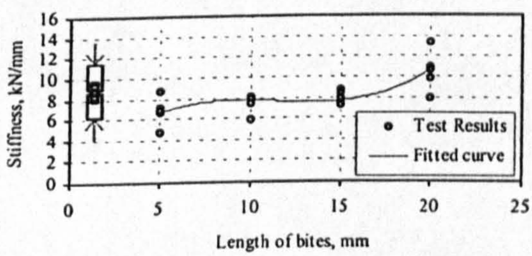
Plate ref. number	Length of bites (mm)	Average load at 4.5mm displacement (N)
M14/1333	5	6012
M14/1333	10	8398
M14/1333	15	9988
M14/1333	20	12490

Table 6.5 The average load at 4.5mm displacement for joints with various bites length subjected to compression force parallel to the grain.

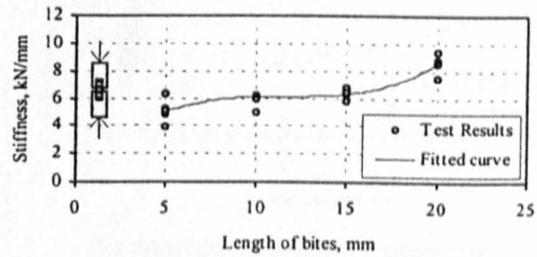
6.4.2.1 The stiffness characteristics of the joints

In order to investigate the effects of length of bites on the performance of the joints subjected to compression load parallel to the grain under short-term duration, the stiffness characteristics of all tested specimens were analysed in detail. The stiffness of the joint (K_C) defined as the ratio between the applied load and the displacement in the joint as described in equation 6.1.

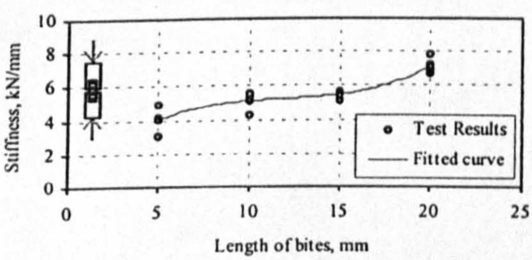
For all specimens tested the displacement at failure was about 4.5mm. The average magnitude of the stiffness sustained by each joints specimen at 0.25mm to 4.5mm displacement level was determined. Figure 6.9 represents results of stiffness versus length of bites in the joints at displacement levels of 0.25mm to 4.5mm. Third order polynomial equations were fitted the non-linear stiffness versus length of bites curves to define them. These equations were directed to pass through the point of origin to simulate the condition of zero stiffness at bites length equals to zero. The equations obtained are tabulated and presented in Table 6.6. These equations were then analysed and an empirical model (i.e. equation 6.3) describing the stiffness of punched metal plate timber connections with different bites length under compression loading was developed.



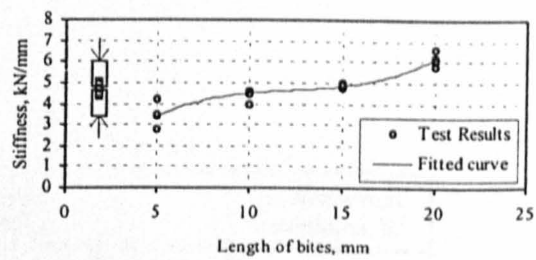
(a) Characteristics at 0.25mm displacement.



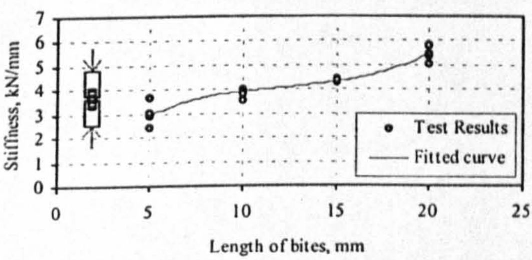
(b) Characteristics at 0.5mm displacement.



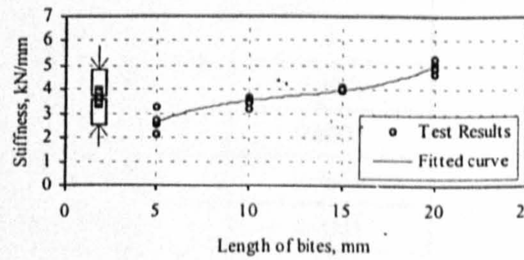
(c) Characteristics at 0.75mm displacement.



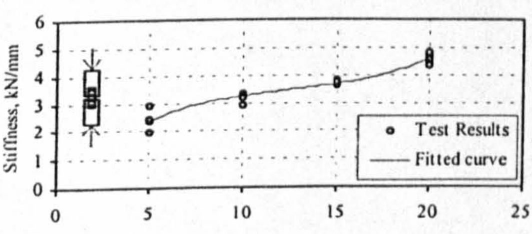
(d) Characteristics at 1mm displacement.



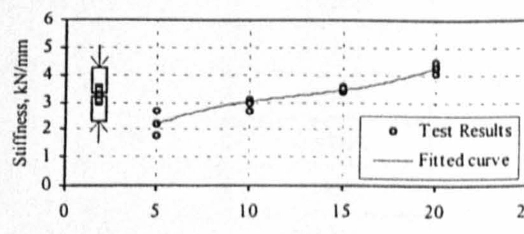
(e) Characteristics at 1.25mm displacement.



(f) Characteristics at 1.5mm displacement.

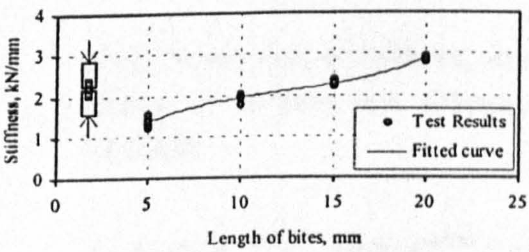


(g) Characteristics at 1.75mm displacement.

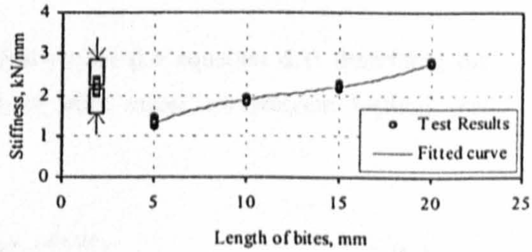


(h) Characteristics at 2mm displacement.

Figure 6.9 Stiffness sustained in the joint versus length of bites under compression loading parallel to the grain.



(s) Characteristics at 4.25mm displacement.



(t) Characteristics at 4.5mm displacement.

Figure 6.9 cont.

Displacement (mm)	Stiffness (KN/mm)	Coefficient of correlation, R^2
0.25	$0.0056\, l^3 - 0.1935\, l^2 + 2.1482\, l$	0.978
0.50	$0.004\, l^3 - 0.1364\, l^2 + 1.5759\, l$	0.9924
0.75	$0.0028\, l^3 - 0.0999\, l^2 + 1.2339\, l$	1
1	$0.0022\, l^3 - 0.0803\, l^2 + 1.0316\, l$	0.9971
1.25	$0.0018\, l^3 - 0.0664\, l^2 + 0.8749\, l$	0.9923
1.50	$0.0015\, l^3 - 0.0567\, l^2 + 0.7704\, l$	0.9951
1.75	$0.0013\, l^3 - 0.0493\, l^2 + 0.6878\, l$	0.9961
2	$0.0012\, l^3 - 0.0439\, l^2 + 0.6253\, l$	0.9969
2.25	$0.0011\, l^3 - 0.0402\, l^2 + 0.5788\, l$	0.9976
2.50	$0.001\, l^3 - 0.0371\, l^2 + 0.5401\, l$	0.9981
2.75	$0.0009\, l^3 - 0.0353\, l^2 + 0.5115\, l$	0.9984
3	$0.0009\, l^3 - 0.0337\, l^2 + 0.4857\, l$	0.9986
3.25	$0.0009\, l^3 - 0.0323\, l^2 + 0.4628\, l$	0.9993
3.50	$0.0008\, l^3 - 0.0307\, l^2 + 0.4413\, l$	0.9995
3.75	$0.0008\, l^3 - 0.0294\, l^2 + 0.4227\, l$	0.9992
4	$0.0008\, l^3 - 0.028\, l^2 + 0.4053\, l$	0.999
4.25	$0.0007\, l^3 - 0.0267\, l^2 + 0.3893\, l$	0.9994
4.50	$0.0007\, l^3 - 0.0252\, l^2 + 0.3736\, l$	0.9992

l = length of bites in the joints (mm).

Table 6.6 The equations of the various curves in Figure 6.9.

Using the equations in Table 6.6, an empirical model (i.e equation 6.3) describing the stiffness of the joints with different length of bites under compression loading was developed.

$$K_c = 0.0021\,\delta^{-0.7602}\,l^3 - 0.0763\,\delta^{-0.7355}\,l^2 + 0.9794\,\delta^{-0.6326}\,l \qquad (6.3)$$

where K_c = stiffness of the joint under compression loading (kN/mm).

δ = displacement (mm).

l = length of bites in the joint(mm).

In Figure 6.10, the effect of increase in the bites length on the performance of the connections with respect to the stiffness sustained by them at displacement levels of 0.25mm to 4.5mm are shown.

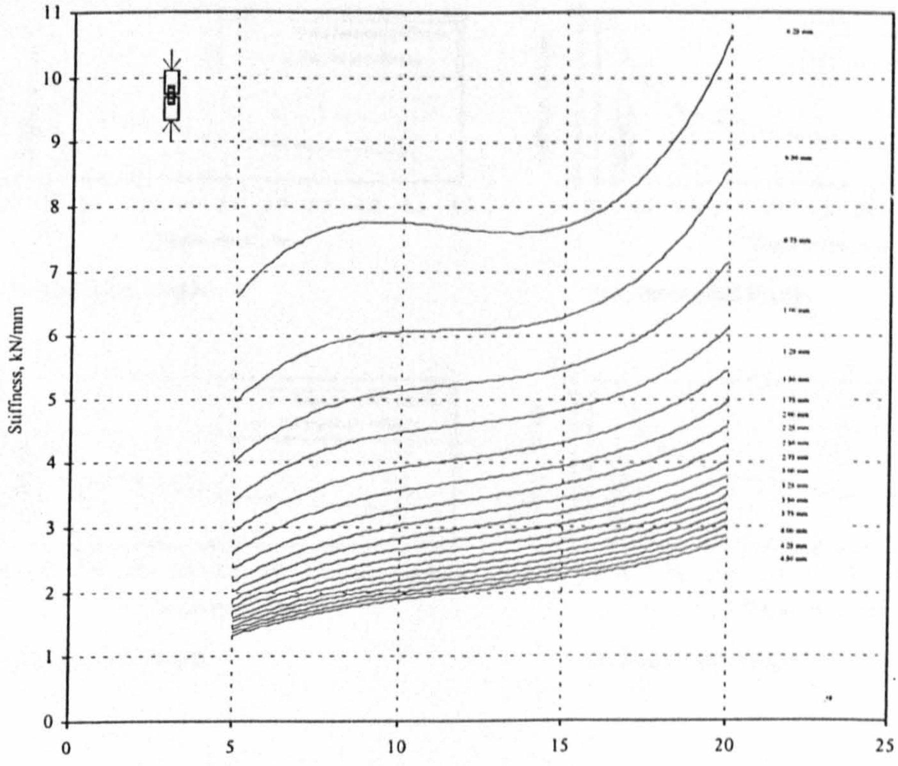
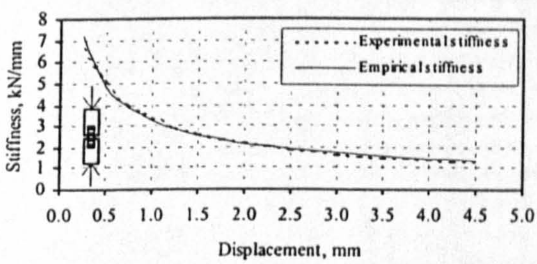


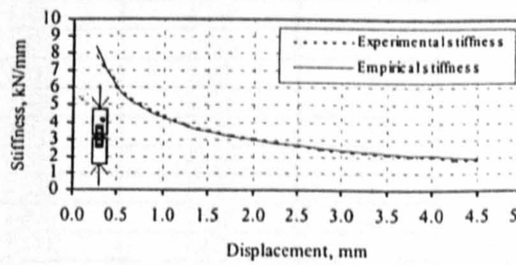
Figure 6.10 Stiffness vs length of bites in joints under compression loading parallel to the grain.

It is clear that the stiffness of the joints were dependent on the length of bites in the joints when loaded in compression parallel to the grain. The stiffness of the joints increased with an increase in the bites length. The rate of increase in stiffness increased as the length of bites increased above approximately 60% of the maximum length of bites available in a tested punched metal plate. At low displacement levels, stiffness was high compared with at high displacement levels. The rate of increasing in stiffness was reduced as displacement was increased.

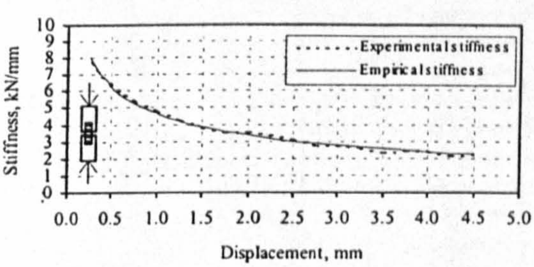
In Figure 6.11, a comparison of stiffness versus displacement relationships between experimental and the developed empirical results for joints with different bites length are represented. There was a good agreement between the empirical model and experimental results.



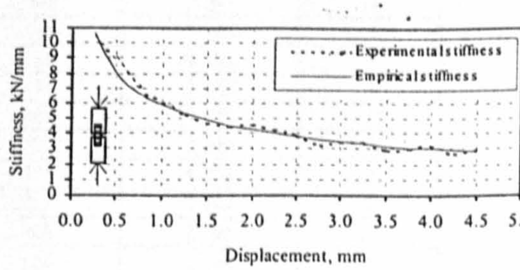
(a) 5mm bites length.



(b) 10mm bites length.



(c) 15mm bites length.



(d) 20mm bites length.

Figure 6.11 Comparison of stiffness vs displacement curve between experimental and empirical (i.e. equation 6.3) results.

In Table 6.7 Comparison between the experimental and empirical (i.e. equation 6.3) stiffness at displacement levels 0.25mm to 4.5mm for the various bites length in the joints are shown.

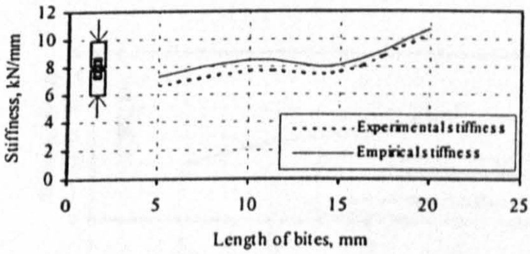
Plate Number	Bites length (mm)	Displacement level (mm)	Experimental stiffness (kN/mm)	Empirical stiffness (kN/mm)	Percentage of Error (%)
M14/1333	5	0.25	6.603	7.236	10
M14/1333	10	0.25	7.732	8.414	9
M14/1333	15	0.25	7.585	8.053	6
M14/1333	20	0.25	10.364	10.67	3
M14/1333	5	0.5	4.970	4.861	-2
M14/1333	10	0.5	6.119	6.037	-1
M14/1333	15	0.5	6.449	6.197	-4
M14/1333	20	0.5	8.958	8.008	-4
M14/1333	5	0.75	4.022	3.844	-4
M14/1333	10	0.75	5.149	4.934	-4
M14/1333	15	0.75	5.481	5.231	-5
M14/1333	20	0.75	7.118	6.693	-6
M14/1333	5	1	3.426	3.252	-5
M14/1333	10	1	4.486	4.264	-5
M14/1333	15	1	4.832	4.611	-5
M14/1333	20	1	6.112	5.868	-4
M14/1333	5	1.25	2.940	2.855	-3
M14/1333	10	1.25	3.909	3.802	-3
M14/1333	15	1.25	4.259	4.170	-2
M14/1333	20	1.25	5.338	5.288	-1
M14/1333	5	1.5	2.622	2.566	-2
M14/1333	10	1.5	3.534	3.459	-2
M14/1333	15	1.5	3.861	3.834	-1
M14/1333	20	1.5	4.728	4.850	3
M14/1333	5	1.75	2.369	2.345	-1
M14/1333	10	1.75	3.248	3.191	-2
M14/1333	15	1.75	3.612	3.568	-1
M14/1333	20	1.75	4.436	4.505	2
M14/1333	5	2	2.179	2.168	-1
M14/1333	10	2	3.063	2.974	-3
M14/1333	15	2	3.552	3.349	-6
M14/1333	20	2	4.546	4.223	-7
M14/1333	5	2.25	2.027	2.023	0
M14/1333	10	2.25	2.868	2.795	-3
M14/1333	15	2.25	3.350	3.166	-5
M14/1333	20	2.25	4.296	3.987	-7
M14/1333	5	2.5	1.898	1.901	0
M14/1333	10	2.5	2.691	2.643	-2
M14/1333	15	2.5	3.129	3.010	-4
M14/1333	20	2.5	3.962	3.786	-4

Table 6.7 Comparison between experimental and empirical stiffness at displacement level of 0.25mm to 4.5mm for various bites length in the joints.

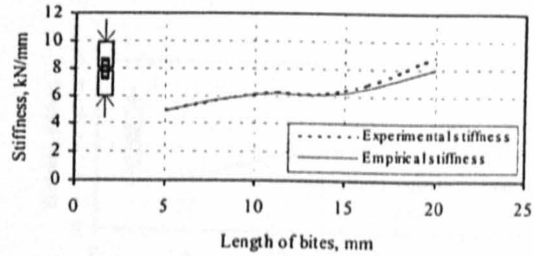
Plate Number	Bites length (mm)	Displacement level (mm)	Experimental stiffness (kN/mm)	Empirical stiffness (kN/mm)	Percentage of Error (%)
M14/1333	5	2.75	1.787	1.798	1
M14/1333	10	2.75	2.485	2.512	1
M14/1333	15	2.75	2.768	2.874	4
M14/1333	20	2.75	3.310	3.613	9
M14/1333	5	3	1.699	1.708	1
M14/1333	10	3	2.387	2.398	0
M14/1333	15	3	2.741	2.754	0
M14/1333	20	3	3.434	3.460	1
M14/1333	5	3.25	1.619	1.629	1
M14/1333	10	3.25	2.298	2.297	0
M14/1333	15	3.25	2.712	2.648	-2
M14/1333	20	3.25	3.536	3.325	-6
M14/1333	5	3.5	1.539	1.559	1
M14/1333	10	3.5	2.143	2.208	3
M14/1333	15	3.5	2.412	2.553	6
M14/1333	20	3.5	2.946	3.204	9
M14/1333	5	3.75	1.479	1.497	1
M14/1333	10	3.75	2.087	2.127	2
M14/1333	15	3.75	2.426	2.468	2
M14/1333	20	3.75	3.094	3.095	0
M14/1333	5	4	1.426	1.441	1
M14/1333	10	4	2.053	2.054	0
M14/1333	15	4	2.479	2.390	-4
M14/1333	20	4	3.306	2.996	-9
M14/1333	5	4.25	1.366	1.390	2
M14/1333	10	4.25	1.923	1.988	3
M14/1333	15	4.25	2.194	2.319	6
M14/1333	20	4.25	2.706	2.906	7
M14/1333	5	4.5	1.325	1.344	1
M14/1333	10	4.5	1.916	1.927	1
M14/1333	15	4.5	2.296	2.253	-2
M14/1333	20	4.5	2.992	2.823	-6

Table 6.7 cont.

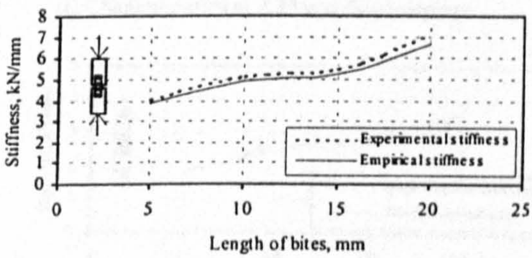
In Figure 6.12, a comparison of stiffness versus length of bites curves between experimental and empirical (i.e. equation 6.3) results for various joints with different length of bites at displacement levels of 0.25mm to 4.5mm are represented. There was a good agreement between the empirical model and experimental results.



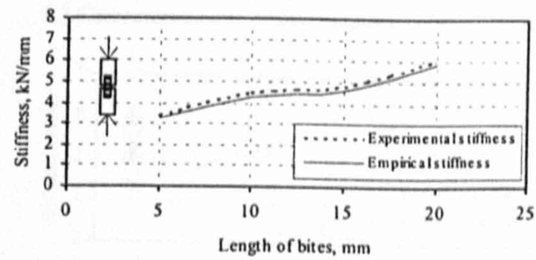
(a) Characteristics at 0.25mm displacement.



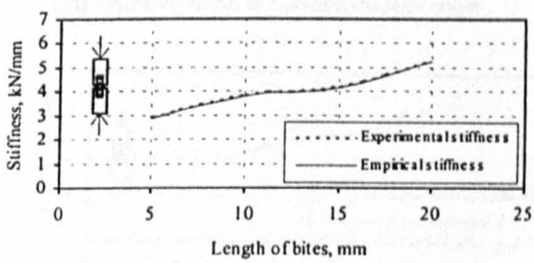
(b) Characteristics at 0.5mm displacement.



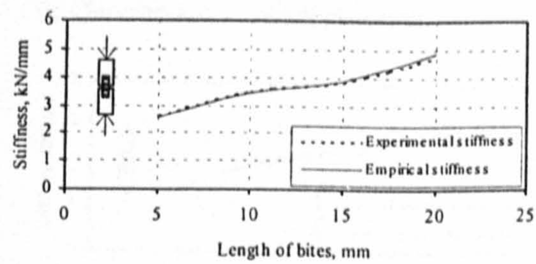
(c) Characteristics at 0.75mm displacement.



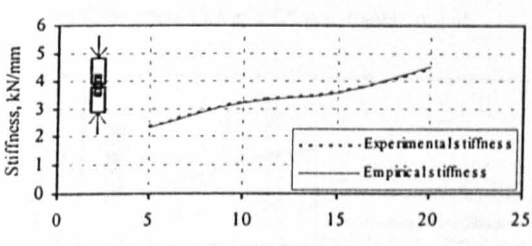
(d) Characteristics at 1mm displacement.



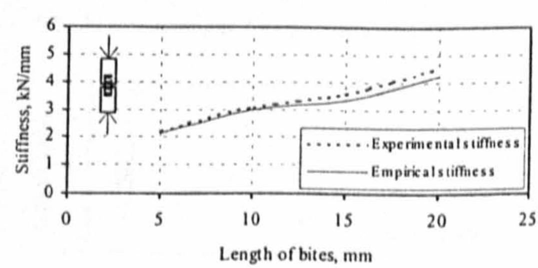
(e) Characteristics at 1.25mm displacement.



(f) Characteristics at 1.5mm displacement.

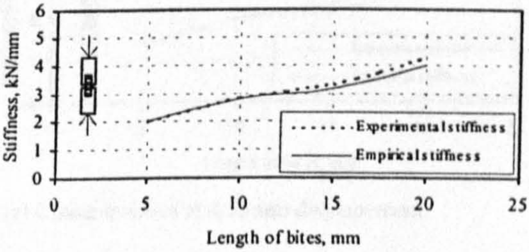


(g) Characteristics at 1.75mm displacement.

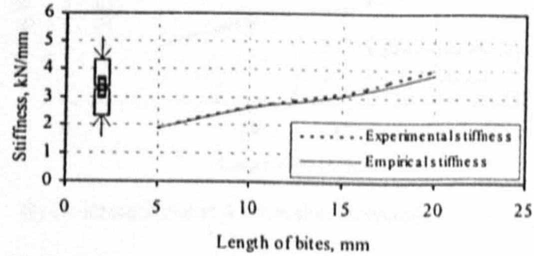


(h) Characteristics at 2mm displacement.

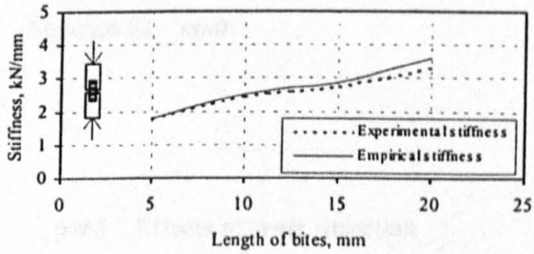
Figure 6.12 Comparison of stiffness vs length of bites between experimental and empirical (i.e. equation 6.3) results.



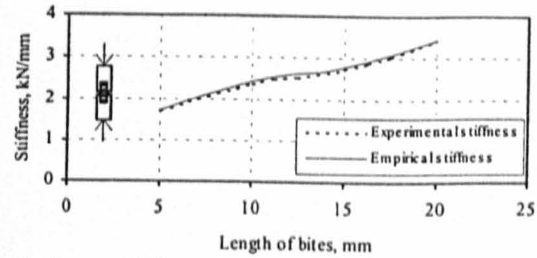
(i) Characteristics at 2.25mm displacement.



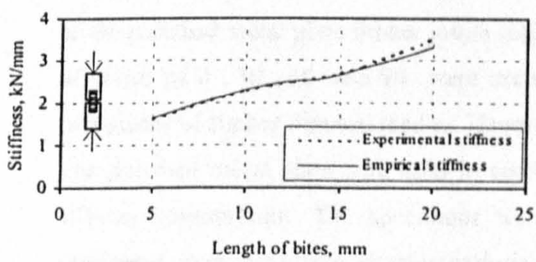
(k) Characteristics at 2.5mm displacement.



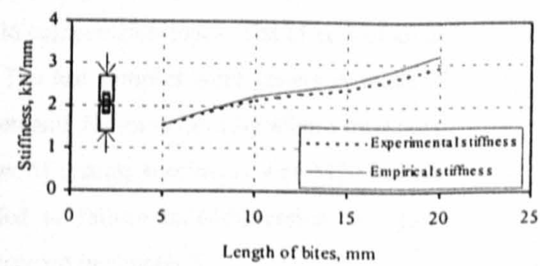
(m) Characteristics at 2.75mm displacement.



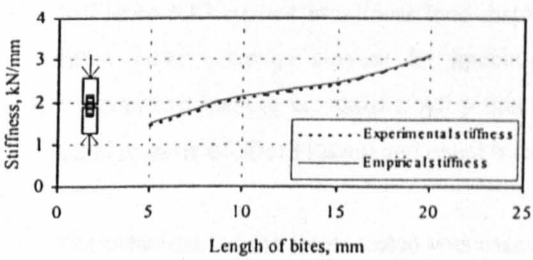
(n) Characteristics at 3mm displacement.



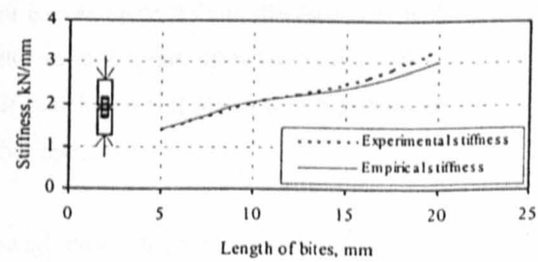
(o) Characteristics at 3.25mm displacement.



(p) Characteristics at 3.5mm displacement.

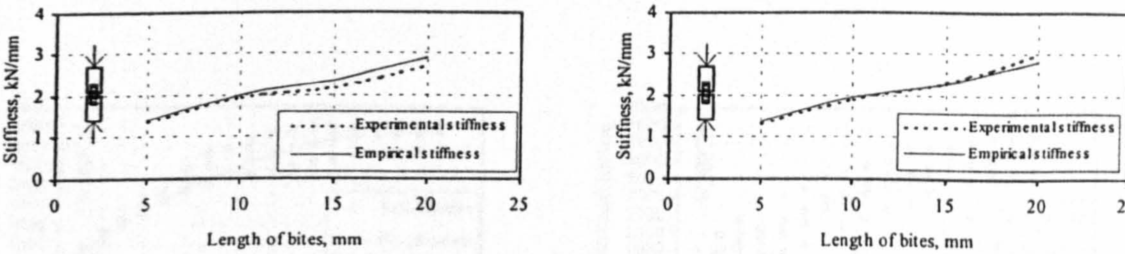


(q) Characteristics at 3.75mm displacement.



(r) Characteristics at 4mm displacement.

Figure 6.12 cont.



(s) Characteristics at 4.25mm displacement.

(t) Characteristics at 4.5mm displacement.

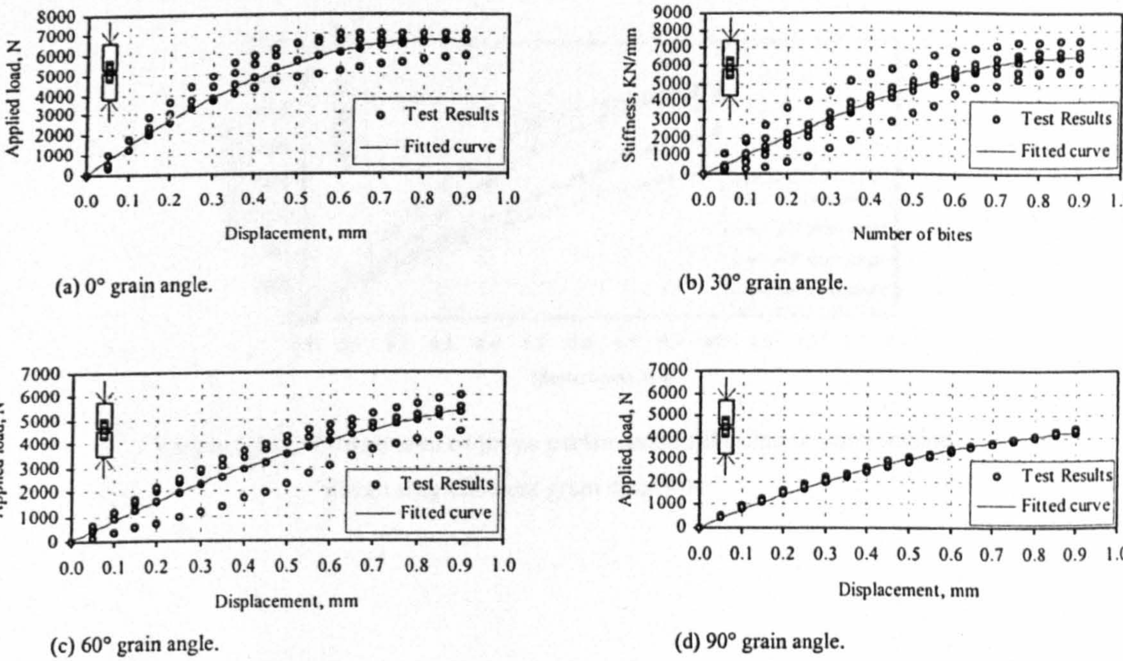
Figure 6.12 cont.

6.4.3 Effects of grain direction

Tests were carried out to determine the influences of the grain direction on the performance of the punched metal plate timber joints subjected to compression loads. The effects of angle of grains of 0 , 30 , 60 and 90 were examined. The test samples were generally made of two pieces of timber dimensioned as 73mm×170mm and 73mm×67mm by 45mm thickness. The punched metal plate type used in construction of testing specimens was M20/0310B-101mm×25mm×1mm. The specimens were loaded to failure in compression. All joint specimens were manufactured using material as explained in chapter 3.

In Figure 6.13 typical non-linear load-displacement curves up to 0.9mm displacement with fitted curve (average curves) for specimens with various grain direction subjected to compression loading are shown. All joints made of punched metal plates M20/0310B with equal number of bites (8bites) and equal bites length (8mm).

The behaviour of the joints tested was assessed through observation of the failed specimens and their load-displacement relation. The load-displacement behaviour of each joint specimen was examined and third order polynomial equations were fitted to define the curves. The fitted curves simulated the load-displacement behaviour of the connection with good accuracy. These equations were directed to pass through the point of origin to simulate the condition of zero deformation at zero loads.



(a) 0° grain angle.

(b) 30° grain angle.

(c) 60° grain angle.

(d) 90° grain angle.

Figure 6.13 Load – displacement behaviour of joints with different grain direction under compression loading.

A comparison of performance of joints in relation to the grain direction tested up to 0.9mm displacement is presented in Figure 6.14. The average load at 0.9mm displacement for each group of specimens is shown in Table 6.8.

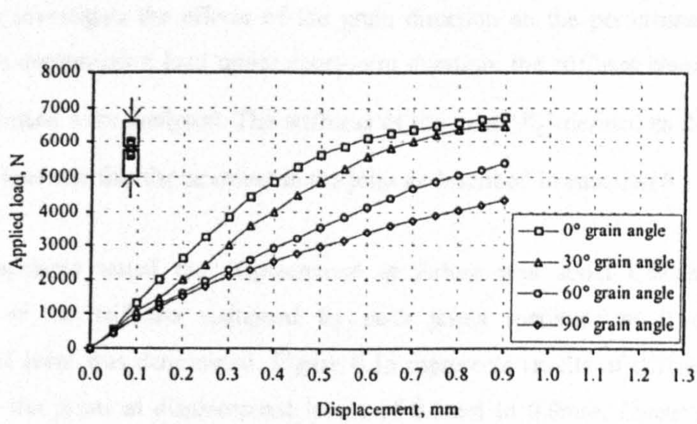


Figure 6.14 Comparison of joints performance subjected to compression force using different grain direction.

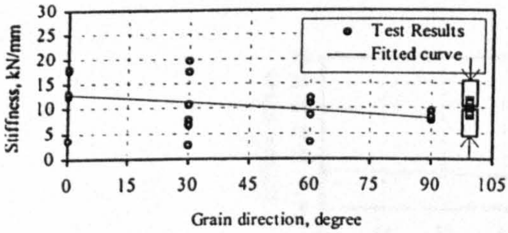
Plate ref. number	Grain direction (degree)	Average load at 0.9mm displacement (N)
M20/0310B	0	6691
M20/0310B	30	6447
M20/0310B	60	5362
M20/0310B	90	4321

Table 6.8 The average load at 0.9mm displacement for joints with various grain direction subjected to compression force.

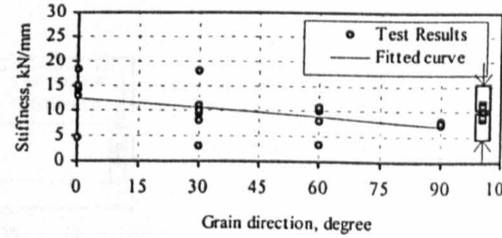
6.4.3.1 The stiffness characteristics of the joints

In order to investigate the effects of the grain direction on the performance of the joints subjected to compression load under short-term duration, the stiffness characteristics of all tested specimens were analysed. The stiffness of the joint (K_C) defined as the ratio between the applied load and the displacement in the joint as described in equation 6.1.

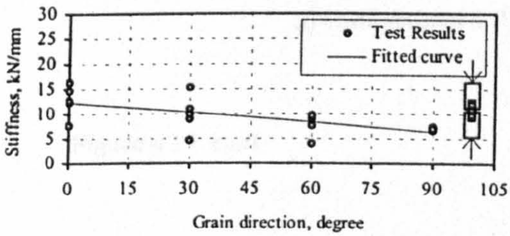
For all specimens tested the displacement at failure was about 0.9mm. The average magnitude of the stiffness sustained by each joints specimen at 0.1mm to 0.9mm displacement level was determined. Figure 6.15 represents results of stiffness versus grain direction in the joints at displacement levels of 0.1mm to 0.9mm. Linear equations were fitted the stiffness versus grain direction curves to define them. The equations obtained are tabulated and presented in Table 6.9. These equations were then analysed and an empirical model (i.e. equation 6.4) describing the stiffness of punched metal plate timber connections with different grain direction under compression loading was developed.



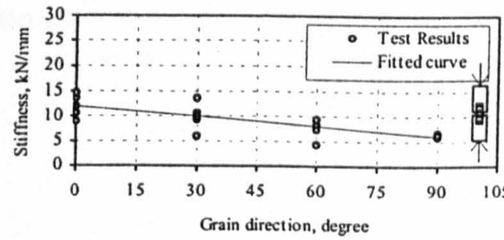
(a) Characteristics at 0.1mm displacement.



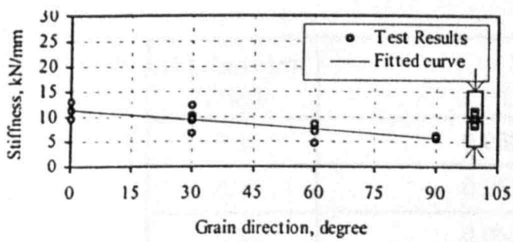
(b) Characteristics at 0.2mm displacement.



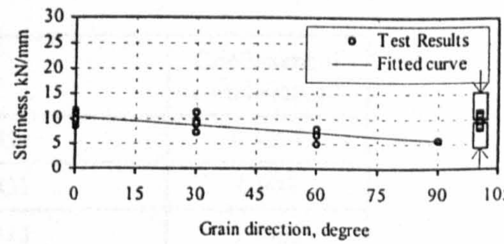
(c) Characteristics at 0.3mm displacement.



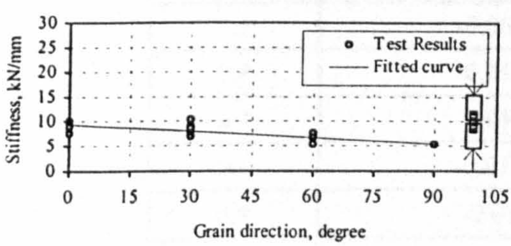
(d) Characteristics at 0.4mm displacement.



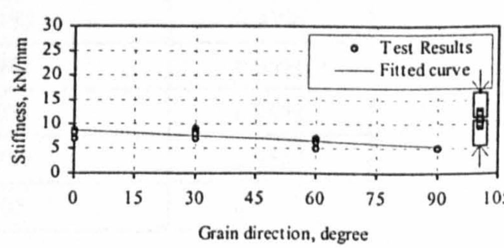
(e) Characteristics at 0.5mm displacement.



(f) Characteristics at 0.6mm displacement.

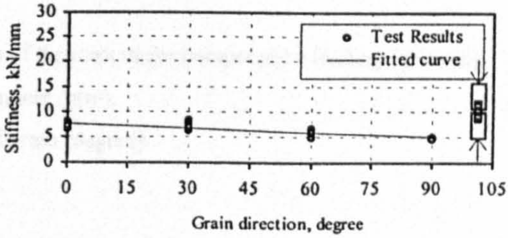


(g) Characteristics at 0.7mm displacement.



(h) Characteristics at 0.8mm displacement.

Figure 6.15 Stiffness sustained in the joint versus grain direction under compression loading.



(i) Characteristics at 0.9mm displacement.

Figure 6.15 cont.

Displacement (mm)	Stiffness (KN/mm)	Coefficient of correlation, R^2
0.1	-0.0508 g + 12.526	0.9214
0.2	-0.0614 g + 12.431	0.909
0.3	-0.0664 g + 12.313	0.9463
0.4	-0.0671 g + 11.924	0.9762
0.5	-0.0617 g + 11.264	0.9796
0.6	-0.0536 g + 10.383	0.9691
0.7	-0.0443 g + 9.3934	0.9592
0.8	-0.0373 g + 8.5444	0.9382
0.9	-0.0304 g + 7.705	0.9443

g = angle of grain (degree).

Table 6.9 The equations of the various curves in Figure 6.15.

Using the equations in Table 6.9, an empirical model (i.e equation 6.4) describing the stiffness of the joints with different grain direction under compression loading was developed.

$$K_C = 0.1306\delta^2 g - 0.0954\delta g - 0.0462g - 7.0196\delta^2 + 0.6328\delta + 12.627 \quad (6.4)$$

where K_c = stiffness of the joint under compression loading (kN/mm).

δ = displacement (mm).

g = angle of grain (degree).

In Figure 6.16, the effect of grain direction on the performance of the connections with respect to the stiffness sustained by them at displacement levels of 0.1mm to 0.9mm are shown.

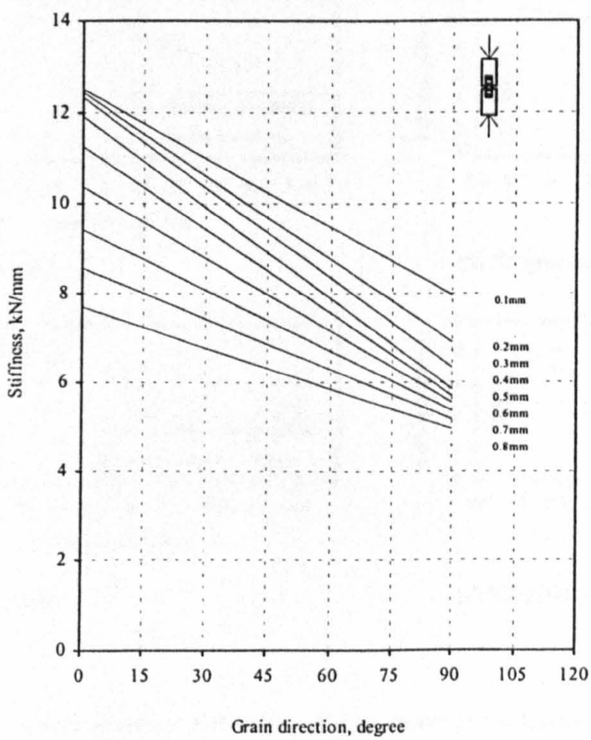
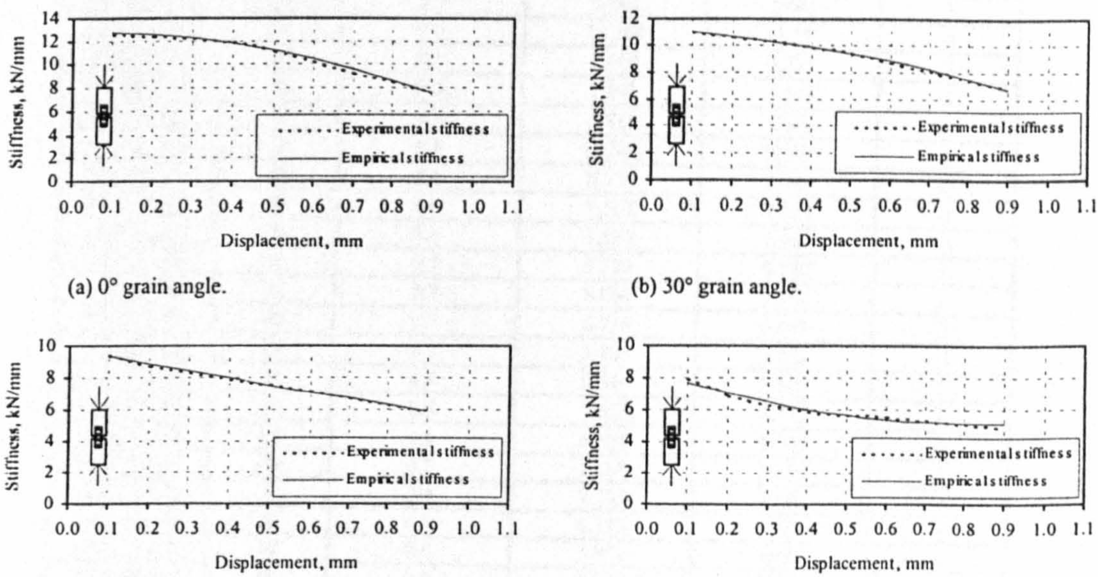


Figure 6.16 Stiffness vs grain direction in joints under compression loading.

It is clear that the stiffness of the joints were dependent on the grain direction in the joints under compression loading. The stiffness of the joints decreased with an increase in the angle of grain. The rate of decrease in stiffness increased as the angle of grain increased. At low displacement (0.1mm), stiffness was high comparing with high displacement (0.9mm). The rate of increasing in stiffness was reduced as displacement was increased.

In Figure 6.17, a comparison of stiffness versus displacement between experimental and empirical (i.e. equation 6.4) results for joints with different grain direction are represented. There was a good agreement between the empirical model and experimental results.



(a) 0° grain angle.

(b) 30° grain angle.

(c) 60° grain angle.

(d) 90° grain angle.

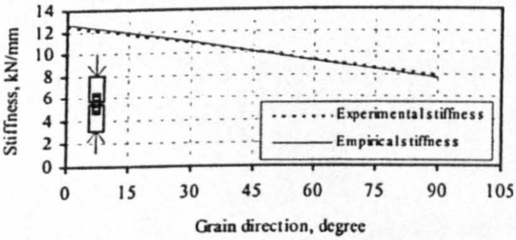
Figure 6.17 Comparison of stiffness vs displacement curve between experimental and empirical (i.e. equation 6.4) results.

In Table 6.10 Comparison between the experimental and empirical (i.e. equation 6.4) stiffness at displacement levels 0.1mm to 0.9mm for the various grain direction in the joints are shown.

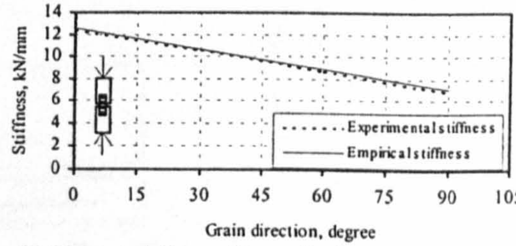
Plate Number	Grain direction (degree)	Displacement level (mm)	Experimental stiffness (kN/mm)	Empirical stiffness (kN/mm)	Percentage of Error (%)
M20/0310B	0	0.1	12.526	12.620	1
M20/0310B	30	0.1	11.002	10.987	0
M20/0310B	60	0.1	9.478	9.354	-1
M20/0310B	90	0.1	7.954	7.721	-3
M20/0310B	0	0.2	12.431	12.473	0
M20/0310B	30	0.2	10.589	10.671	1
M20/0310B	60	0.2	8.747	8.869	1
M20/0310B	90	0.2	6.905	7.068	2
M20/0310B	0	0.3	12.313	12.185	-1
M20/0310B	30	0.3	10.321	10.293	0
M20/0310B	60	0.3	8.329	8.401	1
M20/0310B	90	0.3	6.337	6.509	3
M20/0310B	0	0.4	11.924	11.757	-1
M20/0310B	30	0.4	9.911	9.853	-1
M20/0310B	60	0.4	7.898	7.949	1
M20/0310B	90	0.4	5.885	6.045	3
M20/0310B	0	0.5	11.264	11.189	-1
M20/0310B	30	0.5	9.413	9.351	-1
M20/0310B	60	0.5	7.562	7.514	-1
M20/0310B	90	0.5	5.711	5.676	-1
M20/0310B	0	0.6	10.383	10.480	1
M20/0310B	30	0.6	8.775	8.787	0
M20/0310B	60	0.6	7.167	7.094	-1
M20/0310B	90	0.6	5.559	5.401	-3
M20/0310B	0	0.7	9.393	9.630	3
M20/0310B	30	0.7	8.064	8.161	1
M20/0310B	60	0.7	6.735	6.691	-1
M20/0310B	90	0.7	5.406	5.222	-3
M20/0310B	0	0.8	8.544	8.641	1
M20/0310B	30	0.8	7.425	7.473	1
M20/0310B	60	0.8	6.306	6.305	0
M20/0310B	90	0.8	5.187	5.136	-1
M20/0310B	0	0.9	7.705	7.511	-3
M20/0310B	30	0.9	6.793	6.722	-1
M20/0310B	60	0.9	5.881	5.934	1
M20/0310B	90	0.9	4.969	5.146	4

Table 6.10 Comparison between experimental and empirical stiffness at displacement level from 0.1mm to 0.9mm for various grain direction in the joints.

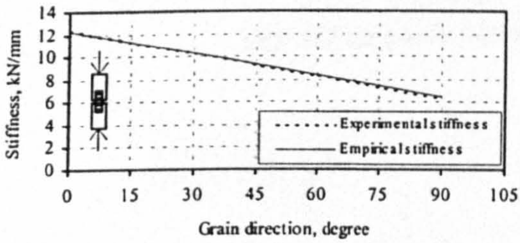
In Figure 6.18, a comparison of stiffness versus grain direction curves between experimental and empirical (i.e. equation 6.4) results for various joints with different grain direction at displacement levels from 0.1mm to 0.9mm are represented. There was a good agreement between the empirical model and experimental results.



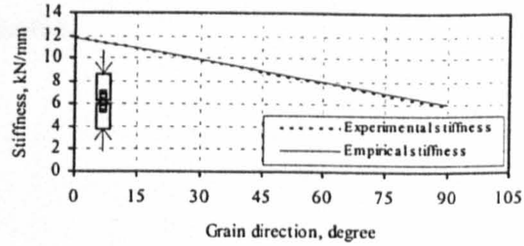
(a) Characteristics at 0.1mm displacement.



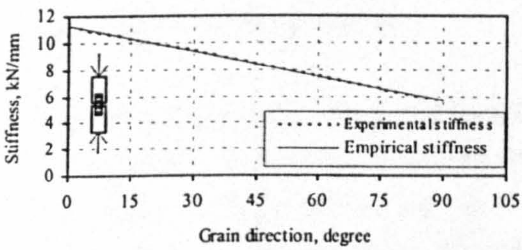
(b) Characteristics at 0.2mm displacement.



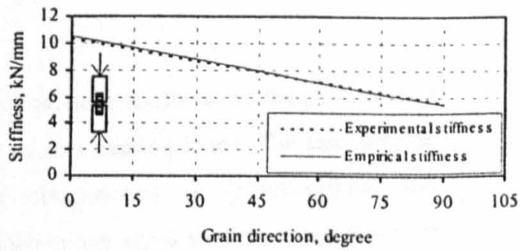
(c) Characteristics at 0.3mm displacement.



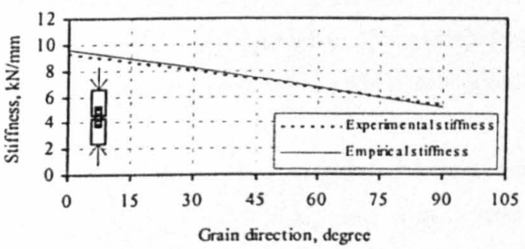
(d) Characteristics at 0.4mm displacement.



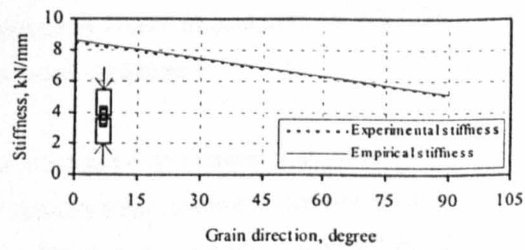
(e) Characteristics at 0.5mm displacement.



(f) Characteristics at 0.6mm displacement.

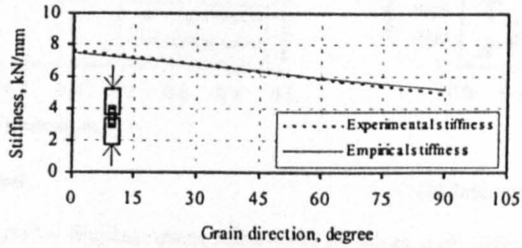


(g) Characteristics at 0.7mm displacement.



(h) Characteristics at 0.8mm displacement.

Figure 6.18 Comparison of stiffness vs grain direction between experimental and empirical (i.e. equation 6.4) results.



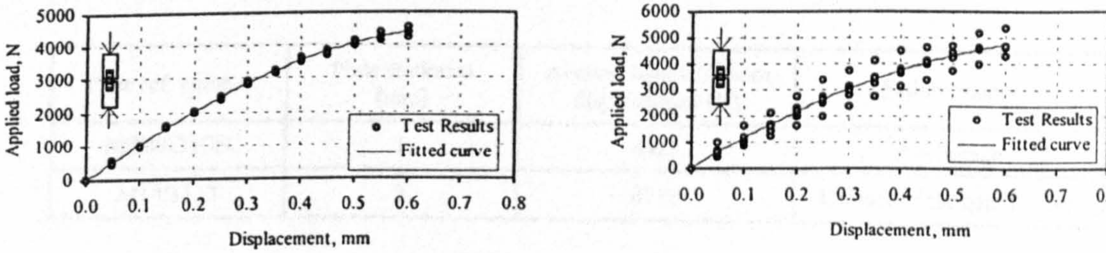
(i) Characteristics at 0.9mm displacement.

Figure 6.18 cont.

6.4.4 Effects of plate thickness

Tests were carried out to determine the influences of the plate thickness on the performance of the punched metal plate timber joints subjected to compression loads. The test samples were generally made of two pieces of timber dimensioned as 73mm×170mm and 73mm×67mm by 45mm thickness. The punched metal plate types used in construction of testing specimens were M20/0310B, 1mm thickness and small strip of plates cut from M14/1333, 2mm thickness. The specimens were loaded to failure in compression. All joint specimens were manufactured using material as explained in chapter 3.

In Figure 6.19 typical load-displacement curves up to 0.6mm displacement with fitted curve (average curves) for specimens with various plate thickness subjected to compression loading are shown. Joints were made of two different plates. The first group made of punched metal plates M20/0310B with 1mm plate thickness and the second group made of small strip of punched metal plate M14/1333 with 2mm plate thickness. All plates having equal number of bites (8bites) and load applied parallel to the grain of timber.



(a) 1mm plate thickness. (b) 2mm plate thickness.

Figure 6.19 Load – displacement behaviour of joints with different plate thickness loaded in compression parallel to the grain.

The behaviour of the joints tested was assessed through observation of the failed specimens and their load-displacement relation. The load-displacement behaviour of each joint specimen was examined and second order polynomial equations were fitted to define the curves. The fitted curves simulated the load-displacement behaviour of the connection with good accuracy. These equations were directed to pass through the point of origin to simulate the condition of zero deformation at zero loads.

A comparison of performance of joints in relation to the thickness of plate tested up to 0.6mmmm displacement is presented in Figure 6.20. The average load at 0.6mm displacement for each group of specimens is shown in Table 6.11.

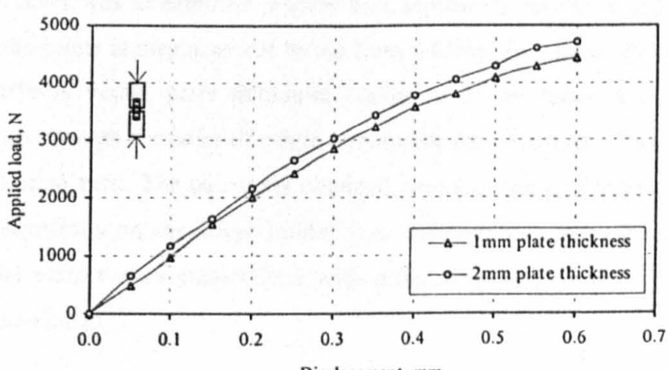


Figure 6.20 Comparison of joints performance subjected to compression force parallel to the grain using different plate thickness.

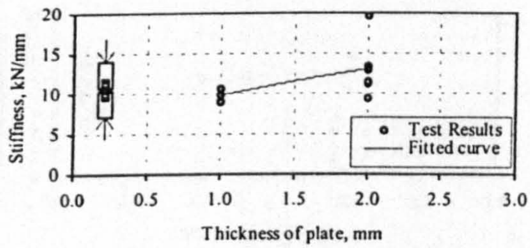
Plate ref. number	Plate thickness (mm)	Average load at 0.6mm displacement (N)	Failure modes
M20/0310B	1	4423	Anchorage
M14/1333	2	4717	Closure of the gap-Timber

Table 6.11 The average load at 0.6mm displacement for joints with various plate thickness subjected to compression force parallel to the grain.

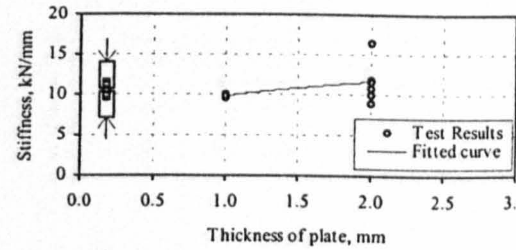
6.4.4.1 The stiffness characteristics of the joints

In order to investigate the effects of plate thickness on the performance of the joints subjected to compression load parallel to the grain under short-term duration, the stiffness characteristics of all tested specimens were analysed in detail. The stiffness of the joint (K_c) defined as the ratio between the applied load and the displacement in the joint as described in equation 6.1.

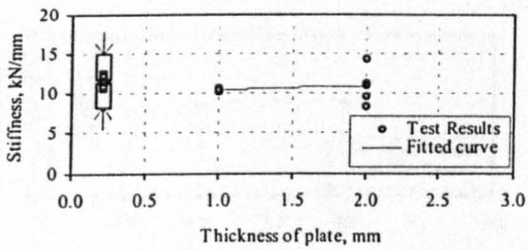
For all specimens tested the displacement at failure was about 0.6mm. The average magnitude of the stiffness sustained by each joints specimen at 0.05mm to 0.6mm displacement level was determined. Figure 6.21 represents results of stiffness versus plate thickness in the joints at displacement levels from 0.05mm to 0.6mm. Power equations were fitted the stiffness versus plate thickness curves to define them. These equations were directed to pass through the point of origin to simulate the condition of zero stiffness at plate thickness equals to zero. The equations obtained are tabulated and presented in Table 6.12. From these equations an empirical model (i.e. equation 6.5) describing the stiffness of punched metal plate timber connections with different plate thickness under compression loading was developed.



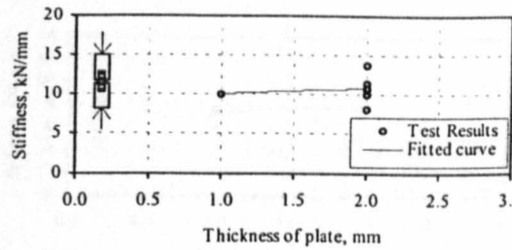
(a) Characteristics at 0.05mm displacement.



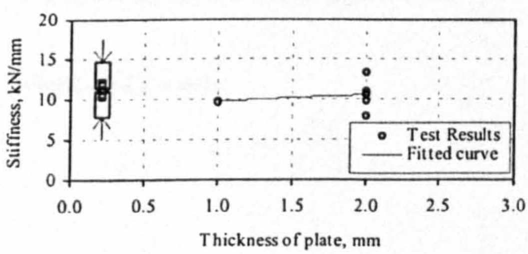
(b) Characteristics at 0.1mm displacement.



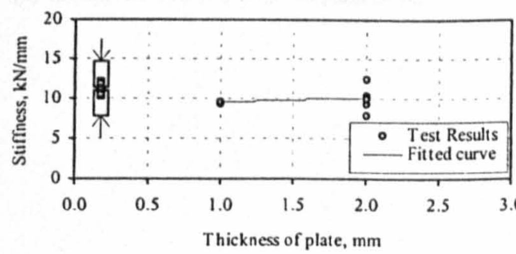
(c) Characteristics at 0.15mm displacement.



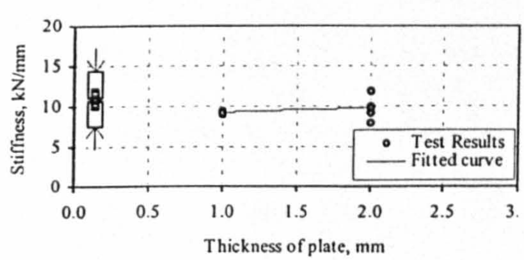
(d) Characteristics at 0.2mm displacement.



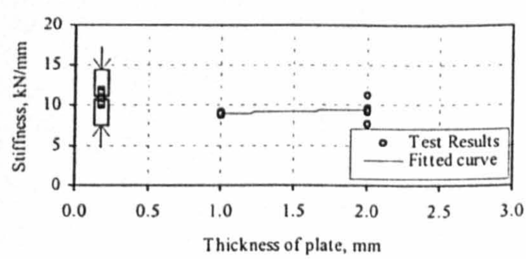
(e) Characteristics at 0.25mm displacement.



(f) Characteristics at 0.3mm displacement.

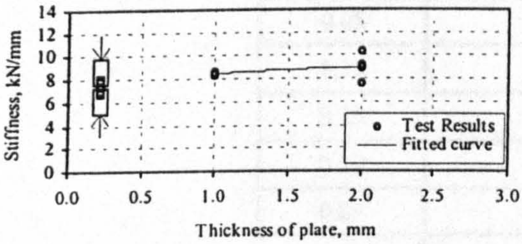


(g) Characteristics at 0.35mm displacement.

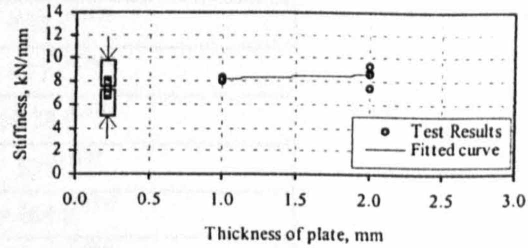


(h) Characteristics at 0.4mm displacement.

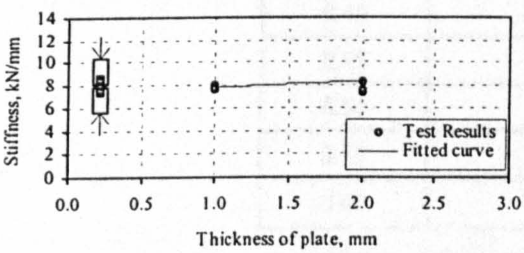
Figure 6.21 Stiffness sustained in the joint versus plate thickness under compression loading parallel to the grain.



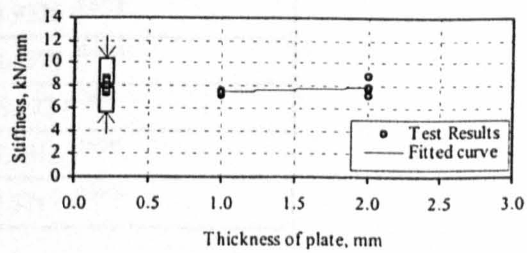
(i) Characteristics at 0.45mm displacement.



(k) Characteristics at 0.5mm displacement.



(m) Characteristics at 0.55mm displacement.



(n) Characteristics at 0.6mm displacement.

Figure 6.21 cont.

Displacement (mm)	Stiffness (KN/mm)
0.05	$9.78\ t^{0.4128}$
0.10	$9.77\ t^{0.2564}$
0.15	$10.38\ t^{0.0767}$
0.20	$10\ t^{0.1137}$
0.25	$9.664\ t^{0.1317}$
0.30	$9.51\ t^{0.0859}$
0.35	$9.2029\ t^{0.089}$
0.40	$8.9325\ t^{0.0736}$
0.45	$8.4578\ t^{0.0864}$
0.50	$8.172\ t^{0.0673}$
0.55	$7.7818\ t^{0.0999}$
0.60	$7.3717\ t^{0.0928}$

t = thickness of the plate (mm).

Table 6.12 The equations of the various curves in Figure 6.21.

Using the equations in Table 6.12, an empirical model (i.e equation 6.5) describing the stiffness of the joints with different plate thickness under compression loading was developed.

$$K_c = -10.723\delta^2 + 2.0714\delta + 9.8642 \quad t^{-8.421\delta^3 + 10.347\delta^2 - 3.9803\delta + 0.5584} \qquad (6.5)$$

where K_c = stiffness of the joint under compression loading (kN/mm).

δ = displacement (mm).

t = thickness of plate(mm).

In Figure 6.22, the effect of increase in the plate thickness on the performance of the connections with respect to the stiffness sustained by them at displacement levels of 0.05mm to 0.6mm are shown.

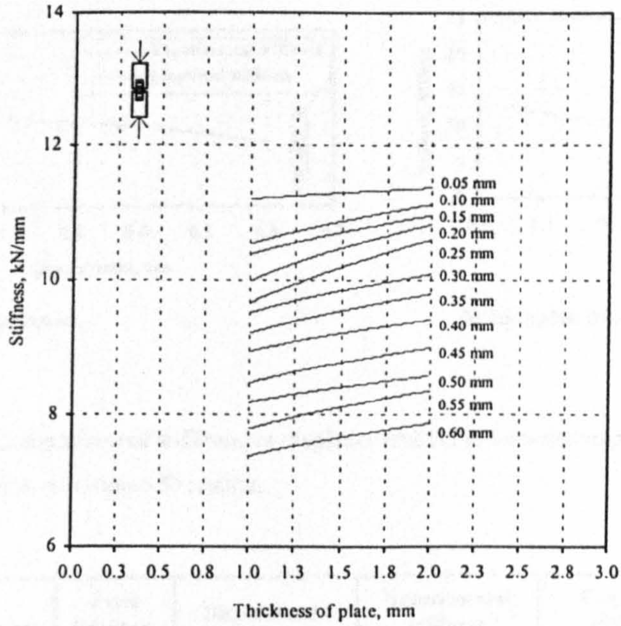
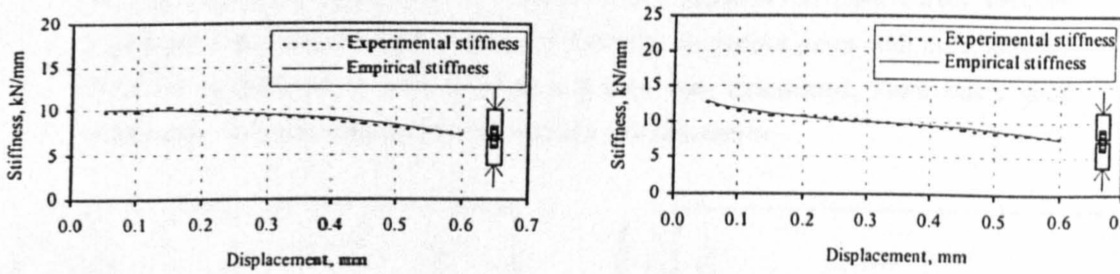


Figure 6.22 Stiffness vs thickness of plate in joints under compression loading parallel to the grain.

It is clear that the stiffness of the joints were dependent on the thickness of plate in the joints when loaded in compression parallel to the grain. The stiffness of the joints increased with an increase in the plate thickness. At low displacement (0.05mm), stiffness was high comparing with high displacement (0.6mm). The rate of increasing in stiffness was reduced as displacement was increased.

In Figure 6.23, a comparison of stiffness versus displacement between experimental and empirical (i.e. equation 6.5) results for joints with different plate thickness are represented. There was a good agreement between the empirical model and experimental results.

In Table 6.13 Comparison between the experimental and empirical (i.e. equation 6.5) stiffness at displacement levels 0.05mm to 0.6mm for the various plate thickness in the joints are shown.



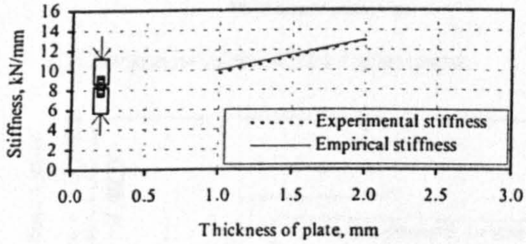
(a) 1mm plate thickness. (b) 2mm plate thickness.

Figure 6.23 Comparison of stiffness vs displacement curve between experimental and empirical (i.e. equation 6.5) results.

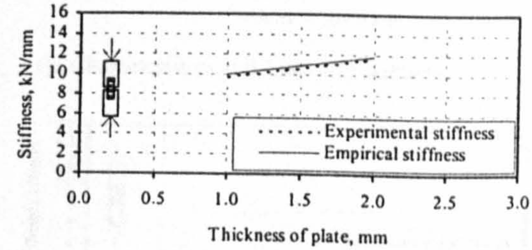
Plate Number	Plate thickness (mm)	Displacement level (mm)	Experimental stiffness (kN/mm)	Empirical stiffness (kN/mm)	Percentage of Error (%)
M20/0310B	1	0.05	9.78	9.941	2
M14/1333	2	0.05	13.02	12.974	0
M20/0310B	1	0.1	9.77	9.964	2
M14/1333	2	0.1	11.67	11.894	2
M20/0310B	1	0.15	10.380	9.934	-4
M14/1333	2	0.15	10.947	11.143	2
M20/0310B	1	0.2	10	9.850	-2
M14/1333	2	0.2	10.82	10.621	-2
M20/0310B	1	0.25	9.664	9.712	0
M14/1333	2	0.25	10.588	10.254	-3
M20/0310B	1	0.3	9.510	9.521	0
M14/1333	2	0.3	10.093	9.981	-1
M20/0310B	1	0.35	9.203	9.276	1
M14/1333	2	0.35	9.789	9.749	0
M20/0310B	1	0.4	8.932	8.977	1
M14/1333	2	0.4	9.400	9.508	1
M20/0310B	1	0.45	8.458	8.625	2
M14/1333	2	0.45	8.980	9.213	3
M20/0310B	1	0.5	8.172	8.219	1
M14/1333	2	0.5	8.562	8.824	3
M20/0310B	1	0.55	7.782	7.760	0
M14/1333	2	0.55	8.340	8.306	0
M20/0310B	1	0.6	7.372	7.247	-2
M14/1333	2	0.6	7.861	7.640	-3

Table 6.13 Comparison between experimental and empirical stiffness at displacement level from 0.05mm to 0.6mm for various plate thickness in the joints.

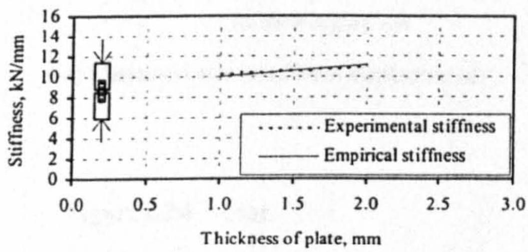
In Figure 6.24, a comparison of stiffness versus thickness of plate curves between experimental and empirical (i.e. equation 6.5) results for various joints with different plate thickness at displacement level 0.05mm to 0.6mm were represented. There was a good agreement between the empirical model and experimental results.



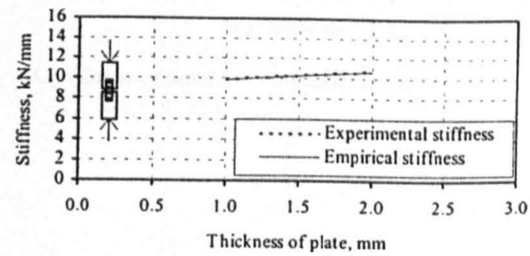
(a) Characteristics at 0.05mm displacement.



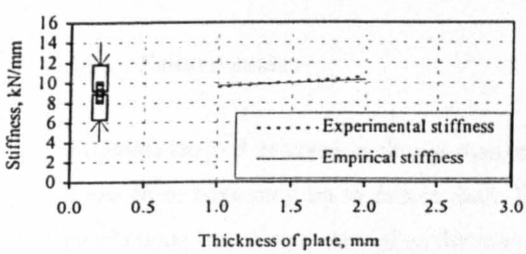
(b) Characteristics at 0.1mm displacement.



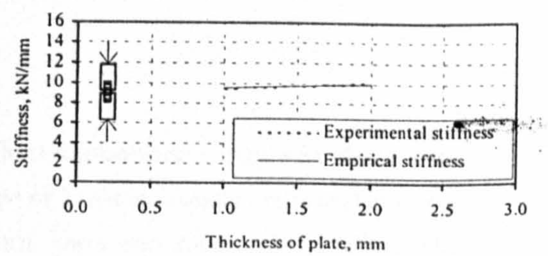
(c) Characteristics at 0.15mm displacement.



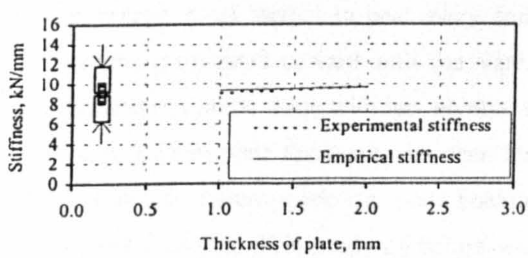
(d) Characteristics at 0.2mm displacement.



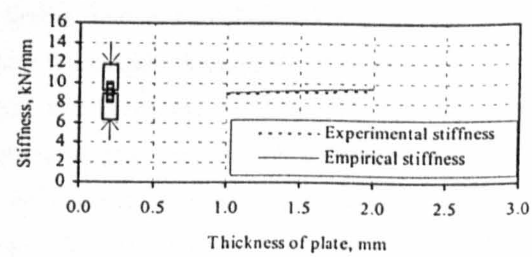
(e) Characteristics at 0.25mm displacement.



(f) Characteristics at 0.3mm displacement.

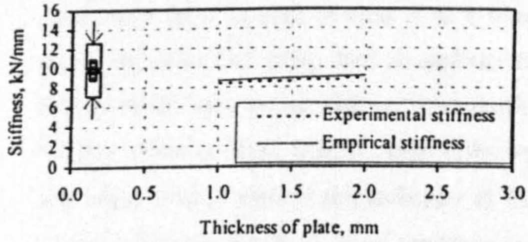


(g) Characteristics at 0.35mm displacement.

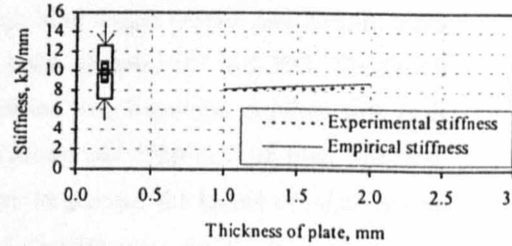


(h) Characteristics at 0.4mm displacement.

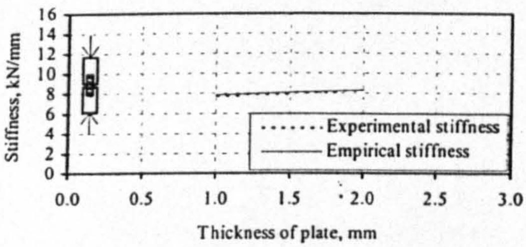
Figure 6.24 Comparison of stiffness vs thickness of plate between experimental and empirical (i.e. equation 6.5) results.



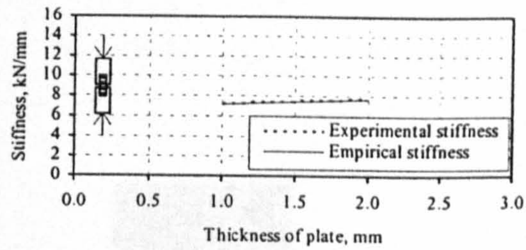
(i) Characteristics at 0.45mm displacement.



(k) Characteristics at 0.5mm displacement.



(m) Characteristics at 0.55mm displacement.



(n) Characteristics at 0.6mm displacement.

Figure 6.24 cont.

6.5 Failure modes

All joints studied behaved in similar manner. The load-displacement curves were clearly non-linear from beginning up to failure load. The slope of load-displacement relationship of the connections tested was reduced as the load increased. There were four modes of failure. The most common mode of failure was anchorage failure (teeth withdrawal). As the load increased, plate started to peel away from the timber members at their lower end. This peeling progressed upward until the plate withdrew completely. This mode of failure was common in joints made with low number of bites (1 to 5 bites), low bites length (5mm and 10mm), 1mm plate thickness and when load is applied at low grain direction (0° and 30°). The second failure mode was plate buckling, as the load increased the middle of the plate started buckling. This mode of failure was happened in joints with high number of bites (7and 8 bites) and when load is applied parallel to the grain. The third failure mode was the closure of the gap between the connected members. This mode of failure was happened in joints with high number of bites (6 to 8 bites), high bites length (15mm and 20mm), 2mm plate thickness and when load is applied at low grain direction (0° and 30°). The fourth failure mode was timber failure. This mode of failure was happened in joints with high number of bites (7and 8 bites), high bites length (15mm and 20mm), 2mm plate thickness and when load is applied perpendicular to the grain. In general, the failure of joints can be characterised as ductile. A considerable amount of ductility was usually observed prior to failure. Typical anchorage failure of joint is shown in Figure 6.25.

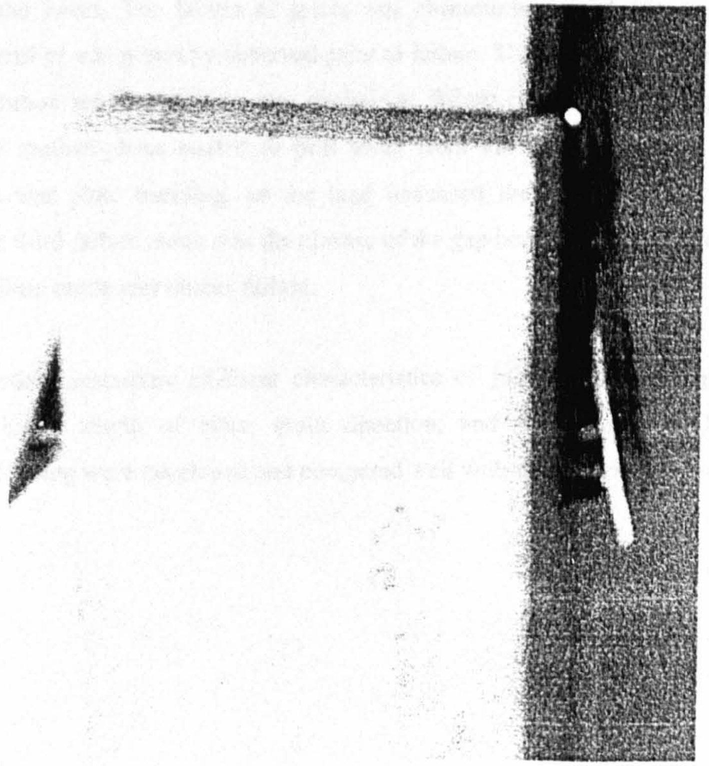


Figure 6.25 Typical anchorage failures of joint when loaded in compression parallel to the grains.

6.6 SUMMARY

In this chapter details of experimental work carried out to study the load-displacement characteristics of the punched metal plate timber connections, using joints with different parameters such as number of bites, length of bites, grain direction and thickness of the plate. The specimens tested were subjected to compression loading.

From the results obtained, it was found that the number of bites, length of bites, the grain direction and the plate thickness in the joints have a significant effects on the load-displacement characteristics of the joints. Increasing number of bites, length of bites, thickness of plate and decreasing angle of grain direction would increase the strength and stiffness of the joints. The failure of joints was characterised as ductile, a considerable amount of ductility was generally observed prior to failure. There were four modes of failure, the most common mode of failure was anchorage failure (teeth withdrawal); as the load increased the toothed-plates started to peel away from the timber members. The second failure mode was plate buckling, as the load increased the middle of the plate started buckling. The third failure mode was the closure of the gap between the connected members. The fourth failure mode was timber failure.

Empirical models describing stiffness characteristics of joints with different parameters (number of bites, length of bites, grain direction, and plate thickness) subjected to compression loading were developed and compared well with the experimental results.

CHAPTER SEVEN

INFLUENCE OF FACTORS AFFECTING THE BEHAVIOUR OF THE PUNCHED METAL PLATE TIMBER JOINTS

7. INFLUENCE OF FACTORS AFFECTING THE BEHAVIOUR OF THE PUNCHED METAL PLATE TIMBER JOINTS

7.1 INTRODUCTION

In the previous chapters it was established that the structural behaviour and load carrying capacity of punched metal plate timber connections depends on many factors including number and length of bites, plate and grain directions. In this chapter, a statistical approach is used to classify the level of importance of these factors on the performance of the joints.

In addition, this chapter presents a comparison of the stiffness of the joints in relation to the grain direction between the empirical models developed in chapter 5 and 6 and the procedure described by Foschi (1977). Also, in this chapter the effects of the teeth directions on the performance of the punched metal plate timber joints under tensile loading are examined. An empirical model describing the stiffness characteristics of the joints in relation to the different teeth directions is developed.

7.2 CLASSIFICATION OF FACTORS INFLUENCING THE BEHAVIOUR OF THE JOINTS

In this section, a series of tests have been carried out on punched metal plate timber joints in order to classify the level of importance of factors such as, number of bites, length of bites and grain directions on the performance of the joints. The specimens were loaded to failure both in tension and in compression. The importance of such factors was classified using a statistical technique described by Taguchi [Grove and Davis, 1992].

In this method, two extreme levels of each factor were selected. For the number of bites plates with 1 bite and 8 bites, for the length of bites 5mm and 20mm long bites and for the grain direction parallel (0°) and perpendicular (90°) were selected.

7.2.1 TESTING PROGRAM

Testing programme is summarised in table 7.1.

Plate ref. number	Plate properties (mm)			Bite properties		Grain direction
	Length	Width	Thickness	Number	Length (mm)	
M14/1333	133	38	2	1	5	0
M14/1333	133	38	2	1	5	90
M14/1333	133	38	2	1	20	0
M14/1333	133	38	2	1	20	90
M14/1333	133	38	2	8	5	0
M14/1333	133	38	2	8	5	90
M14/1333	133	38	2	8	20	0
M14/1333	133	38	2	8	20	90

Table 7.1. Testing programme for joints subjected to tension and compression loading.

The preparations of test samples were similar to those explained in chapter 3, 5 and 6. The punched metal plate type used in construction of testing specimens was M14/1333-133mm×38mm×2mm. The specimens were loaded to failure in tension and compression.

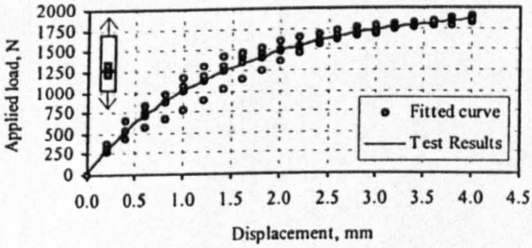
7.2.2 Tension tests - the strength characteristics

In Figure 7.1 the load-displacement (average curves) behaviour of the joints for specimens using different plate configuration and grain direction subjected to tensile loading are shown. A comparison of joints performance up to failure is presented in Figure 7.2. Table 7.2 shows the average ultimate loads for joint specimens with different plate configuration and grain direction subjected to tensile loading.

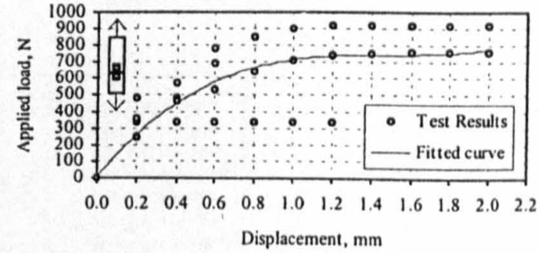
To evaluate the importance of each factor, the total average ultimate loads sustained in the joint specimens when that factor was at level 1 is compared with the total average ultimate loads sustained in the joint specimens when that factor was at level 2. Level 1 and level 2 which used for number of bites were 1 and 8 bites, for length of bites were 5mm and 20mm and for grain direction were 0° and 90° respectively. In other words, the results were contrasted according to the level of each factor. So, for example, take number of bites factor. The total average ultimate load for specimens with 1 bites is 3783 N (1008+143+1869+763) and the total average ultimate load for specimens with 8 bites is 16821 N (5599+521+8599+2102). The difference between the two levels is 13038 N (16821-3783). A similar calculation was carried out for the other factors. Factor with highest difference in average ultimate load between the two levels was considered as the most important factor, which was the grain direction factor in this case. Table 7.3 shows the classification of the importance of different factors affecting the ultimate load carrying capacity of the joints subjected to tensile loading.

Run	Bite properties		Grain direction	Av. ultimate load (N)
	Number	Length (mm)		
1	1	5	0	1008
2	1	5	90	143
3	1	20	0	1869
4	1	20	90	763
5	8	5	0	5599
6	8	5	90	521
7	8	20	0	8599
8	8	20	90	2102

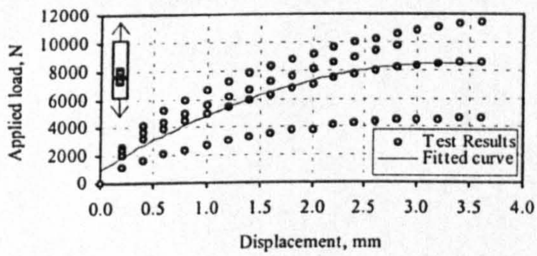
Table 7.2 Average ultimate load for joints subjected to tensile loading.



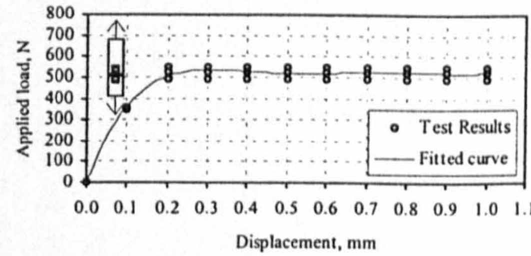
(a) One bite-20mm length- Loaded parallel to the grain.



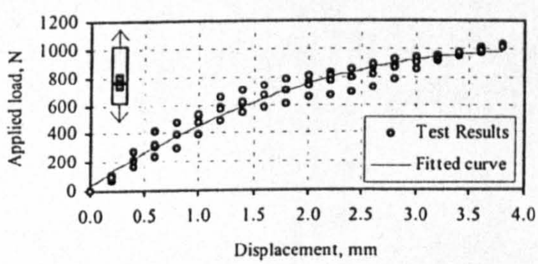
(b) One bite-20mm length- Loaded perpendicular to the grain.



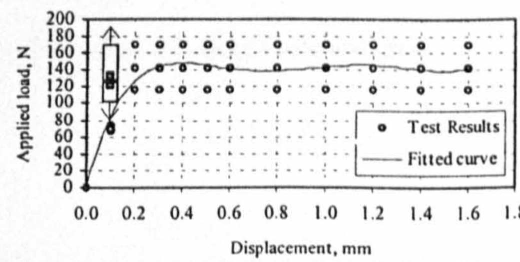
(c) Eight bites-20mm length- Loaded parallel to the grain.



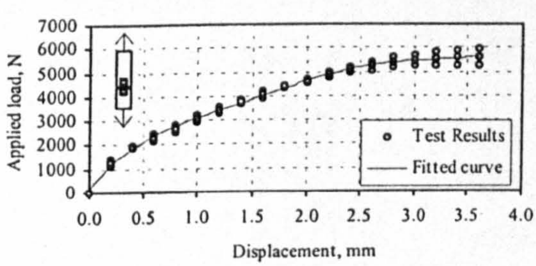
(d) Eight bites-20mm length- Loaded perpendicular to the grain.



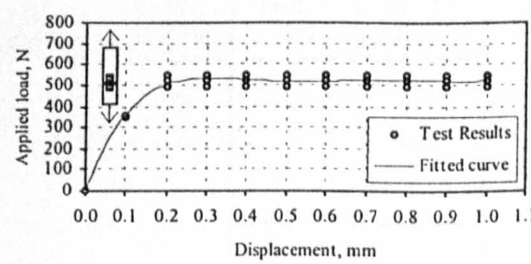
(e) One bite-5mm length- Loaded parallel to the grain.



(f) One bite-5mm length- Loaded perpendicular to the grain.



(g) Eight bites-5mm length- Loaded parallel to the grain.



(h) Eight bites-5mm length- Loaded perpendicular to the grain.

Figure 7.1 Load-displacement behaviour of joints with different plate configuration and grain direction loaded in tension.

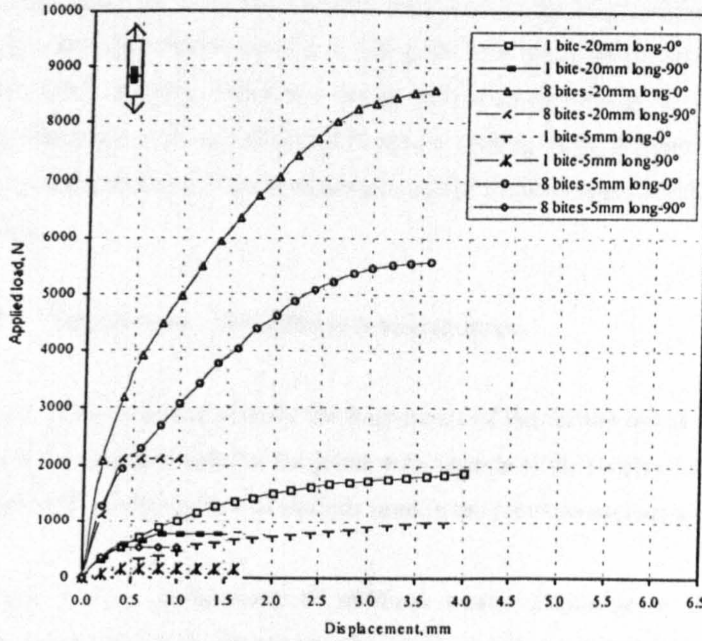


Figure 7.2 Comparison of joints performance with different plate configuration and grain direction subjected to tension force.

Factor	Number of bites		Length of bites (mm)		Grain direction (degree)	
Level	Level 1 (1 bite)	Level 2 (8 bite)	Level 1 (5mm)	Level 2 (20mm)	Level 1 (0°)	Level 2 (90°)
Total ultimate load (N)	3783	16821	7271	13333	3529	17075
Difference between level 1 and level 2 (N)	13038		6062		13546	
Classification	2		3		1	

Table 7.3 Classification of the importance of different factors affecting the ultimate load carrying capacity of the joints subjected to tensile loading.

It is clear from Table 7.3 that, the difference between the ultimate load capacities of joints are quite large when loaded parallel to the grain than when loaded perpendicular to the grain under tensile loading. There is a strong indication that the grain direction effects is very important when joints are subjected to tensile loading. Also, increasing number of bits in the plate is more important than increasing length of the bites when joints are subjected to tensile loading.

7.2.3 Tension tests - the stiffness characteristics

In order to evaluate and classify the importance of the factors tested under tensile loading, the stiffness characteristics of the joints with regards to the levels of the displacement were determined. Similar method of analysis used in the previous section was applied.

In Figure 7.3, a comparison of stiffness versus displacement using different plate configurations and grain directions subjected to tensile loading is shown. Table 7.4 shows the classifications of the importance of different factors affecting the stiffness characteristics of the joints under tensile loading.

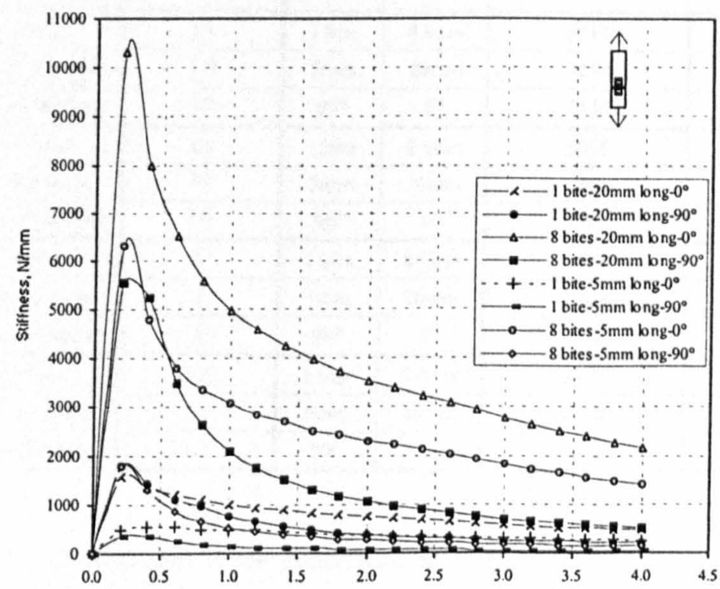


Figure 7.3 Stiffness vs displacement for joints with different plate configuration and grain direction subjected to tension force.

Factor	Displacement level (mm)	Level of factor		Difference between total stiffness at level 1 and level 2 (N/mm)	Classification
		Level 1	Level 2		
Number of bites	0.2	1 bite	8 bites	19785	1
Length of bites (mm)	0.2	5mm	20mm	10295	2
Grain direction (degree)	0.2	90°	0°	9245	3
Number of bites	0.4	1 bite	8 bites	15637	1
Length of bites (mm)	0.4	5mm	20mm	9017	2
Grain direction (degree)	0.4	90°	0°	6293	3
Number of bites	0.6	1 bite	8 bites	11649	1
Length of bites (mm)	0.6	5mm	20mm	6837	2
Grain direction (degree)	0.6	90°	0°	6361	3
Number of bites	0.8	1 bite	8 bites	9521	1
Length of bites (mm)	0.8	5mm	20mm	5583	3
Grain direction (degree)	0.8	90°	0°	6101	2
Number of bites	1	1 bite	8 bites	8296	1
Length of bites (mm)	1	5mm	20mm	4628	3
Grain direction (degree)	1	90°	0°	6020	2
Number of bites	1.2	1 bite	8 bites	7450	1
Length of bites (mm)	1.2	5mm	20mm	4038	3
Grain direction (degree)	1.2	90°	0°	5916	2
Number of bites	1.4	1 bite	8 bites	6842	1
Length of bites (mm)	1.4	5mm	20mm	3572	3
Grain direction (degree)	1.4	90°	0°	5768	2
Number of bites	1.6	1 bite	8 bites	6314	1
Length of bites (mm)	1.6	5mm	20mm	3254	3
Grain direction (degree)	1.6	90°	0°	5534	2
Number of bites	1.8	1 bite	8 bites	5955	1
Length of bites (mm)	1.8	5mm	20mm	2931	3
Grain direction (degree)	1.8	90°	0°	5387	2
Number of bites	2	1 bite	8 bites	5572	1
Length of bites (mm)	2	5mm	20mm	2688	3
Grain direction (degree)	2	90°	0°	5176	2
Number of bites	2.2	1 bite	8 bites	5316	1
Length of bites (mm)	2.2	5mm	20mm	2520	3
Grain direction (degree)	2.2	90°	0°	5042	2

Table 7.4 Classifications of the importance of different factors affecting the stiffness characteristics of the joints under tensile loading.

Factor	Displacement level (mm)	Level of factor		Difference between total stiffness at level 1 and level 2 (N/mm)	Classification
		Level 1	Level 2		
Number of bites	2.4	1 bite	8 bites	5049	1
Length of bites (mm)	2.4	5mm	20mm	2353	3
Grain direction (degree)	2.4	90°	0°	4871	2
Number of bites	2.6	1 bite	8 bites	4791	1
Length of bites (mm)	2.6	5mm	20mm	2235	3
Grain direction (degree)	2.6	90°	0°	4685	2
Number of bites	2.8	1 bite	8 bites	4563	1
Length of bites (mm)	2.8	5mm	20mm	2113	3
Grain direction (degree)	2.8	90°	0°	4515	2
Number of bites	3	1 bite	8 bites	4302	2
Length of bites (mm)	3	5mm	20mm	1966	3
Grain direction (degree)	3	90°	0°	4306	1
Number of bites	3.2	1 bite	8 bites	4057	2
Length of bites (mm)	3.2	5mm	20mm	1857	3
Grain direction (degree)	3.2	90°	0°	4103	1
Number of bites	3.4	1 bite	8 bites	3839	2
Length of bites (mm)	3.4	5mm	20mm	1757	3
Grain direction (degree)	3.4	90°	0°	3919	1
Number of bites	3.6	1 bite	8 bites	3641	2
Length of bites (mm)	3.6	5mm	20mm	1673	3
Grain direction (degree)	3.6	90°	0°	3743	1
Number of bites	3.8	1 bite	8 bites	3437	2
Length of bites (mm)	3.8	5mm	20mm	1589	3
Grain direction (degree)	3.8	90°	0°	3557	1
Number of bites	4	1 bite	8 bites	3260	2
Length of bites (mm)	4	5mm	20mm	1516	3
Grain direction (degree)	4	90°	0°	3386	1

Table 7.4 cont.

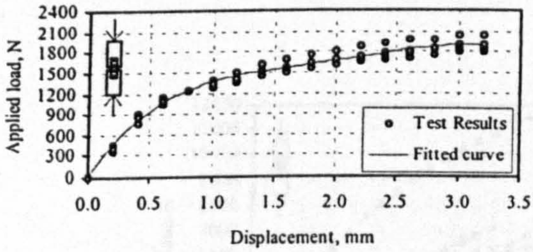
It is clear from Table 7.4 that, at low displacement levels, the most important factor affecting the stiffness of the joints was the number of bites. The grain direction importance at low displacement level was low comparing with the number of bites. As the displacement levels increased, the importance of the grain direction increased. At high displacement levels, the most important factor was the grain directions.

The examination of the results show that in the joints with low number of bites failure occurs at small displacement levels with failure modes being predominantly anchorage failure. With increase in number and length of bites the stiffness of the plates increase leading to increase in the stiffness of the joints. This is illustrated in Figure 7.3. Therefore, at low displacement levels the number of bites were more influential in resisting loads than the other factors.

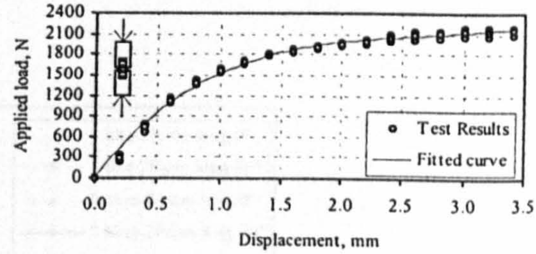
Also, from Figure 7.3 it is evident that in the joints with high grain directions the stiffness of the joints was very low and failure occurred in the timber member at low displacement levels. As the load increased, plates started to peel away from the timber members. This peeling caused the cut of the timber cells (grains). With decrease in the grain direction there was a sharp increase in the stiffness of the joints and failure occured at high displacement levels. Therefore, at high displacement levels the grain directions were more influential in resisting loads than the other factors.

7.2.4 Compression tests - the strength characteristics

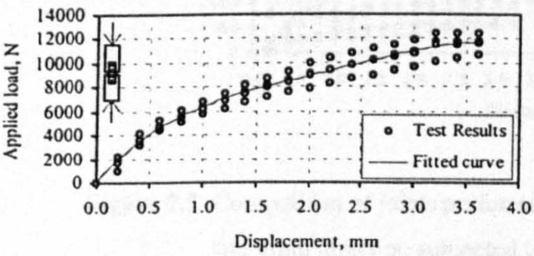
In Figure 7.4, the load-displacement behaviour (average curves) of the joints specimens using different plate configuration and grain direction subjected to compression loading are shown. A comparison of joints performance up to failure is presented in Figure 7.5. Table 7.5 shows the average ultimate loads for joint specimens with different plate configuration and grain direction subjected to compression loading. Similar method of analysis used in tension test was applied to compression tests. Table 7.6 shows the classification of the importance of different factors affecting the ultimate load carrying capacity of the joints subjected to compression loading.



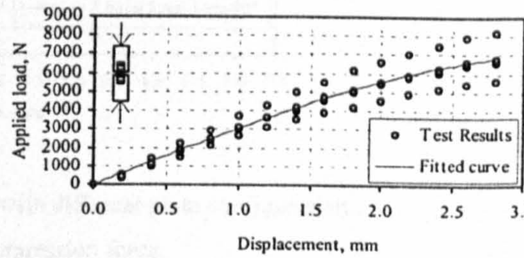
(a) One bite-20mm length-Loaded parallel to the grain.



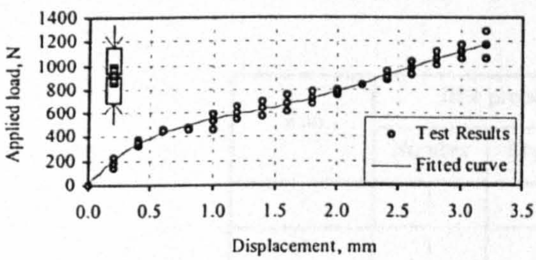
(b) One bite-20mm length-Loaded perpendicular to the grain.



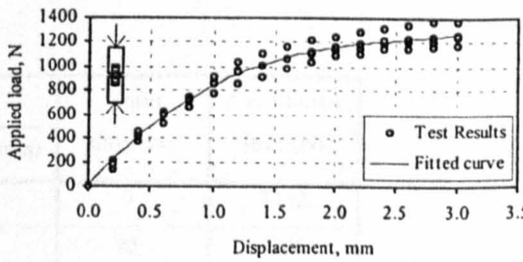
(c) Eight bite-20mm length-Loaded parallel to the grain.



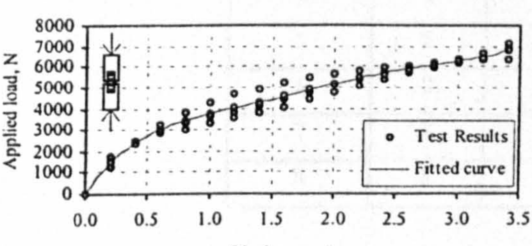
(d) Eight bite-20mm length-Loaded perpendicular to the grain.



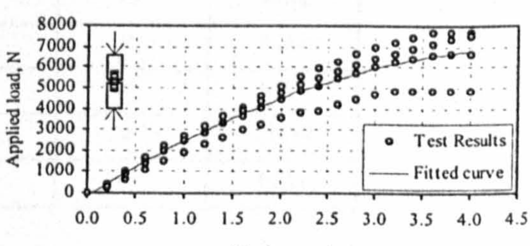
(e) One bite-5mm length-Loaded parallel to the grain.



(f) One bite-5mm length-Loaded perpendicular to the grain.



(g) Eight bite-5mm length-Loaded parallel to the grain.



(h) Eight bite-5mm length-Loaded perpendicular to the grain.

Figure 7.4 Load-displacement behaviour of joints with different plate configuration and grain direction loaded in compression.

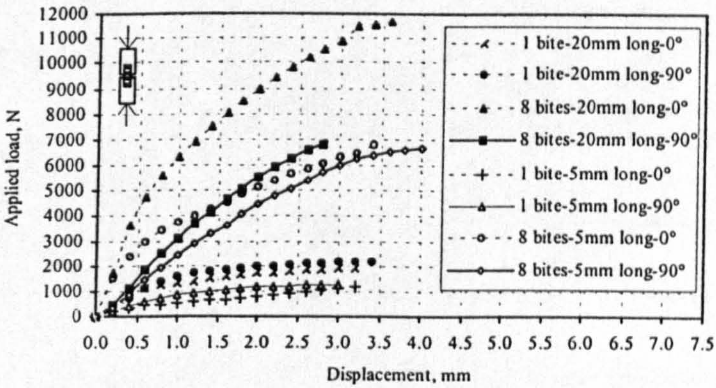


Figure 7.5 Comparison of joints performance with different plate configuration and grain direction subjected to compression force.

Run	Bite properties		Grain direction	Av. ultimate load (N)
	Number	Length (mm)		
1	1	5	0	1172
2	1	5	90	1266
3	1	20	0	1901
4	1	20	90	2154
5	8	5	0	6787
6	8	5	90	6670
7	8	20	0	11650
8	8	20	90	6814

Table 7.5 Average ultimate load for joints subjected to compressive loading.

Factor	Number of bites		Length of bites (mm)		Grain direction (degree)	
Level	Level 1 (1 bite)	Level 2 (8 bite)	Level 1 (5mm)	Level 2 (20mm)	Level 1 (0°)	Level 2 (90°)
Total ultimate load (N)	6493	31921	15895	22519	16904	21510
Difference between level 1 and level 2 (N)	25428		6624		4606	
Classification	1		2		3	

Table 7.6 Classification of the importance of different factors affecting the ultimate load carrying capacity of the joints subjected to compressive loading.

The compound influence of the increase in the number of bites in comparison with the other factors is illustrated in the values shown in Table 7.6. Also, increasing number of bits is more effective than increasing length of bites in the joints. Unlike joints subjected to tensile loading, the grain direction is less effective when joints subjected to compressive loading.

7.2.5 Compression tests - the stiffness characteristics

In order to evaluate and classify the importance of the factors tested, the stiffness characteristics of the joints at various displacement levels were determined. Similar method of analysis used in the tension tests was applied.

In Figure 7.6, a comparison of stiffness versus displacement using different plate configurations and grain directions subjected to compression loading is shown. Table 7.7 shows the classifications of the importance of different factors affecting the stiffness characteristics of the joints under compression loading.

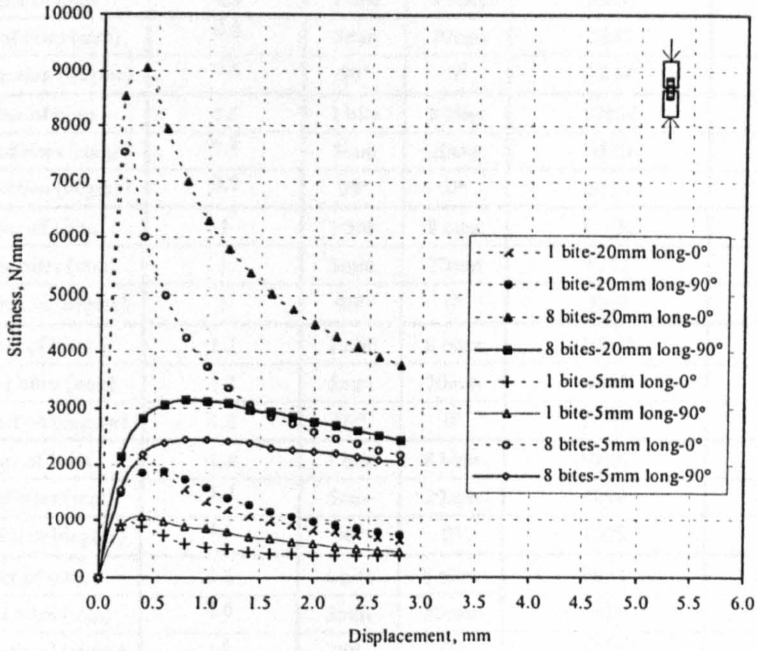


Figure 7.6 Stiffness vs displacement for joints with different plate configuration and grain direction subjected to compression force.

Factor	Displacement level (mm)	Level of factor		Difference between total stiffness at level 1 and level 2 (N/mm)	Classification
		Level 1	Level 2		
Number of bites	0.2	1 bite	8 bites	14475	1
Length of bites (mm)	0.2	5mm	20mm	3255	3
Grain direction (degree)	0.2	90°	0°	12945	2
Number of bites	0.4	1 bite	8 bites	14110	1
Length of bites (mm)	0.4	5mm	20mm	5726	3
Grain direction (degree)	0.4	90°	0°	10160	2
Number of bites	0.6	1 bite	8 bites	12935	1
Length of bites (mm)	0.6	5mm	20mm	5653	3
Grain direction (degree)	0.6	90°	0°	7237	2
Number of bites	0.8	1 bite	8 bites	12038	1
Length of bites (mm)	0.8	5mm	20mm	5250	2
Grain direction (degree)	0.8	90°	0°	5176	3
Number of bites	1	1 bite	8 bites	11332	1
Length of bites (mm)	1	5mm	20mm	4772	2
Grain direction (degree)	1	90°	0°	3940	3
Number of bites	1.2	1 bite	8 bites	10719	1
Length of bites (mm)	1.2	5mm	20mm	4385	2
Grain direction (degree)	1.2	90°	0°	3109	3
Number of bites	1.4	1 bite	8 bites	10232	1
Length of bites (mm)	1.4	5mm	20mm	4090	2
Grain direction (degree)	1.4	90°	0°	2628	3
Number of bites	1.6	1 bite	8 bites	9841	1
Length of bites (mm)	1.6	5mm	20mm	3859	2
Grain direction (degree)	1.6	90°	0°	2253	3
Number of bites	1.8	1 bite	8 bites	9555	1
Length of bites (mm)	1.8	5mm	20mm	3527	2
Grain direction (degree)	1.8	90°	0°	1985	3
Number of bites	2	1 bite	8 bites	9285	1
Length of bites (mm)	2	5mm	20mm	3301	2
Grain direction (degree)	2	90°	0°	1751	3
Number of bites	2.2	1 bite	8 bites	8997	1
Length of bites (mm)	2.2	5mm	20mm	3085	2
Grain direction (degree)	2.2	90°	0°	1591	3

Table 7.7 Classifications of the importance of different factors affecting the stiffness characteristics of the joints under compression loading.

Factor	Displacement level (mm)	Level of factor		Difference between total stiffness at level 1 and level 2 (N/mm)	Classification
		Level 1	Level 2		
Number of bites	2.4	1 bite	8 bites	8684	1
Length of bites (mm)	2.4	5mm	20mm	2916	2
Grain direction (degree)	2.4	90°	0°	1474	3
Number of bites	2.6	1 bite	8 bites	8448	1
Length of bites (mm)	2.6	5mm	20mm	2750	2
Grain direction (degree)	2.6	90°	0°	1358	3
Number of bites	2.8	1 bite	8 bites	8174	1
Length of bites (mm)	2.8	5mm	20mm	2576	2
Grain direction (degree)	2.8	90°	0°	1292	3

Table 7.7 cont.

The compound influence of the increase in the number of bites in comparison with the other factors is illustrated in the values shown in Table 7.7.

The importance of the grain direction effects was more than the length of bites effects at low displacement levels, but at high displacement levels, the length of bites was more important. When load was applied perpendicular to the grain, the stiffness was low and failure occurred suddenly at low displacement levels but when loaded parallel to the grain, the stiffness was high and failure occurred at high displacement levels. Therefore, the grain direction effects are more important than the length of bites effects at low displacement levels.

The stiffness of the joints was high when high stiffness plate was used and when load applied parallel to the grain. The failure mode was the closure of the gap between the connected members and these failures occurred at high displacement levels.

7.3 EFFECTS OF GRAIN DIRECTION

This section presents a comparison between the empirical models developed (i.e. equations 5.4 and 6.4) and Foschi's formulae [1977] (equation 7.1 and 7.2). The procedure described by Foschi was based on Hankinson's equation. It was used to obtain the stiffness of the joints for different grain directions when load is applied both parallel and/or perpendicular to the plate major axis.

$$k_a = \frac{KAA\ KAE}{KAA\sin^2(\varphi-\omega)+KAE\cos^2(\varphi-\omega)} \tag{7.1}$$

where K_a = stiffness of the joint when load is applied parallel to the plate major axis (kN/mm).

KAA = stiffness of the joint when load is applied parallel to the plate major axis and parallel to the grain (kN/mm).

KAE = stiffness of the joint when load is applied parallel to the plate major axis and perpendicular to the grain (kN/mm).

φ = is the angle between the plate major axis and the x-direction, measured counter clockwise (degree).

ω = is the angle between the grain direction and the x-axis, (degree).

$$k_e = \frac{KEE\ KEA}{KEE\sin^2(\varphi-\omega)+KEA\cos^2(\varphi-\omega)} \tag{7.2}$$

where K_e = stiffness of the joint when load is applied perpendicular to the plate major axis (kN/mm).

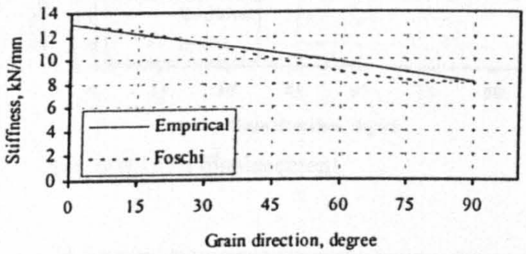
KEA = stiffness of the joint when load is applied perpendicular to the plate major axis and parallel to the grain (kN/mm).

KEE = stiffness of the joint when load is applied perpendicular to the plate major axis and perpendicular to the grain (kN/mm).

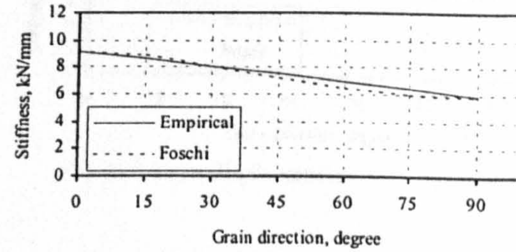
A comparison of the performance of the joints in relation to the grain directions at displacement levels 0.1mm to 0.8mm between the empirical models developed (i.e. equation 5.4) and Foschi formulae (equation 7.1) under tensile loading is presented in Figure 7.7. There was a good agreement between the developed empirical model and Foschi's formula under tensile loading.

Figure 7.8 presents a comparison of performance of joints in relation to the grain directions at displacement levels 0.1mm to 0.8mm between the empirical models developed (i.e. equation 6.4) and Foschi formulas (equation 7.1) under compressive loading. There was a good agreement between the empirical model and Foschi formula under compressive loading.

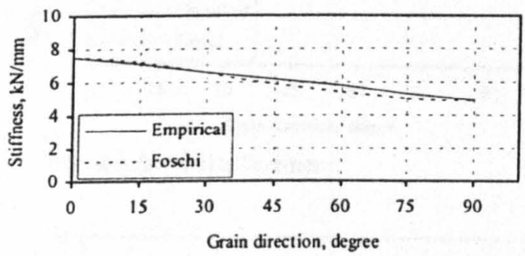
In Table 7.8 and 7.9 Comparison between the stiffness of the joints using empirical equations (i.e. 5.4 and 6.4) and Foschi's formula for different grain directions under tension and compression loading are shown respectively.



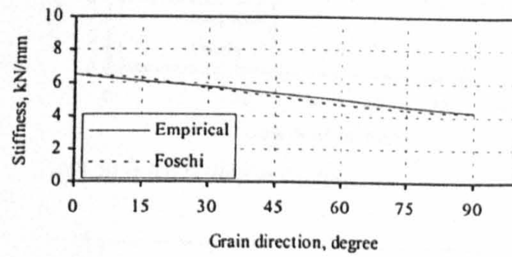
(a) Characteristics at 0.1mm displacement.



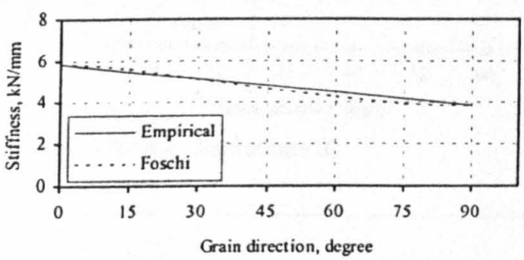
(b) Characteristics at 0.2mm displacement.



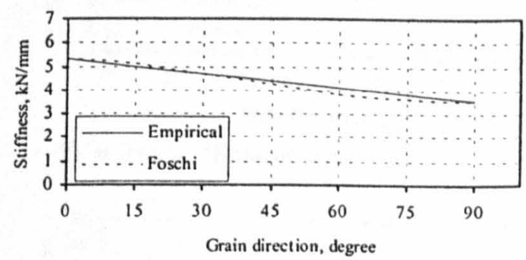
(c) Characteristics at 0.3mm displacement.



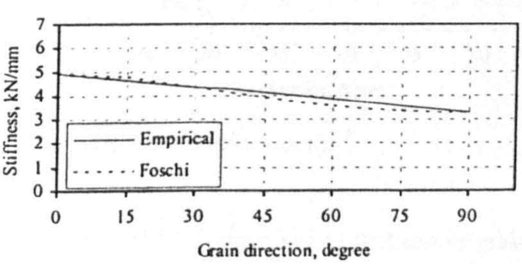
(d) Characteristics at 0.4mm displacement.



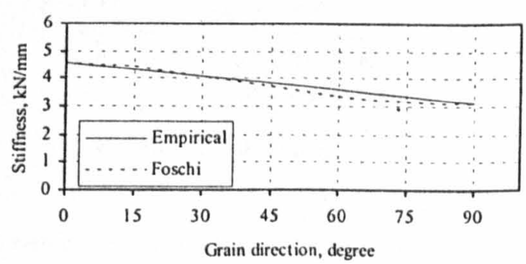
(e) Characteristics at 0.5mm displacement.



(f) Characteristics at 0.6mm displacement.

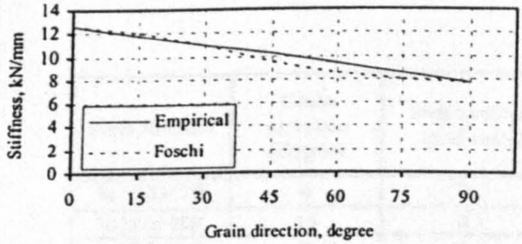


(g) Characteristics at 0.7mm displacement.

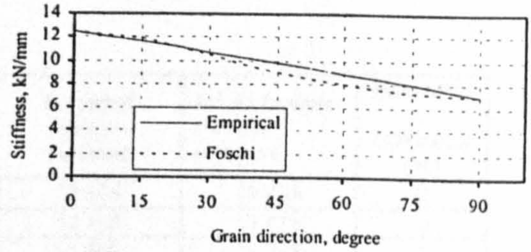


(h) Characteristics at 0.8mm displacement.

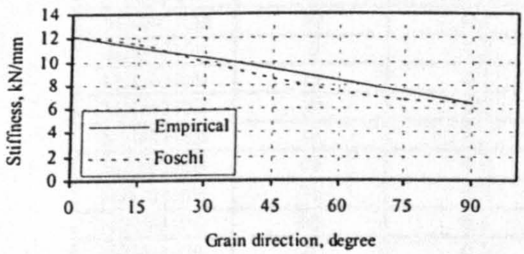
Figure 7.7 Comparison of stiffness vs grain direction between empirical model (i.e. equation 5.4) and Foschi's formulae (i.e. equation7.1) under tension loading.



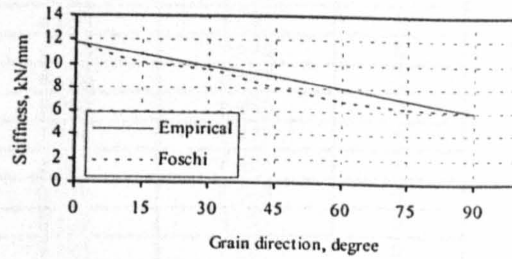
(a) at 0.1mm displacement.



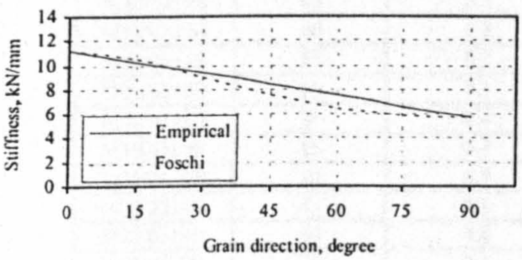
(b) at 0.2mm displacement.



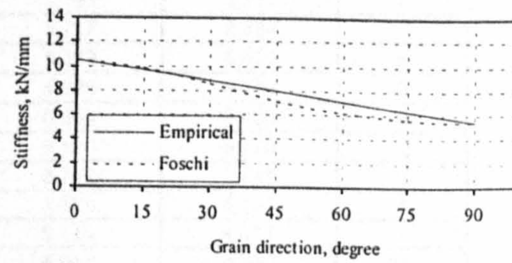
(c) at 0.3mm displacement.



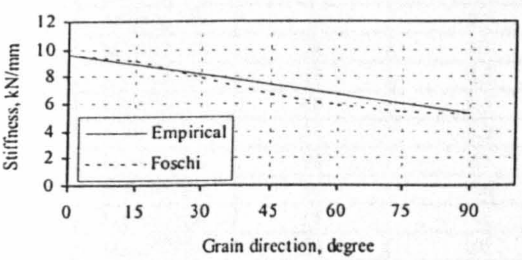
(d) at 0.4mm displacement.



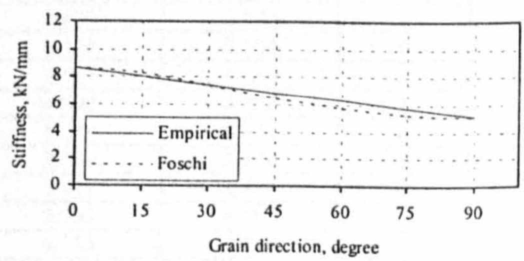
(e) at 0.5mm displacement.



(f) at 0.6mm displacement.



(g) at 0.7mm displacement.



(h) at 0.8mm displacement.

Figure 7.8 Comparison of stiffness vs grain direction between empirical model (i.e. equation 6.4) and Foschi's formulae (i.e. equation 7.1) under compressive loading.

Plate Number	Grain direction (degree)	Displacement level (mm)	Empirical stiffness (kN/mm)	Foschi formula stiffness (kN/mm)	Percentage of Difference (%)
M20/0310B	0	0.1	12.984	12.984	0
M20/0310B	15	0.1	12.168	12.478	-3
M20/0310B	30	0.1	11.353	11.279	1
M20/0310B	45	0.1	10.537	9.970	5
M20/0310B	60	0.1	9.722	8.933	8
M20/0310B	75	0.1	8.907	8.300	7
M20/0310B	90	0.1	8.091	8.091	0
M20/0310B	0	0.2	9.178	9.178	0
M20/0310B	15	0.2	8.630	8.847	-3
M20/0310B	30	0.2	8.083	8.055	0
M20/0310B	45	0.2	7.535	7.177	5
M20/0310B	60	0.2	6.987	6.471	7
M20/0310B	75	0.2	6.439	6.040	6
M20/0310B	90	0.2	5.892	5.892	0
M20/0310B	0	0.3	7.493	7.493	0
M20/0310B	15	0.3	7.059	7.234	-2
M20/0310B	30	0.3	6.625	6.613	0
M20/0310B	45	0.3	6.191	5.917	4
M20/0310B	60	0.3	5.757	5.354	7
M20/0310B	75	0.3	5.323	5.010	6
M20/0310B	90	0.3	4.889	4.889	0
M20/0310B	0	0.4	6.488	6.488	0
M20/0310B	15	0.4	6.120	6.270	-2
M20/0310B	30	0.4	5.752	5.747	0
M20/0310B	45	0.4	5.384	5.158	4
M20/0310B	60	0.4	5.016	4.678	7
M20/0310B	75	0.4	4.648	4.380	6
M20/0310B	90	0.4	4.280	4.280	0
M20/0310B	0	0.5	5.803	5.803	0
M20/0310B	15	0.5	5.479	5.614	-2
M20/0310B	30	0.5	5.155	5.155	0
M20/0310B	45	0.5	4.831	4.640	4
M20/0310B	60	0.5	4.508	4.213	7
M20/0310B	75	0.5	4.184	3.950	6
M20/0310B	90	0.5	3.860	3.860	0
M20/0310B	0	0.6	5.297	5.297	0
M20/0310B	15	0.6	5.005	5.127	-2
M20/0310B	30	0.6	4.714	4.716	0
M20/0310B	45	0.6	4.422	4.250	4
M20/0310B	60	0.6	4.130	3.870	6
M20/0310B	75	0.6	3.839	3.630	5
M20/0310B	90	0.6	3.547	3.547	0
M20/0310B	0	0.7	4.904	4.904	0
M20/0310B	15	0.7	4.637	4.750	-2

Table 7.8 Comparison of stiffness vs grain direction between empirical model (i.e. equation 5.4) and Foschi's formulae at displacement levels 0.1mm to 1mm under tensile

Plate Number	Grain direction (degree)	Displacement level (mm)	Empirical stiffness (kN/mm)	Foschi formula stiffness (kN/mm)	Percentage of Difference (%)
M20/0310B	30	0.7	4.370	4.370	0
M20/0310B	45	0.7	4.103	3.950	4
M20/0310B	60	0.7	3.836	3.600	6
M20/0310B	75	0.7	3.569	3.380	5
M20/0310B	90	0.7	3.302	3.302	0
M20/0310B	0	0.8	4.587	4.587	0
M20/0310B	15	0.8	4.339	4.445	-2
M20/0310B	30	0.8	4.092	4.097	0
M20/0310B	45	0.8	3.845	3.702	4
M20/0310B	60	0.8	3.598	3.380	6
M20/0310B	75	0.8	3.351	3.172	5
M20/0310B	90	0.8	3.103	3.103	0
M20/0310B	0	0.9	4.324	4.324	0
M20/0310B	15	0.9	4.093	4.192	-2
M20/0310B	30	0.9	3.862	3.868	0
M20/0310B	45	0.9	3.631	3.500	4
M20/0310B	60	0.9	3.400	3.194	6
M20/0310B	75	0.9	3.169	3.003	5
M20/0310B	90	0.9	2.938	2.938	0
M20/0310B	0	1	4.102	4.102	0
M20/0310B	15	1	3.885	3.977	-2
M20/0310B	30	1	3.667	3.673	0
M20/0310B	45	1	3.450	3.326	4
M20/0310B	60	1	3.232	3.039	6
M20/0310B	75	1	3.014	2.860	5
M20/0310B	90	1	2.797	2.797	0

Table 7.8 cont.

Plate Number	Grain direction (degree)	Displacement level (mm)	Empirical stiffness (kN/mm)	Foschi formula stiffness (kN/mm)	Percentage of Difference (%)
M20/0310B	0	0.1	12.620	12.620	0
M20/0310B	15	0.1	11.804	12.105	-3
M20/0310B	30	0.1	10.987	10.892	1
M20/0310B	45	0.1	10.171	9.580	6
M20/0310B	60	0.1	9.354	8.551	9
M20/0310B	75	0.1	8.538	7.930	7
M20/0310B	90	0.1	7.721	7.721	0
M20/0310B	0	0.2	12.473	12.473	0
M20/0310B	15	0.2	11.572	11.865	-3
M20/0310B	30	0.2	10.671	10.471	2
M20/0310B	45	0.2	9.770	9.023	8
M20/0310B	60	0.2	8.869	7.930	11
M20/0310B	75	0.2	7.969	7.280	9
M20/0310B	90	0.2	7.068	7.068	0
M20/0310B	0	0.3	12.185	12.185	0
M20/0310B	15	0.3	11.239	11.512	-2
M20/0310B	30	0.3	10.293	10.004	3
M20/0310B	45	0.3	9.347	8.486	9
M20/0310B	60	0.3	8.401	7.370	12
M20/0310B	75	0.3	7.455	6.721	10
M20/0310B	90	0.3	6.509	6.509	0
M20/0310B	0	0.4	11.757	11.757	0
M20/0310B	15	0.4	10.805	10.060	7
M20/0310B	30	0.4	9.853	9.512	3
M20/0310B	45	0.4	8.901	7.986	10
M20/0310B	60	0.4	7.949	6.882	13
M20/0310B	75	0.4	6.997	6.250	11
M20/0310B	90	0.4	6.045	6.045	0
M20/0310B	0	0.5	11.189	11.189	0
M20/0310B	15	0.5	10.270	10.505	-2
M20/0310B	30	0.5	9.351	9.003	4
M20/0310B	45	0.5	8.432	7.534	11
M20/0310B	60	0.5	7.514	6.473	14
M20/0310B	75	0.5	6.595	5.870	11
M20/0310B	90	0.5	5.676	5.676	0
M20/0310B	0	0.6	10.480	10.480	0
M20/0310B	15	0.6	9.633	9.859	-2
M20/0310B	30	0.6	8.787	8.486	3
M20/0310B	45	0.6	7.941	7.129	10
M20/0310B	60	0.6	7.094	6.146	13
M20/0310B	75	0.6	6.248	5.582	11
M20/0310B	90	0.6	5.401	5.401	0
M20/0310B	0	0.7	9.630	9.630	0
M20/0310B	15	0.7	8.896	9.115	-2

Table 7.9 Comparison of stiffness vs grain direction between empirical model (i.e. equation 6.4) and Foschi's formulae at displacement levels 0.1mm to 0.9mm under compressive

Plate Number	Grain direction (degree)	Displacement level (mm)	Empirical stiffness (kN/mm)	Foschi formula stiffness (kN/mm)	Percentage of Difference (%)
M20/0310B	30	0.7	8.161	7.953	3
M20/0310B	45	0.7	7.426	6.772	9
M20/0310B	60	0.7	6.691	5.900	12
M20/0310B	75	0.7	5.956	5.400	9
M20/0310B	90	0.7	5.222	5.222	0
M20/0310B	0	0.8	8.641	8.641	0
M20/0310B	15	0.8	8.057	8.263	-3
M20/0310B	30	0.8	7.473	7.382	1
M20/0310B	45	0.8	6.889	6.443	6
M20/0310B	60	0.8	6.305	5.716	9
M20/0310B	75	0.8	5.720	5.283	8
M20/0310B	90	0.8	5.136	5.136	0
M20/0310B	0	0.9	7.511	7.511	0
M20/0310B	15	0.9	7.117	7.287	-2
M20/0310B	30	0.9	6.722	6.737	0
M20/0310B	45	0.9	6.328	6.108	3
M20/0310B	60	0.9	5.934	5.586	6
M20/0310B	75	0.9	5.540	5.263	5
M20/0310B	90	0.9	5.146	5.146	0

Table 7.9 cont.

7.4 EFFECTS OF THE PLATE DIRECTIONS

In this section, tests were carried out in order to determine the influence of the direction of the plate on the performance of the punched metal plate timber joints subjected to tensile loading. The effects of plate direction of 0°, 45° and 90° were examined. The preparations of test samples were similar to those explained in chapter 3 and 5. The punched metal plate type used in construction of testing specimens was M20/0310-101mm×25mm×1mm. Different directions of plate are shown in Figure 7.9.

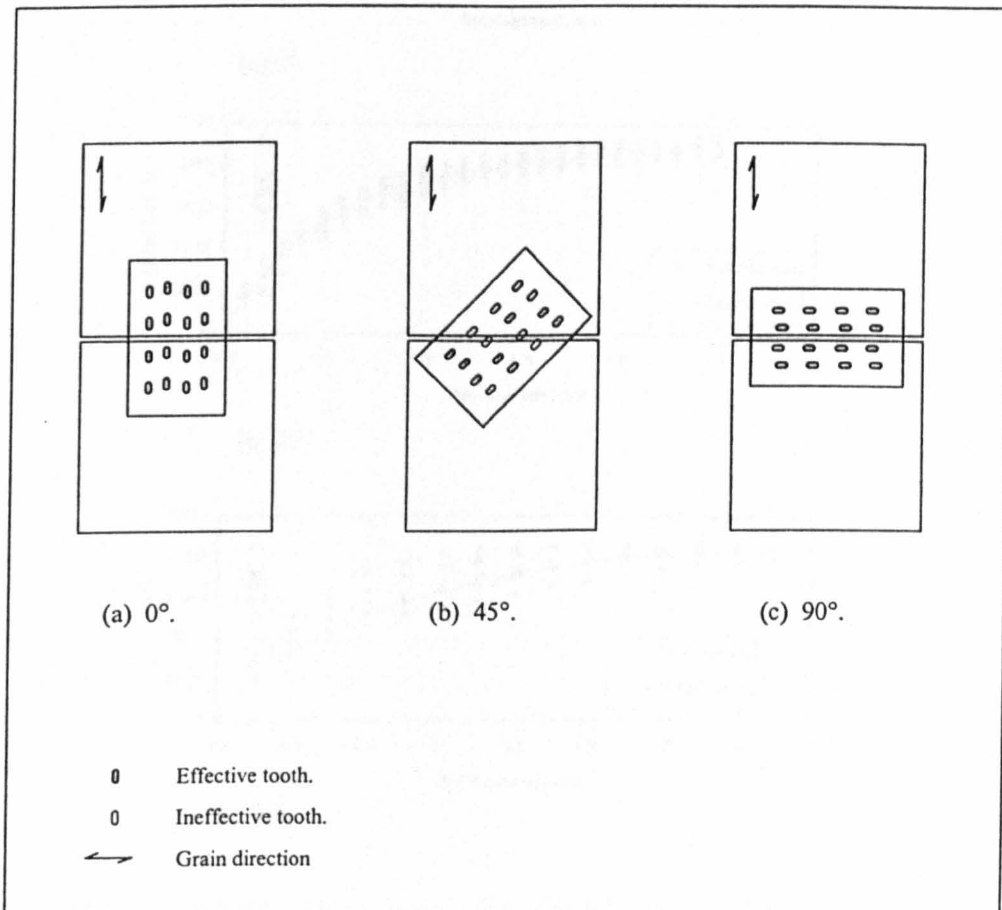
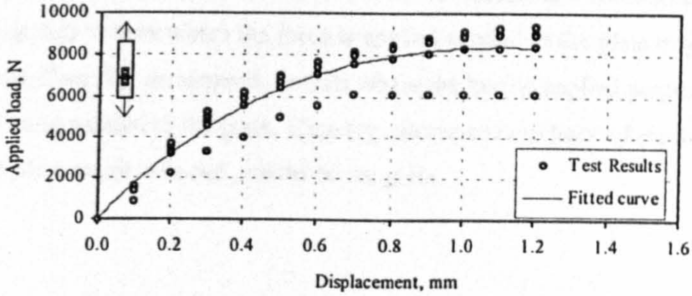
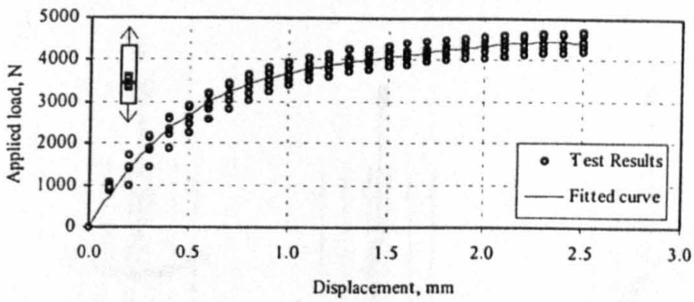


Figure 7.9 Punched metal plate timber connections with different plate direction configurations.

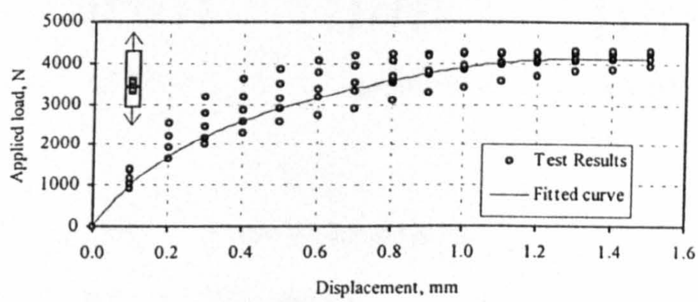
In Figure 7.10, the load-displacement (average curves) behaviour of the joints for specimens with various plate directions subjected to tensile loading are shown.



(a) 0°.



(b) 45°.



(c) 90°.

Figure 7.10 Load-displacement behaviour of joints with different plate direction under tensile loading.

It is clear from Figure 7.9 that with the plate direction at 45°, bites were not all effective. Only 6 out of 8 bites were effective, this was considered in the determination of the effects of the teeth directions. Different directions of the teeth (bites) with respect to timber grain direction are illustrated in Figure 7.11, where A-A represents a cross section of a tooth. Case (a), corresponds to tests where the force is applied parallel to the plate major axis and parallel to the grain. Case (b), corresponds to tests where the load is applied perpendicular to the plate major axis and parallel to the grain. Case (c), corresponds to tests where the load is applied at 45° to the plate major axis and parallel to the grain.

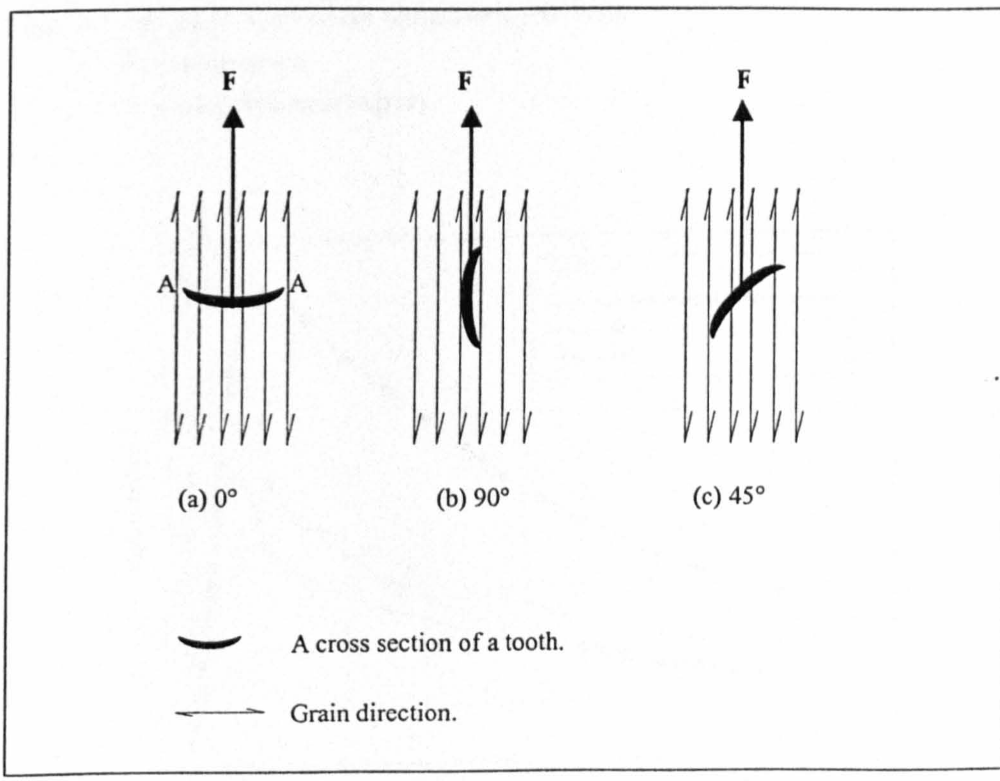


Figure 7.11 Different direction of teeth in punched metal plate timber connections.

The method of analysis developed in chapter 5 and 6 was applied to this section to determine the effects of the teeth directions on the behaviour of the punched metal plate timber connections. A comparison of the stiffness of the joints with different teeth directions is presented in Figure 7.12. The dotted curve illustrates stiffness of the plates positioned at 45° assuming all their teeth are effective. Table 7.10 shows the average stiffness for joint specimens with different teeth directions under tensile loading. Empirical model (i.e. equation 7.3) describing the stiffness of the joints with different teeth directions under tensile loading was developed.

$$K_t = (0.0017 \quad - 0.0011\delta)\alpha^2 + (0.1319\delta - 2413)\alpha - 8.4911\delta + 17.191 \qquad (7.3)$$

where k_t = stiffness of the joint under tensile loading (kN/mm).

δ = displacement (mm).

α = directions of the teeth (degree).

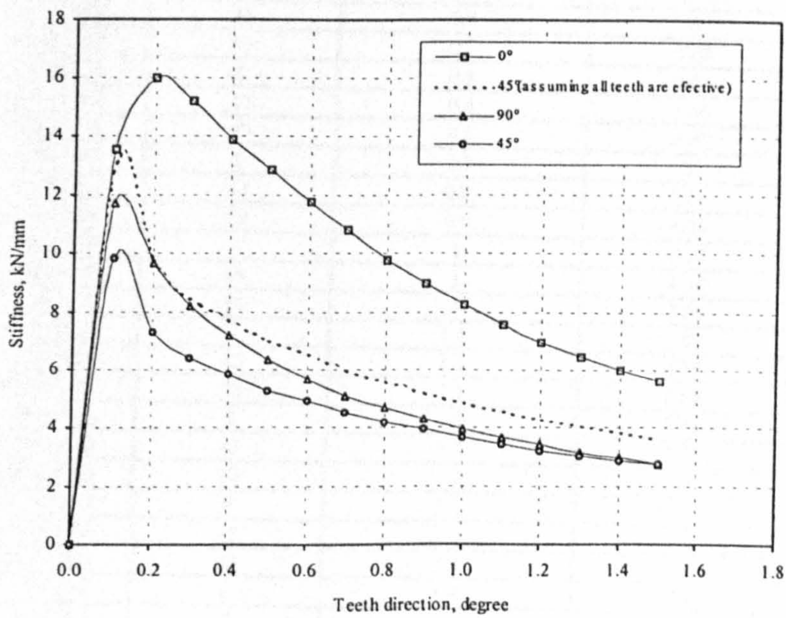


Figure 7.12 Comparison of joints performance with different teeth direction under tensile loading.

Plate Number	Teeth directions (degree)	Displacement level (mm)	Stiffness (kN/mm)
M20/0310B	0	0.1	13.56
M20/0310B	45	0.1	13.12
M20/0310B	90	0.1	11.73
M20/0310B	0	0.2	16.03
M20/0310B	45	0.2	9.75
M20/0310B	90	0.2	9.69
M20/0310B	0	0.3	15.21
M20/0310B	45	0.3	8.49
M20/0310B	90	0.3	8.21
M20/0310B	0	0.4	13.93
M20/0310B	45	0.4	7.77
M20/0310B	90	0.4	7.18
M20/0310B	0	0.5	12.85
M20/0310B	45	0.5	6.99
M20/0310B	90	0.5	6.32
M20/0310B	0	0.6	11.78
M20/0310B	45	0.6	6.53
M20/0310B	90	0.6	5.64
M20/0310B	0	0.7	10.83
M20/0310B	45	0.7	6
M20/0310B	90	0.7	5.08
M20/0310B	0	0.8	9.81
M20/0310B	45	0.8	5.56
M20/0310B	90	0.8	4.65
M20/0310B	0	0.9	9
M20/0310B	45	0.9	5.21
M20/0310B	90	0.9	4.26
M20/0310B	0	1	8.28
M20/0310B	45	1	4.86
M20/0310B	90	1	3.94
M20/0310B	0	1.1	7.59
M20/0310B	45	1.1	4.56
M20/0310B	90	1.1	3.66
M20/0310B	0	1.2	6.98
M20/0310B	45	1.2	4.29
M20/0310B	90	1.2	3.4
M20/0310B	0	1.3	6.44
M20/0310B	45	1.3	4.04
M20/0310B	90	1.3	3.16
M20/0310B	0	1.4	5.98
M20/0310B	45	1.4	3.82
M20/0310B	90	1.4	2.94

Table 7.10 Average stiffness for joint specimens with different teeth directions under tensile loading.

It is clear that the stiffness of the joints were dependent on the teeth directions. The stiffness of the joints decreased with an increase in the angle of the teeth directions. The rate of decrease in stiffness increased as the angle of the teeth directions increased. At low displacement levels, stiffness was high compared with high displacement levels. The rate of increasing in stiffness was reduced as displacement was increased.

In Figure 7.13, the effect of teeth directions on the performance of the connections with respect to the stiffness sustained by them at displacement levels of 0.1mm to 1.4mm are shown.

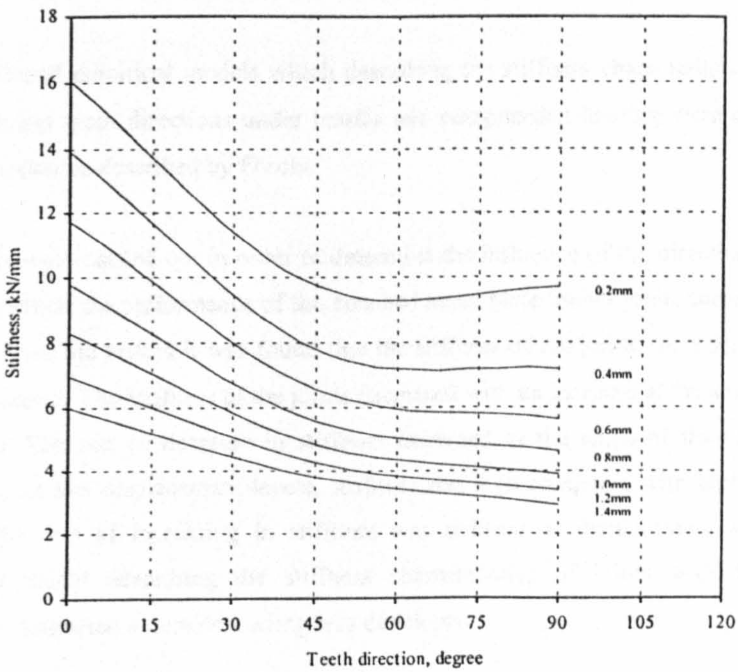


Figure 7.13 Stiffness vs teeth direction in joints under tensile loading.

7.5 SUMMARY

This chapter described a series of tests carried out on punched metal plate timber joints in order to classify the importance of factors such as, number of bites, length of bites and grain directions on the performance of the joints. The specimens were loaded to failure both in tension and in compression. Taguchi methodology was used to analyse and classify the importance of such factors. From the test results and analysis carried out, it was found that the grain direction has large effects on the performance of the joints under tensile loading and the effectiveness of the grain direction was less when joints were subjected to compressive loading. Also, it was clear that increasing the number of bites in the joints was more important than increasing the length of bites. There was also a strong indication that the number of bites effects was dominant when joints were subjected to compressive loading.

The developed empirical models which describing the stiffness characteristics of the joints with different grain directions under tensile and compression loading were compared well with the formulae described by Foschi.

Also, tests were carried out in order to determine the influence of the directions of the plate and the teeth on the performance of the punched metal plate timber joints subjected to tensile loading. From the results it was found that the stiffness of the joints were dependent on the teeth directions. The stiffness of the joints decreased with an increase in the angle of the teeth directions. The rate of decrease in stiffness increased as the angle of the teeth directions increased. At low displacement levels, stiffness was high compared with high displacement levels. The rate of increasing in stiffness was reduced as displacement was increased. Empirical model describing the stiffness characteristics of joints with different teeth directions subjected to tensile loading was developed.

CHAPTER EIGHT

THE MOMENT-ROTATION CHARACTERISTICS OF THE PUNCHED METAL PLATE TIMBER FASTENERS

8. THE MOMENT-ROTATION CHARACTERISTICS OF THE PUNCHED METAL PLATE TIMBER FASTENERS

8.1 INTRODUCTION

Punched metal plate joints are used widely for the construction of timber roof trusses. Traditional approaches to the analysis and design of the trusses are based on the assumption that the joints are either pinned or completely rigid. These are simply the extreme cases of true joints behaviour. In either of these two conditions, the forces and displacement obtained are unreliable and do not represent the actual structural behaviour, leading to over or under designed members and joints. The actual joints can be characterised as semi-rigid. These joints allow some relative movement (axial, translation, and rotation) between the connected members in the plane of the truss due to concentric or eccentric forces in the members. However, in engineering practice a connection can be considered pinned if its stiffness is so small that the connection is incapable of transmitting any significant moment, thus permitting almost free rotation. Similarly, a connection can be considered rigid if its rigidity is so large that the connection is capable of transmitting significant moment and will not permit any rotation.

The assumptions that the joints are either pinned or rigid are not entirely consistent with practical conditions. However, they have been accepted because of the simplicity in design and analysis procedures of truss roof structures.

In this chapter the semi-rigidity effects of the punched metal plate timber joints are discussed. Details of experimental work investigating the moment-rotation characteristics of the joints are given using joints with different variables such as number of bites, length of bites, grain directions and plate thickness. Empirical models describing moment-rotation behaviour and rotational stiffness of the joints were developed and compared with the experimental results.

8.2 TESTING PROGRAM

Tests were carried out to determine the influences of different variables such as number of bites, length of bites, grain directions and plate thickness on the performance of the punched metal plate timber joints subjected to moment force. Testing programme for different variables (number of bites, length of bites, grain directions, plate thickness) are summarised in Table 8.1. Minimum of 5 specimens per joint type were tested, totalling over 70 specimen joints.

Plate ref. number	Plate properties (mm)			Bite properties		Grain direction
	Length	Width	Thickness	Number	Length (mm)	
M20/0310B	101	25	1	1	8	90
M20/0310B	101	25	1	2	8	90
M20/0310B	101	25	1	3	8	90
M20/0310B	101	25	1	4	8	90
M20/0310B	101	25	1	5	8	90
M20/0310B	101	25	1	6	8	90
M20/0310B	101	25	1	7	8	90
M20/0310B	101	25	1	8	8	90
M20/0310B	101	25	1	8	8	0
M20/0310B	101	25	1	8	8	30
M20/0310B	101	25	1	8	8	60
M14/1333	133	38	2	8	5	90
M14/1333	133	38	2	8	10	90
M14/1333	133	38	2	8	15	90

Table 8.1 Testing programme for joints subjected to moment force.

8.3 LABORATORY WORK

The punched metal plate type used in construction of number of bites and grain directions testing specimens was M20/0310B-101mm×25mm×1mm and for length of bites testing specimens was a small strip 130mm×38mm×2mm which cut from plate number M14/1333 as supplied by MiTek industries. The specimens were loaded to failure in bending. All joint specimens were manufactured using material as explained in chapter 3. The average moisture content at the time of testing was 12 % and the mean density was 475 kg/m^3.

The test samples were generally made of two pieces of timber dimensioned as 65mm×300mm and 65mm×130mm by 45mm thickness. Typical test set-up is shown in Figure 8.1. The instrumentation and loading procedures were as explained in chapter 3.

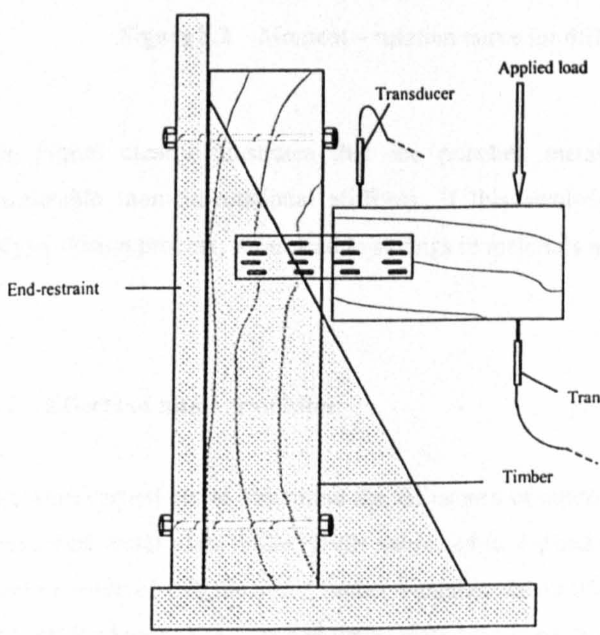


Figure 8.1 Moment test set-up.

8.4 RESULTS AND DISCUSSION

A typical moment-rotation behaviour of the joints tested is shown in Figure 8.2 and is compared with the idealised behaviour of fully pinned and fully rigid joints.

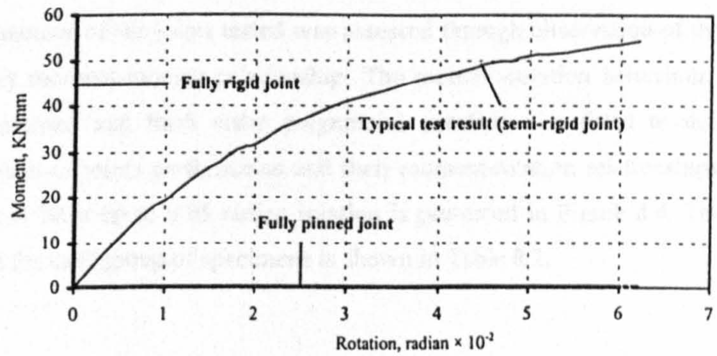


Figure 8.2 Moment – rotation curve for different joints.

This Figure clearly illustrates that the punched metal plate connected joints posses considerable moment-rotational stiffness. If this semi-rigid behaviour is utilized in the analysis-design process, it can lead to savings in materials used.

8.4.1 Effects of number of bites

Tests were carried out to determine the influences of number of bites on the performance of the punched metal plate timber joints subjected to applied moments. The test samples were generally made of two pieces of timber dimensioned as 65mm×300mm and 65mm×133mm by 45mm thickness. The punched metal plate type used in construction of testing specimens was M20/0310B-101mm×25mm×1mm. The specimens were loaded to failure in bending. All joint specimens were manufactured using material as explained in chapter 3.

In Figure 8.3 typical non-linear moment-rotation curves up to 0.05 radian rotation with best fit (average curves) for specimens with various number of bites subjected to moments are shown. All joints made of punched metal plates M20/0310B with equal length of bites (8mm) and the loads applied perpendicular to the grain of timber. The induced deformation rate during loading was 1mm/min. The timber average moisture content at the time of testing was 12 % and the mean density was 475 kg/m^3.

The behaviour of the joints tested was assessed through observation of the failed specimens and their moment-rotation relationship. The moment-rotation behaviour of each specimen was examined and forth order polynomial equation was fitted to define the curve. A comparison of joints performance and their moment-rotation relationships in relation to the number of bites up to 0.05 radian rotation is presented in Figure 8.4. The average induced moment for each group of specimens is shown in Table 8.2.

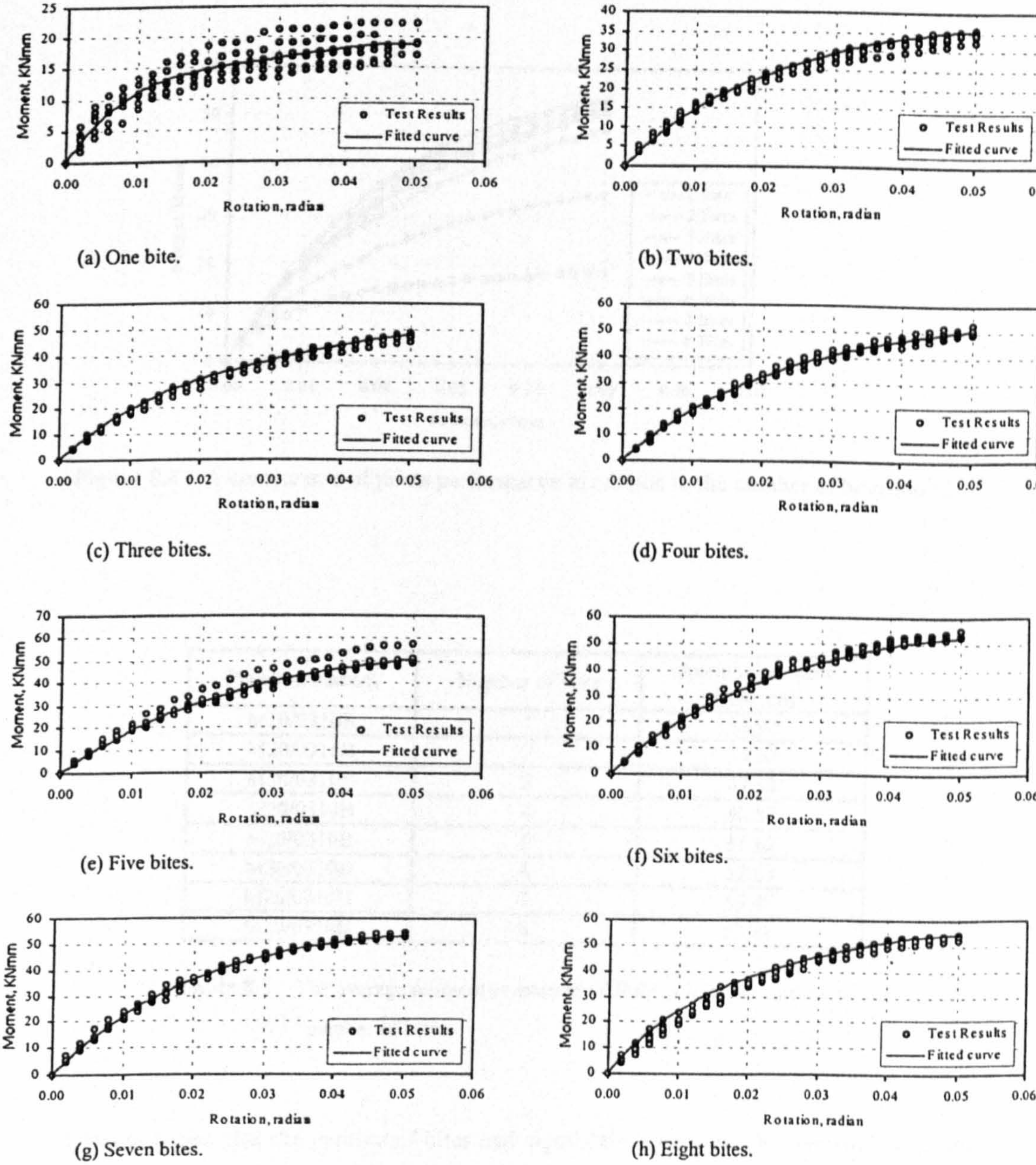


Figure 8.3 Moment-rotation behaviour of joints with various number of bites subjected to applied moments.

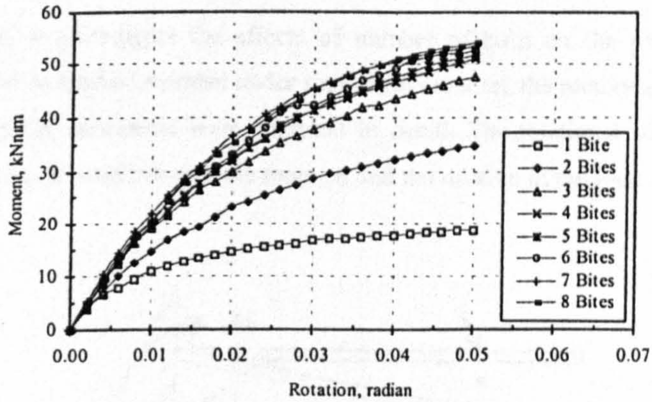


Figure 8.4 A comparison of joints performance in relation to the number of bites tested.

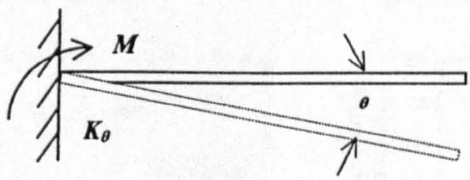
Plate ref. number	Number of bites	Average moment (KNmm)
M20/0310B	1	18.90
M20/0310B	2	34.62
M20/0310B	3	47.58
M20/0310B	4	50.80
M20/0310B	5	51.62
M20/0310B	6	52.63
M20/0310B	7	53.45
M20/0310B	8	53.88

Table 8.2 The average moment at rotation of 0.05 radian for various number of bites.

It was observed that the number of bites had significant effects on the performance of the joints. All joints studied behaved in similar manner. They showed a non-linear response from beginning up to the failure load.

8.4.1.1 Rotational stiffness characteristics of the joints

In order to investigate the effects of number of bites on the performance of the joints subjected to applied moment under short-term duration, the rotational stiffness characteristics of all tested specimens were analysed in detail. The rotational stiffness of the joint (K_θ) defined as the ratio between the moment and the rotation in the joint.



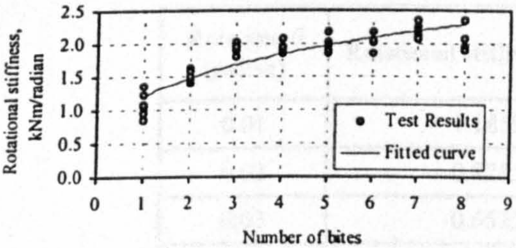
$$K_\theta = \frac{M}{\theta} \tag{8.1}$$

where K_θ = Rotational stiffness (KNmm/radian).

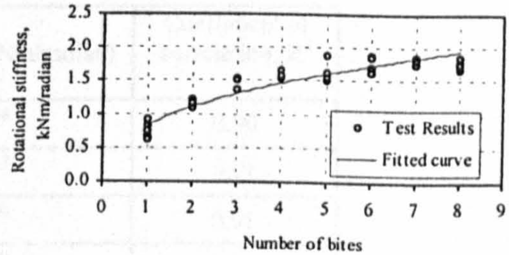
M = Applied moment (KNmm).

θ = Rotation (radian).

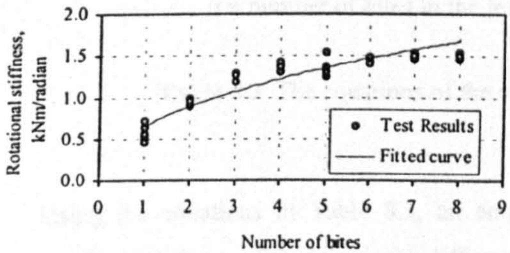
The average magnitude of the rotational stiffness sustained by each joints specimen at 0.01 to 0.05 radian rotation level was determined. Figure 8.5 represents results of rotational stiffness versus number of bites in the joints at rotation levels of 0.01 to 0.05 radian. Power equations were fitted the non-linear rotational stiffness versus number of bites curves to define them. These equations were directed to pass through the point of origin to simulate the condition of zero rotational stiffness at number of bites equals to zero. The equations obtained are tabulated and presented in Table 8.3. These equations have been solved and empirical model (i.e. equation 8.2) describing the rotational stiffness of punched metal plate timber connections with different number of bites was developed.



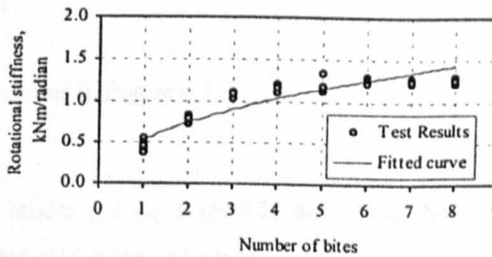
(a) Characteristics at 0.01 radian rotation.



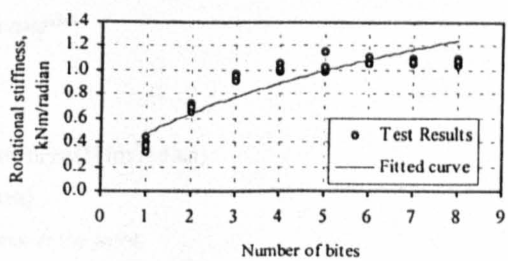
(b) Characteristics at 0.02 radian rotation.



(c) Characteristics at 0.03 radian rotation.



(d) Characteristics at 0.04 radian rotation.



(e) Characteristics at 0.05 radian rotation.

Figure 8.5 Rotational stiffness sustained in the joint versus number of bites in the joint.

Rotation, θ (radian)	Rotational stiffness (kNm/radian)	Coefficient of correlation, R^2
0.01	$1.1859\ n^{0.3166}$	0.90
0.02	$0.8285\ n^{0.4113}$	0.91
0.03	$0.6523\ n^{0.4540}$	0.91
0.04	$0.5323\ n^{0.4800}$	0.89
0.05	$0.4580\ n^{0.4807}$	0.86

n = number of bites in the joints.

Table 8.3 The equations of the various curves in Figure 8.5.

Using the equations in Table 8.3, an empirical model (i.e equation 8.2) describing the rotational stiffness of the joints with different number of bites was developed.

$$K_\theta = 0.0802\theta^{-0.5901} n^{1.1245\theta^{0.2676}} \tag{8.2}$$

where K_θ = Rotational stiffness(kNm/radian).

θ = rotation (radian).

n = number of bites in the joint.

In Figure 8.6, the effect of increase in the number of bites on the performance of the connections with respect to the rotational stiffness sustained by them at rotation levels of 0.01 to 0.05 radian are shown.

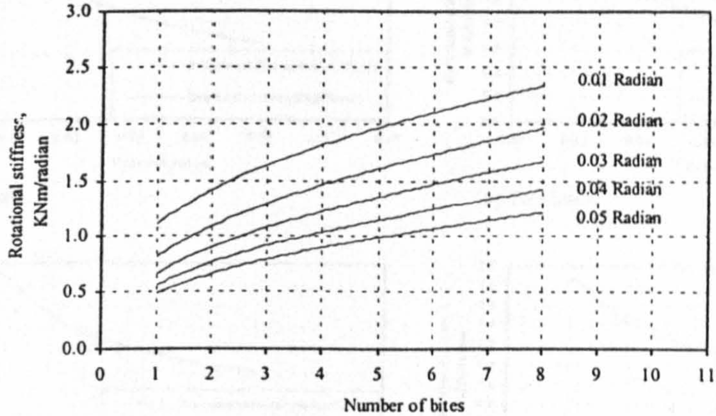
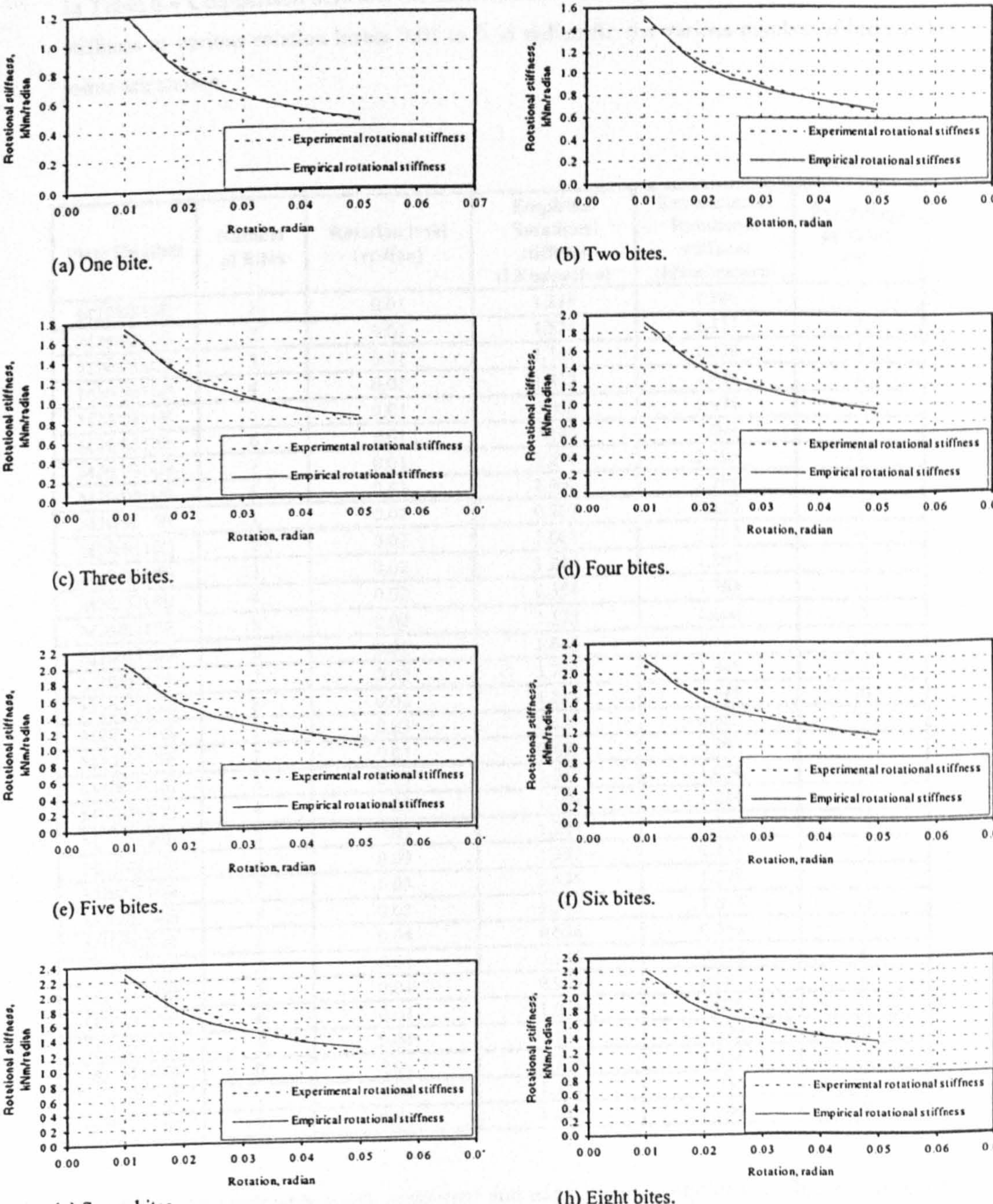


Figure 8.6 Rotational stiffness vs number of bites in the joints.

It is clear that the rotational stiffness were dependent on the number of bites in the joints. Increasing the number of bites will increase the rotational stiffness of the joints. The rate of increase in rotational stiffness reduced as the number of bites increased above approximately 60% of the total number of bites available in a standard toothed-plate size. At low rotation level, the rotational stiffness was high compared with high rotation level. The rate of increase in the rotational stiffness was reduced as the rotation levels were increased.

In Figure 8.7, a comparison of rotational stiffness with respect to increase in rotation levels between experimental and empirical (i.e. equation 8.2) results for various joints with different number of bites are represented. The agreement between the empirical model and experimental observation was good.



(a) One bite.
(b) Two bites.
(c) Three bites.
(d) Four bites.
(e) Five bites.
(f) Six bites.
(g) Seven bites.
(h) Eight bites.

Figure 8.7 Comparison of rotational stiffness vs rotation curve between experimental and empirical (i.e. equation 8.2) results.

In Table 8.4 Comparison between the experimental and empirical (i.e. equation 8.2) rotation stiffness at various rotation levels 0.01 to 0.05 radian for the various number of bites in the joints are shown.

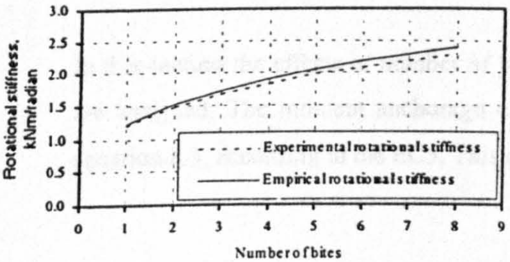
Plate Number	Number of Bites	Rotation level (radian)	Empirical Rotational stiffness (kNm/radian)	Experimental Rotational stiffness (kNm/ radian)	Percentage of Error (%)
M20/0310B	1	0.01	1.214	1.186	2
M20/0310B	2	0.01	1.524	1.477	3
M20/0310B	3	0.01	1.741	1.679	4
M20/0310B	4	0.01	1.913	1.839	4
M20/0310B	5	0.01	2.059	1.974	4
M20/0310B	6	0.01	2.185	2.091	4
M20/0310B	7	0.01	2.299	2.196	5
M20/0310B	8	0.01	2.402	2.291	5
M20/0310B	1	0.02	0.807	0.829	-3
M20/0310B	2	0.02	1.061	1.102	-4
M20/0310B	3	0.02	1.245	1.302	-4
M20/0310B	4	0.02	1.394	1.465	-5
M20/0310B	5	0.02	1.523	1.606	-5
M20/0310B	6	0.02	1.636	1.731	-5
M20/0310B	7	0.02	1.739	1.845	-6
M20/0310B	8	0.02	1.833	1.949	-6
M20/0310B	1	0.03	0.635	0.652	-3
M20/0310B	2	0.03	0.862	0.894	-4
M20/0310B	3	0.03	1.030	1.074	-4
M20/0310B	4	0.03	1.169	1.224	-4
M20/0310B	5	0.03	1.289	1.355	-5
M20/0310B	6	0.03	1.397	1.471	-5
M20/0310B	7	0.03	1.495	1.578	-5
M20/0310B	8	0.03	1.586	1.677	-5
M20/0310B	1	0.04	0.536	0.532	1
M20/0310B	2	0.04	0.745	0.742	0
M20/0310B	3	0.04	0.903	0.902	0
M20/0310B	4	0.04	1.036	1.035	0
M20/0310B	5	0.04	1.151	1.153	0
M20/0310B	6	0.04	1.256	1.258	0
M20/0310B	7	0.04	1.351	1.355	0
M20/0310B	8	0.04	1.440	1.444	0

Table 8.4 Comparison between empirical and experimental rotational stiffness at rotation levels from 0.01 to 0.05 radian for various number of bites in the joints.

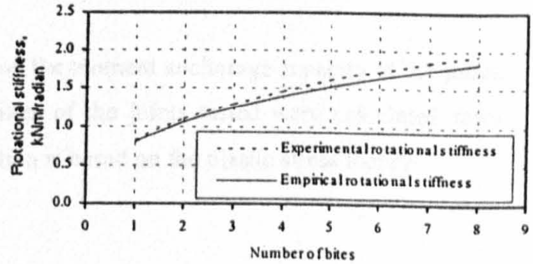
Plate Number	Number of Bites	Rotation level (radian)	Empirical Rotational stiffness (kNm/radian)	Experimental Rotational stiffness (kNm/ radian)	Percentage of Error (%)
M20/0310B	1	0.05	0.47	0.458	3
M20/0310B	2	0.05	0.666	0.639	4
M20/0310B	3	0.05	0.818	0.777	5
M20/0310B	4	0.05	0.945	0.892	6
M20/0310B	5	0.05	1.058	0.993	7
M20/0310B	6	0.05	1.160	1.084	7
M20/0310B	7	0.05	1.254	1.167	7
M20/0310B	8	0.05	1.341	1.244	8

Table 8.4 cont.

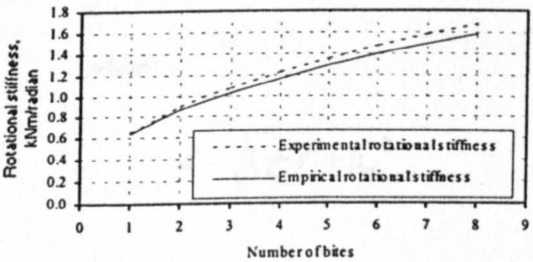
In Figure 8.8, a comparison of rotational stiffness versus number of bites between experimental and empirical (i.e. equation 8.2) results for various joints with different number of bites at rotation levels from 0.01 to 0.05 radian are represented. There was a good agreement between the empirical model and experimental results.



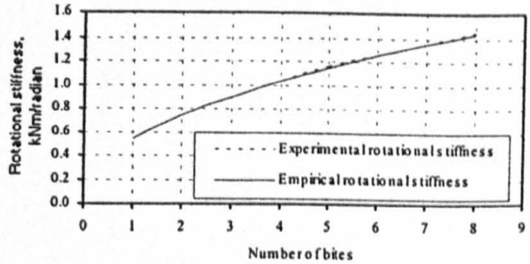
(a) At rotation 0.01 radian.



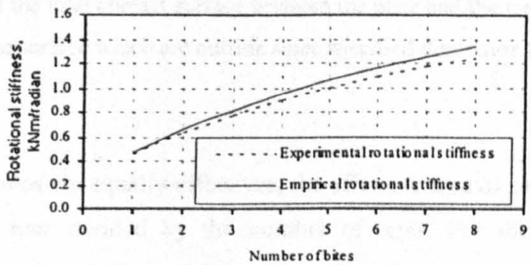
(b) At rotation 0.02 radian.



(c) At rotation 0.03 radian.



(d) At rotation 0.04 radian.



(e) At rotation 0.05 radian.

Figure 8.8 Comparison of rotational stiffness vs number of bites between experimental and empirical (i.e. equation 8.2) results.

8.4.1.2 Moment anchorage stress (τ_M) of the joints

In this section the effects of number of bites on the moment anchorage capacity of the joints are analysed. The moment anchorage capacities of the joints tested were calculated from equation 8.3, according to the EC5. This equation is based on the plastic stress theory.

$$\tau_M = \frac{4M_A}{A_{ef}d} \tag{8.3}$$

where :

$$d = \sqrt{\left(\frac{A_{ef}}{h_{ef}}\right)^2 + h_{ef}^{\ 2}} \tag{8.4}$$

where: M_A = moment acting on the plate at the centroid of the effective area.

h_{ef} = maximum height of the effective anchorage area perpendicular to the longest side.

A_{ef} = area of the total contact surface between the plate and the timber, reduced by those part of the surface which are outside some specified dimension from the edges and ends.

Assuming that all bites are equally effectives, the effective area of each bites will be equal to the total effective area divided by the number of bites. For the plates used in testing M20/0310B of dimensions 101mm×25mm×1mm, the effective area of each bite will be equal to 142.1875 mm^2. The effective area of the plate (8bites) and each bite individually are shown in Figure 8.9.

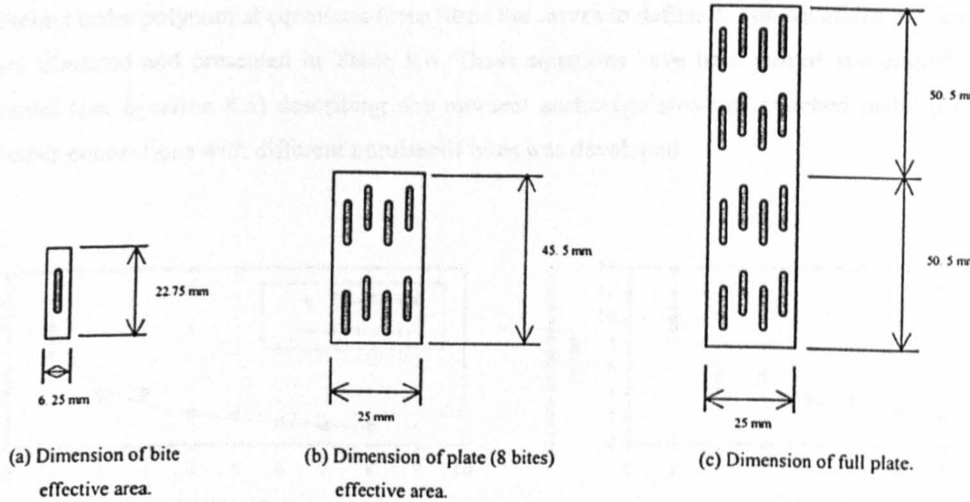


Figure 8.9 Dimensions of plate and bite effective area in the joints.

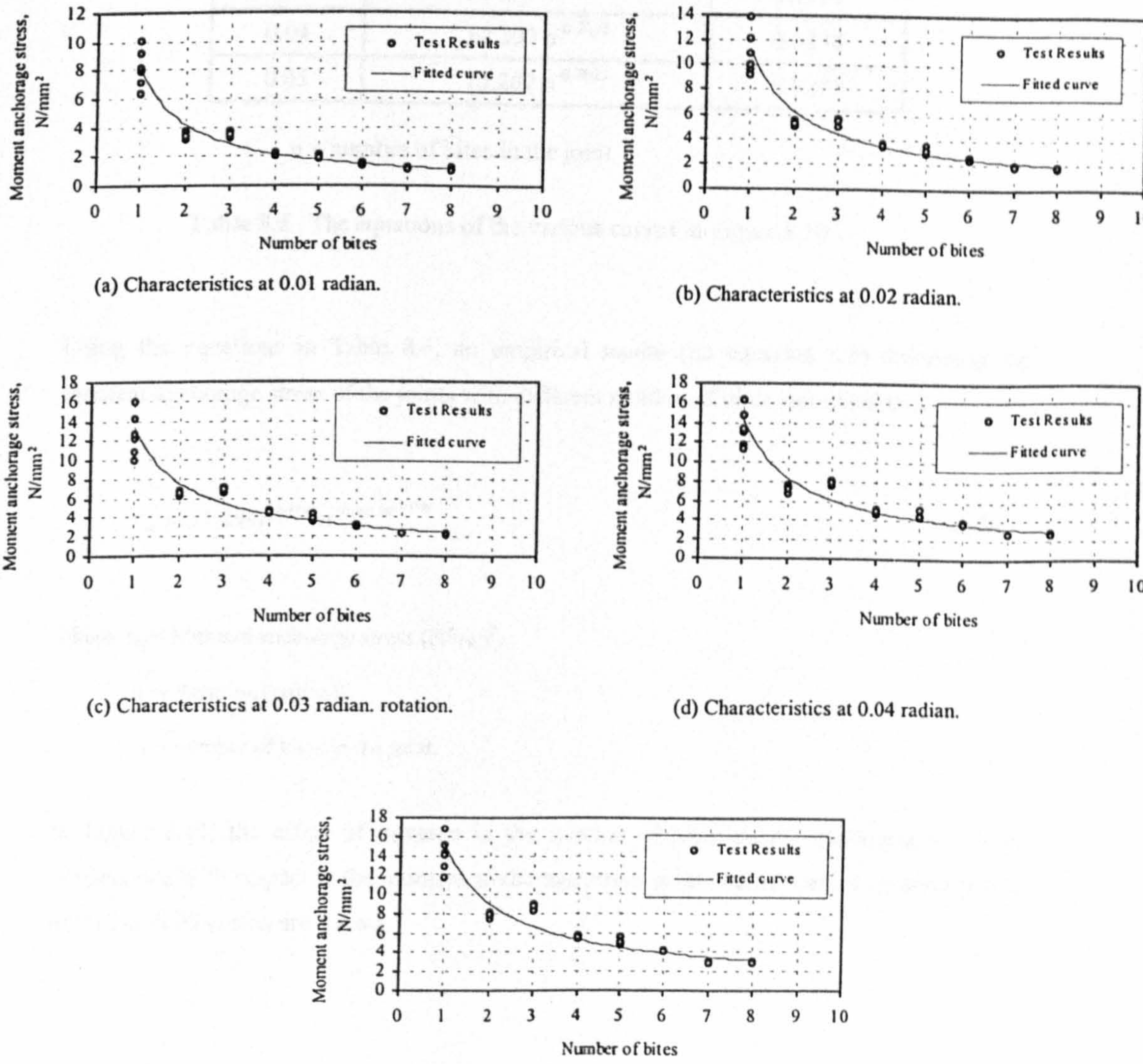
In Table 8.5 the effective area for a joints with various number of bites are shown.

Plate ref. number	Number of bites	Effective area (mm^2)
M20/0310B	1	142.1875
M20/0310B	2	284.3750
M20/0310B	3	426.5625
M20/0310B	4	568.7500
M20/0310B	5	710.9375
M20/0310B	6	853.1250
M20/0310B	7	995.3125
M20/0310B	8	1137.500

Table 8.5 The effective area for a joints with various number of bites.

The average magnitude of the moment anchorage stress sustained by each joint specimen at 0.01 to 0.05 radian rotation level was determined. Figure 8.10 represent results of moment anchorage stress versus number of bites in the joints at rotation levels of 0.01 to 0.05 radians.

Second order polynomial equations were fitted the curves to define it. The equations obtained are tabulated and presented in Table 8.6. These equations have been solved and empirical model (i.e. equation 8.5) describing the moment anchorage stress of punched metal plate timber connections with different number of bites was developed.



(a) Characteristics at 0.01 radian.

(b) Characteristics at 0.02 radian.

(c) Characteristics at 0.03 radian. rotation.

(d) Characteristics at 0.04 radian.

(e) Characteristics at 0.05 radian.

Figure 8.10 Moment anchorage stress sustained in the joint versus number of bites in the joint.

Rotation, θ (radian)	Moment anchorage stress (N/mm^2)	Coefficient of correlation, R^2
0.01	$8.0968\ n^{-0.955}$	0.9662
0.02	$11.313\ n^{-0.8603}$	0.9618
0.03	$13.361\ n^{-0.8176}$	0.9512
0.04	$14.209\ n^{-0.7612}$	0.9378
0.05	$15.282\ n^{-0.7605}$	0.9277

n = number of bites in the joint.

Table 8.6 The equations of the various curves in Figure 8.10

Using the equations in Table 8.6, an empirical model (i.e equation 8.5) describing the moment anchorage stress of the joints with different number of bites was developed.

$$\tau_m = 51.294\theta^{0.3946} n^{-0.4515\theta^{-0.1486}} \tag{8.5}$$

where τ_m = Moment anchorage stress (N/mm^2).

θ = Rotation (radian).

n = number of bites in the joint.

In Figure 8.11, the effect of increase in the number of bites on the performance of the connections with respect to the moment anchorage stress sustained by them at rotation levels of 0.01 to 0.05 radian are shown.

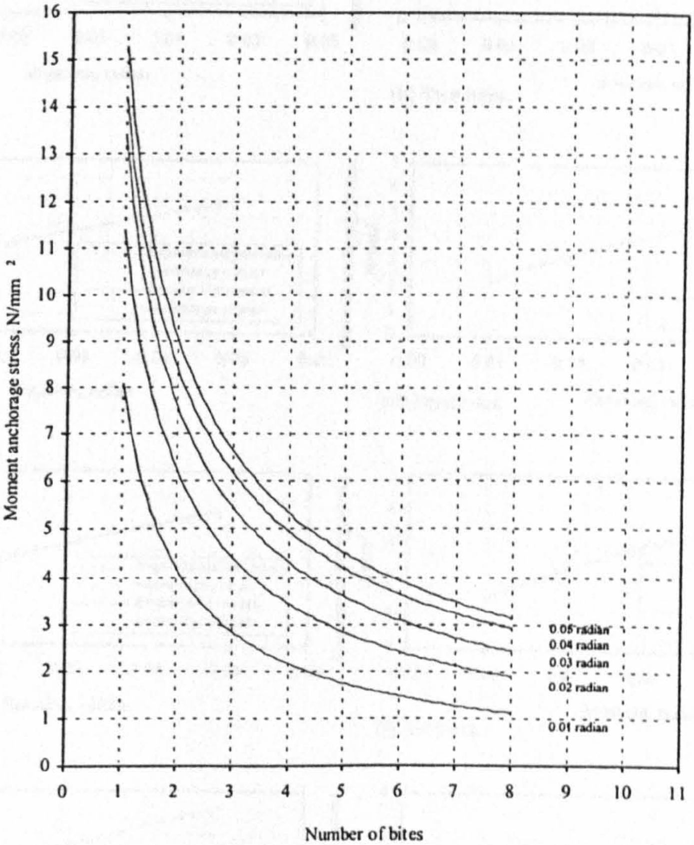
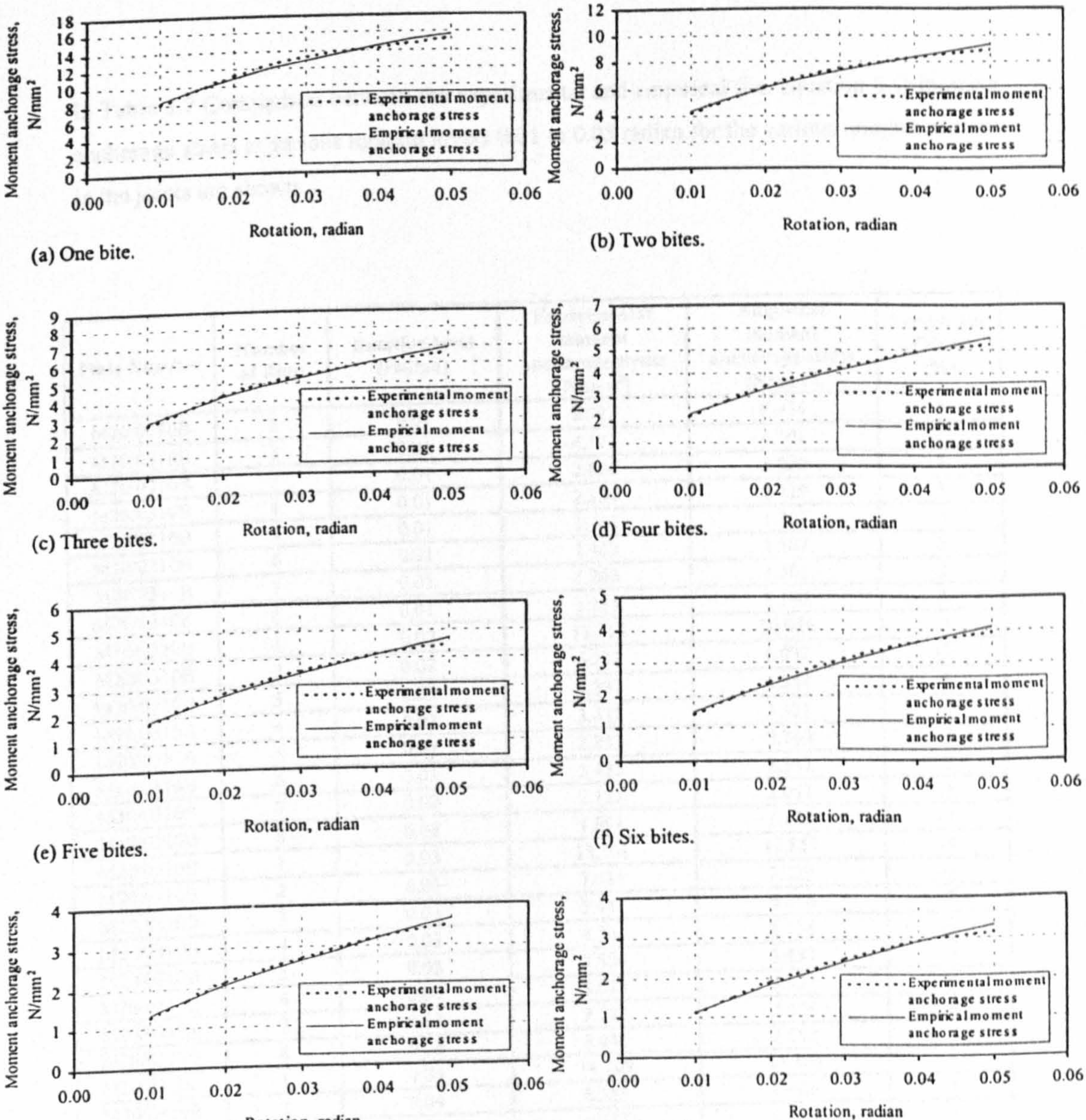


Figure 8.11 Moment anchorage stress vs number of bites in the joints.

In Figure 8.12, a comparison of moment anchorage stress versus rotation curves between experimental and empirical (i.e. equation 8.5) results for various joints with different number of bites were represented. The agreement between the empirical model and experimental observation was good.



(a) One bite.
(b) Two bites.
(c) Three bites.
(d) Four bites.
(e) Five bites.
(f) Six bites.
(g) Seven bites.
(h) Eight bites.

Figure 8.12 Comparison of moment anchorage stress vs rotation curve between experimental and empirical (i.e. equation 8.5) results.

In Table 8.7 Comparison between the experimental and empirical (i.e. equation 8.5) moment anchorage stress at various rotation levels 0.01 to 0.05 radian for the various number of bites in the joints are shown.

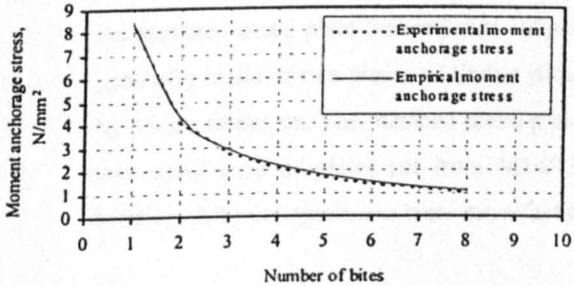
Plate Number	Number of Bites	Rotation level (radian)	Experimental moment anchorage stress (N/mm^2)	Empirical moment anchorage stress (N/mm^2)	Percentage of Error (%)
M20/0310B	1	0.01	8.097	8.334	3
M20/0310B	2	0.01	4.177	4.301	3
M20/0310B	3	0.01	2.836	2.920	3
M20/0310B	4	0.01	2.154	2.219	3
M20/0310B	5	0.01	1.741	1.793	3
M20/0310B	6	0.01	1.463	1.507	3
M20/0310B	7	0.01	1.263	1.301	3
M20/0310B	8	0.01	1.111	1.145	3
M20/0310B	1	0.02	11.313	10.956	-3
M20/0310B	2	0.02	6.232	6.032	-3
M20/0310B	3	0.02	4.397	4.254	-3
M20/0310B	4	0.02	3.433	3.321	-3
M20/0310B	5	0.02	2.833	2.740	-3
M20/0310B	6	0.02	2.422	2.342	-3
M20/0310B	7	0.02	2.121	2.051	-3
M20/0310B	8	0.02	1.891	1.828	-3
M20/0310B	1	0.03	13.361	12.857	-4
M20/0310B	2	0.03	7.581	7.329	-3
M20/0310B	3	0.03	5.442	5.276	-3
M20/0310B	4	0.03	4.301	4.178	-3
M20/0310B	5	0.03	3.584	3.487	-3
M20/0310B	6	0.03	3.088	3.008	-3
M20/0310B	7	0.03	2.722	2.654	-2
M20/0310B	8	0.03	2.440	2.382	-2
M20/0310B	1	0.04	14.209	14.403	1
M20/0310B	2	0.04	8.383	8.406	0
M20/0310B	3	0.04	6.157	6.135	0
M20/0310B	4	0.04	4.946	4.906	-1
M20/0310B	5	0.04	4.174	4.125	-1
M20/0310B	6	0.04	3.633	3.580	-1
M20/0310B	7	0.04	3.231	3.176	-2
M20/0310B	8	0.04	2.918	2.863	-2

Table 8.7 Comparison between empirical and experimental moment anchorage stress at rotation levels of 0.01 to 0.05 radian for various number of bites in the joints.

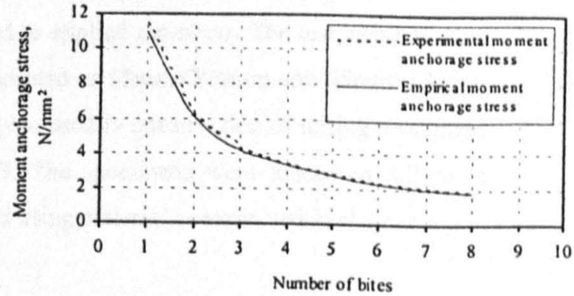
Plate Number	Number of Bites	Rotation level (radian)	Experimental moment anchorage stress (N/mm^2)	Empirical moment anchorage stress (N/mm^2)	Percentage of Error (%)
M20/0310B	1	0.05	15.282	15.728	3
M20/0310B	2	0.05	9.021	9.342	4
M20/0310B	3	0.05	6.627	6.888	4
M20/0310B	4	0.05	5.325	5.549	4
M20/0310B	5	0.05	4.494	4.692	4
M20/0310B	6	0.05	3.912	4.092	5
M20/0310B	7	0.05	3.479	3.644	5
M20/0310B	8	0.05	3.143	3.296	5

Table 8.7 cont.

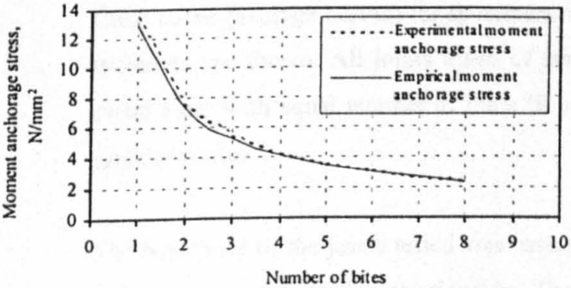
In Figure 8.13, a comparison of moment anchorage stress versus number of bites curves between experimental and empirical (i.e. equation 8.5) results for various joints with different number of bites were represented. The agreement between the empirical model and experimental observation was good.



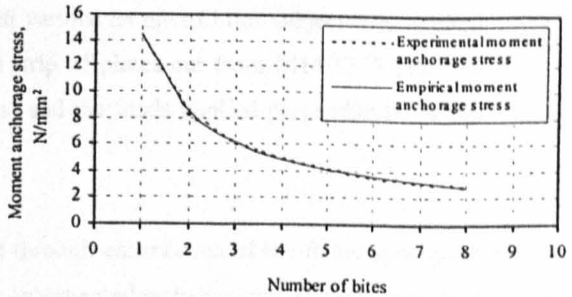
(a) Characteristics at 0.01 radian rotation.



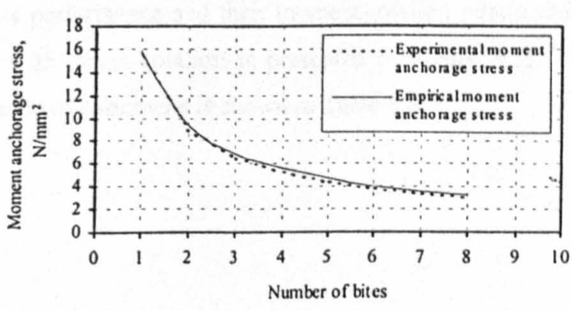
(b) Characteristics at 0.02 radian rotation.



(c) Characteristics at 0.03 radian rotation.



(d) Characteristics at 0.04 radian rotation.



(e) Characteristics at 0.05 radian rotation.

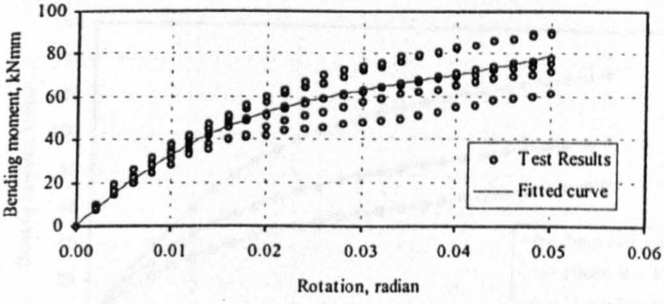
Figure 8.13 Comparison of moment anchorage stress vs number of bites curve between experimental and empirical (i.e. equation 8.5) results.

8.4.2 Effects of length of bites

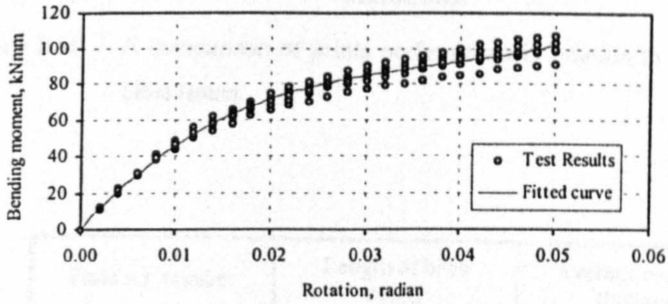
Tests were carried out to determine the influences of length of bites on the performance of the punched metal plate timber joints subjected to applied moments. The test samples were generally made of two pieces of timber dimensioned as 65mm×300mm and 65mm×133mm by 45mm thickness. The punched metal plate type used in construction of testing specimens was small strip of plates cut from M14/1333. The specimens were loaded to failure in bending. All joint specimens were manufactured using material as explained in chapter 3.

In Figure 8.14 typical non-linear moment-rotation curves up to 0.05 radian rotation with fitted curve (average curves) for specimens with various length of bites subjected to applied moments are shown. All joints made of small strip of plates cut from M14/1333 punched metal plate with equal number of bites (8 bites) and the loads applied perpendicular to the grain of timber.

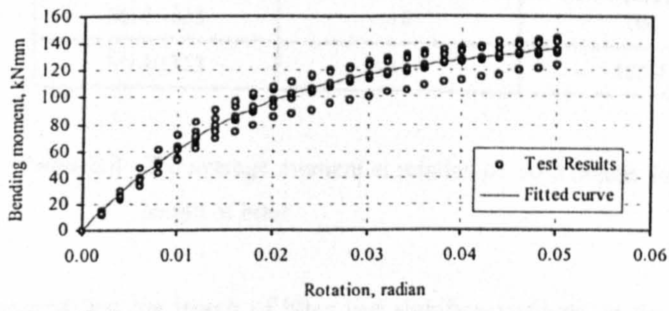
The behaviour of the joints tested was assessed through observation of the failed specimens and their moment-rotation relationship: The moment-rotation behaviour of each specimen was examined and third order polynomial equation was fitted to define the curve. A comparison of joints performance and their moment-rotation relationships in relation to the bites length up to 0.05 radian rotation is presented in Figure 8.15. The average induced moment for each group of specimens is shown in Table 8.8.



(a) 5mm bite length.



(b) 10mm bite length.



(c) 15mm bite length.

Figure 8.14 Moment-rotation behaviour of joints with various length of bites subjected to applied moments.

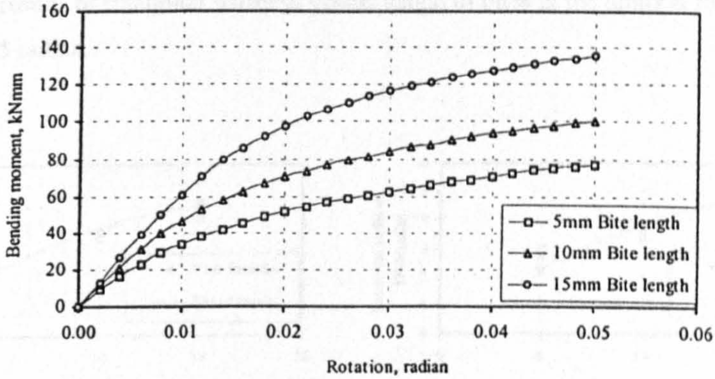


Figure 8.15 A comparison of joints performance in relation to the length of bites tested.

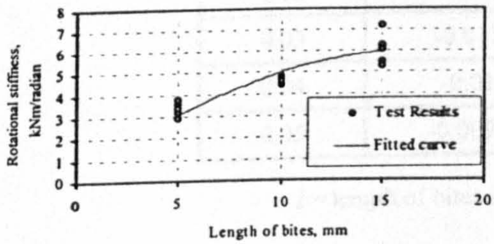
Plate ref. number	Length of bites (mm)	Average moment (kNmm)
M14/1333	5	77.2
M14/1333	10	100
M14/1333	15	135.4

Table 8.8 The average moment at rotation of 0.05 radian for various length of bites.

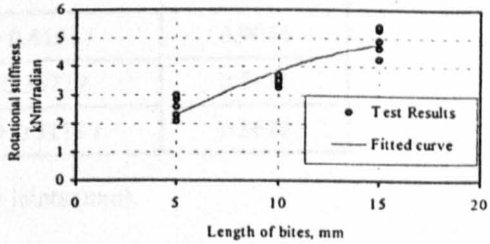
It was observed that the length of bites had significant effects on the performance of the joints. All joints studied behaved in a similar manner. They showed a non-linear response from beginning up to the failure load.

8.4.2.1 Rotational stiffness characteristics of the joints

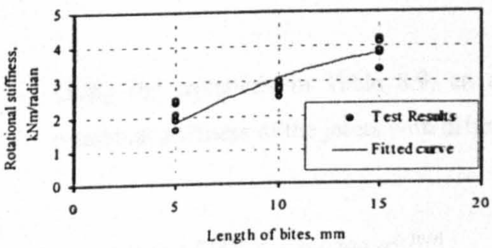
Similar method of analysis used for the number of bites was applied to the length of bites. The equations obtained are tabulated and presented in Table 8.9. These equations have been solved and empirical model (i.e. equation 8.6) describing the rotational stiffness of punched metal plate timber connections with different length of bites was developed. Figure 8.16 represents results of rotational stiffness versus length of bites in the joints at rotation levels of 0.01 to 0.05 radian.



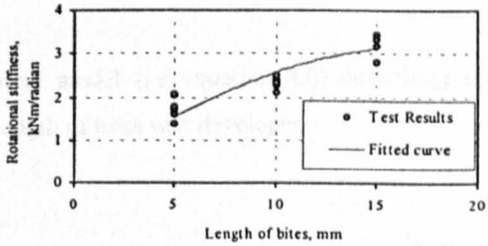
(a) Characteristics at 0.01 radian



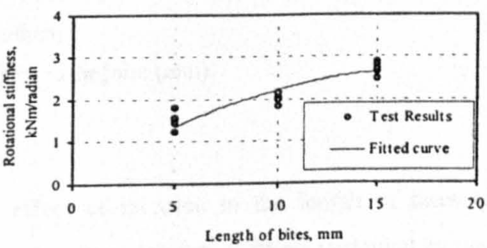
(b) Characteristics at 0.02 radian



(c) Characteristics at 0.03 radian



(d) Characteristics at 0.04 radian



(e) Characteristics at 0.05 radian

Figure 8.16 Rotational stiffness sustained in the joint versus length of bites in the joint.

Rotation, θ (radian)	Rotational stiffness (kNm/radian)	Coefficient of correlation, R^2
0.01	$-0.0203\ l^2 + 0.7021\ l$	0.9196
0.02	$-0.0131\ l^2 + 0.5155\ l$	0.9217
0.03	$-0.011\ l^2 + 0.4182\ l$	0.9044
0.04	$-0.01\ l^2 + 0.3572\ l$	0.8871
0.05	$-0.0091\ l^2 + 0.3118\ l$	0.8626

l = length of bites in the joints (mm).

Table 8.9 The equations of the various curves in Figure 8.16

Using the equations in Table 8.9, an empirical model (i.e equation 8.6) describing the rotational stiffness of the joints with different length of bites was developed.

$$K_\theta = -0.002\ \theta^{-0.4936}\ l^2 + 0.0709\ \theta^{-0.5016}\ l \qquad (8.6)$$

where K_θ = Rotational stiffness(kNm/radian).

θ = rotation (radian).

l = length of bites in the joint (mm).

In Figure 8.17, the effect of increase in the length of bites on the performance of the connections with respect to the rotational stiffness sustained by them at rotation levels of 0.01 to 0.05 radian are shown.

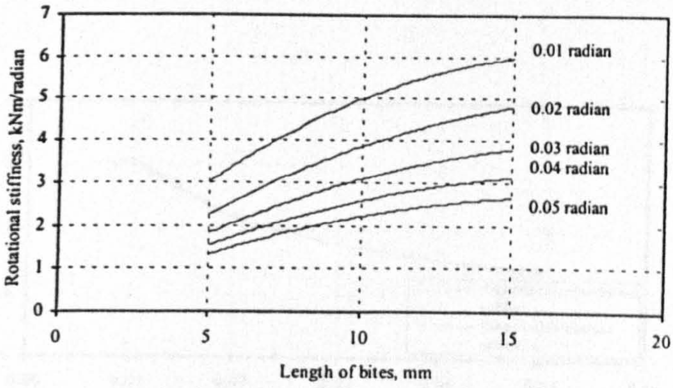
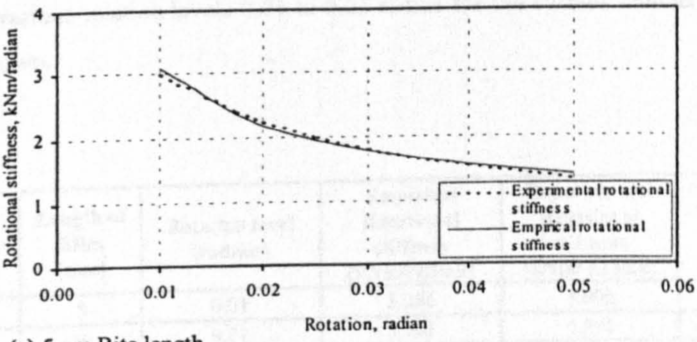


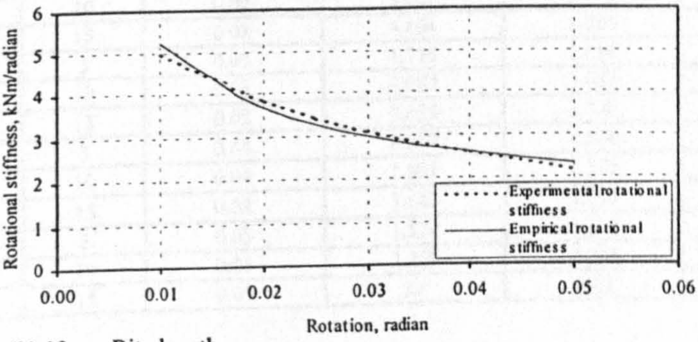
Figure 8.17 Rotational stiffness vs length of bites in the joints.

It is clear that the rotational stiffness were dependent on the length of bites in the joints. Increasing the length of bites will increase the rotational stiffness of the joints. The rate of increase in rotational stiffness increase as the length of bites increased above approximately 50% of the maximum length of bites in a joint tested. At low rotation level, the rotational stiffness was high comparing with high rotation level. The rate of increasing in the rotational stiffness was reduced as the rotation levels were increased.

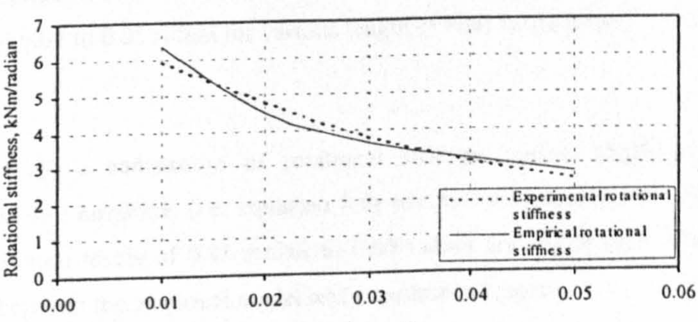
In Figure 8.18, a comparison of rotational stiffness versus rotation curves between experimental and empirical (i.e. equation 8.6) results for various joints with different length of bites are represented. The agreement between the empirical model and experimental observation was good.



(a) 5mm Bite length.



(b) 10mm Bite length.



(c) 15mm Bite length.

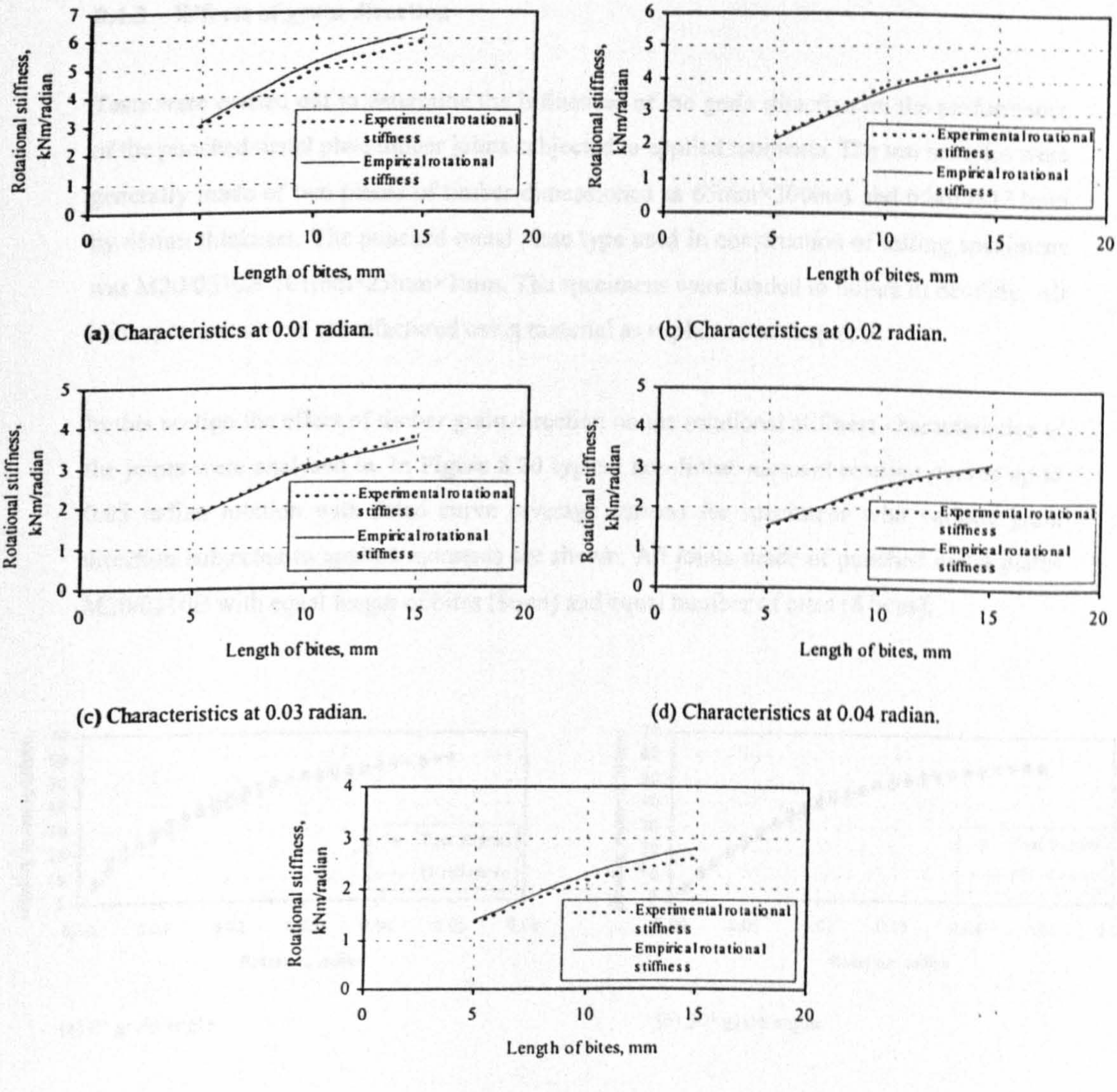
Figure 8.18 Comparison of rotational stiffness vs rotation curve between experimental and empirical (i.e. equation 8.6) results.

In Table 8.10 Comparison between the experimental and empirical (i.e. equation 8.6) rotation stiffness at various rotation levels 0.01 to 0.05 radian for the various number of bites in the joints are shown.

Plate Number	Length of Bites (mm)	Rotation level (radian)	Empirical Rotational stiffness (kNm/radian)	Experimental Rotational stiffness (kNm/ radian)	Percentage of Error (%)
M14/1333	5	0.01	3.086	3.003	3
M14/1333	10	0.01	5.201	4.991	4
M14/1333	15	0.01	6.344	5.964	6
M14/1333	5	0.02	2.178	2.25	-3
M14/1333	10	0.02	3.666	3.845	-5
M14/1333	15	0.02	4.464	4.785	-7
M14/1333	5	0.03	1.776	1.816	-2
M14/1333	10	0.03	2.987	3.082	-3
M14/1333	15	0.03	3.634	3.798	-4
M14/1333	5	0.04	1.537	1.536	0
M14/1333	10	0.04	2.584	2.572	0
M14/1333	15	0.04	3.141	3.108	1
M14/1333	5	0.05	1.374	1.332	3
M14/1333	10	0.05	2.309	2.208	5
M14/1333	15	0.05	2.8	2.63	6

Table 8.10 Comparison between empirical and experimental rotational stiffness at rotation levels of 0.01 to 0.05 radian for various length of bites in the joints.

In Figure 8.19, a comparison of rotational stiffness versus length of bites between experimental and empirical (i.e. equation 8.6) results for various joints with different bite length at rotation levels of 0.01 radian to 0.05 radian are represented. There was a good agreement between the empirical model and experimental results.



(a) Characteristics at 0.01 radian.

(b) Characteristics at 0.02 radian.

(c) Characteristics at 0.03 radian.

(d) Characteristics at 0.04 radian.

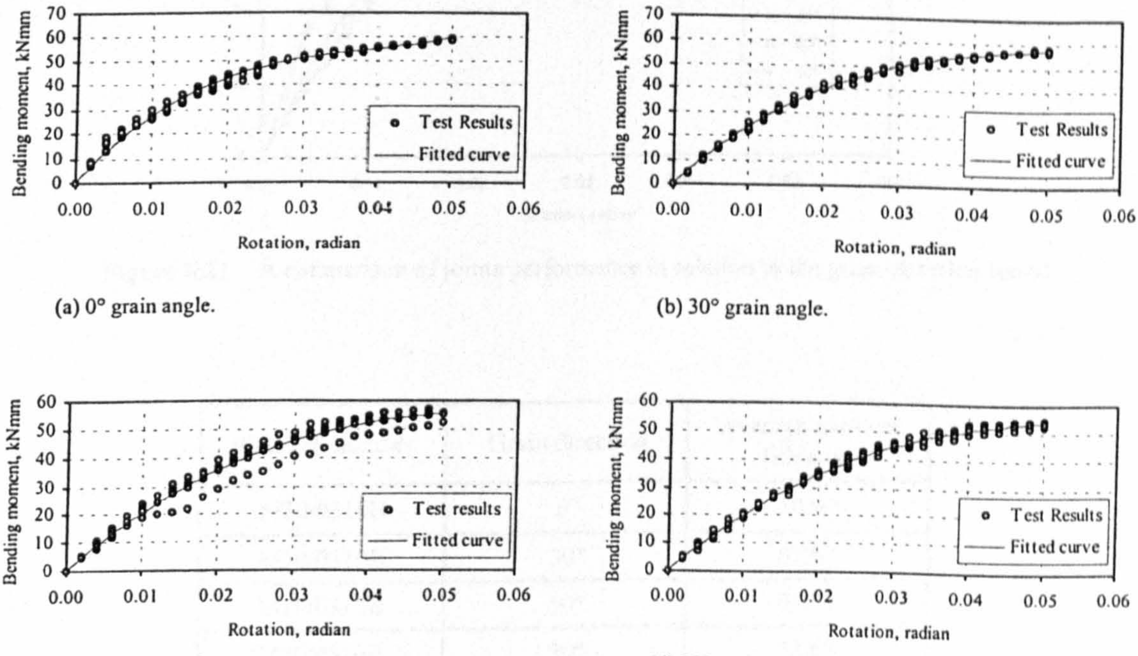
(e) Characteristics at 0.05 radian.

Figure 8.19 Comparison of rotational stiffness vs length of bites between experimental and empirical (i.e. equation 8.6) results.

8.4.3 Effects of grain direction

Tests were carried out to determine the influences of the grain direction on the performance of the punched metal plate timber joints subjected to applied moments. The test samples were generally made of two pieces of timber dimensioned as 65mm×300mm and 65mm×133mm by 45mm thickness. The punched metal plate type used in construction of testing specimens was M20/0310B-101mm×25mm×1mm. The specimens were loaded to failure in bending. All joint specimens were manufactured using material as explained in chapter 3.

In this section the effect of timber grain direction on the rotational stiffness characteristics of the joints were analysed in. In Figure 8.20 typical non-linear moment-rotation curves up to 0.05 radian rotation with fitted curve (average curves) for specimens with various grain direction subjected to applied moments are shown. All joints made of punched metal plates M20/0310B with equal length of bites (8mm) and equal number of bites (8 bites).



(a) 0° grain angle.

(b) 30° grain angle.

(c) 60° grain angle.

(d) 90° grain angle.

Figure 8.20 Moment-rotation behaviour of joints with various grain direction subjected to applied moments.

The behaviour of the joints tested was assessed through observation of the failed specimens and their moment-rotation relationship. The moment-rotation behaviour of each specimen was examined and third order polynomial equation was fitted to define the curve. A comparison of joints performance and their moment-rotation relationships in relation to the grain direction up to 0.05 radian rotation is presented in Figure 8.21. The average induced moment for each group of specimens is shown in Table 8.11.

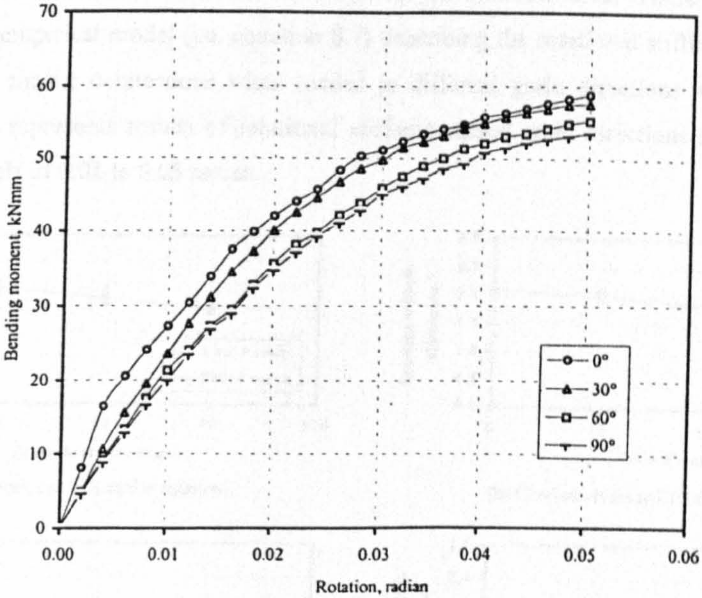


Figure 8.21 A comparison of joints performance in relation to the grain direction tested.

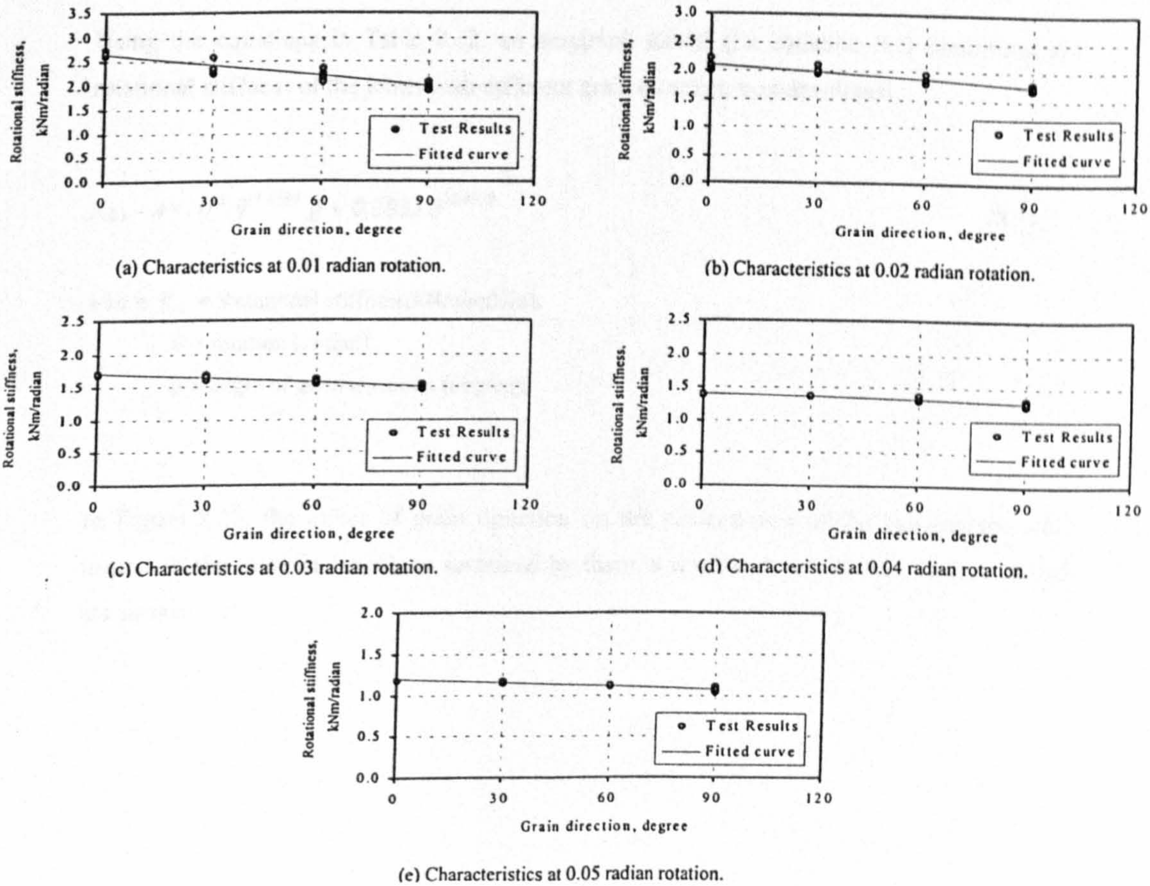
Plate ref. number	Grain direction	Average moment (kNmm)
M20/0310B	0°	58.90
M20/0310B	30°	57.67
M20/0310B	60°	55.32
M20/0310B	90°	53.62

Table 8.11 The average moment at rotation of 0.05 radian for various grain direction.

It was observed that the grain direction had significant effects on the performance of the joints. All joints studied behaved in similar manner. They showed a non-linear response from beginning up to the failure load.

8.4.3.1 Rotational stiffness characteristics of the joints

Similar method of analysis used for the number of bites was applied to the grain directions. The equations obtained are tabulated and presented in Table 8.12. These equations was solved and empirical model (i.e. equation 8.7) describing the rotational stiffness of punched metal plate timber connections when loaded in different grain directions was developed. Figure 8.22 represents results of rotational stiffness versus grain directions in the joints at rotation levels of 0.01 to 0.05 radian.



(a) Characteristics at 0.01 radian rotation.

(b) Characteristics at 0.02 radian rotation.

(c) Characteristics at 0.03 radian rotation.

(d) Characteristics at 0.04 radian rotation.

(e) Characteristics at 0.05 radian rotation.

Figure 8.22 Rotational stiffness sustained in the joint versus grain direction.

Rotation, θ (radian)	Rotational stiffness (kNm/radian)	Coefficient of correlation, R^2
0.01	-0.0073 g + 2.6375	0.9827
0.02	-0.004 g + 2.1004	0.9903
0.03	-0.0023 g + 1.7112	0.9768
0.04	-0.0014 g + 1.4026	0.9554
0.05	-0.0012 g + 1.1825	0.9759

g = angle of grain direction.

Table 8.12 The equations of the various curves in Figure 8.22

Using the equations in Table 8.12, an empirical model (i.e equation 8.7) describing the rotational stiffness of the joints with different grain direction was developed.

$$K_\theta = -4\times10^{-5}\,\theta^{-1.1694}\,g + 0.2885\,\theta^{-0.4919} \tag{8.7}$$

where K_θ = Rotational stiffness(kNm/radian).

θ = rotation (radian).

g = angle of grain direction (degree).

In Figure 8.23, the effect of grain direction on the performance of the connections with respect to the rotational stiffness sustained by them at rotation levels of 0.01 to 0.05 radian are shown.

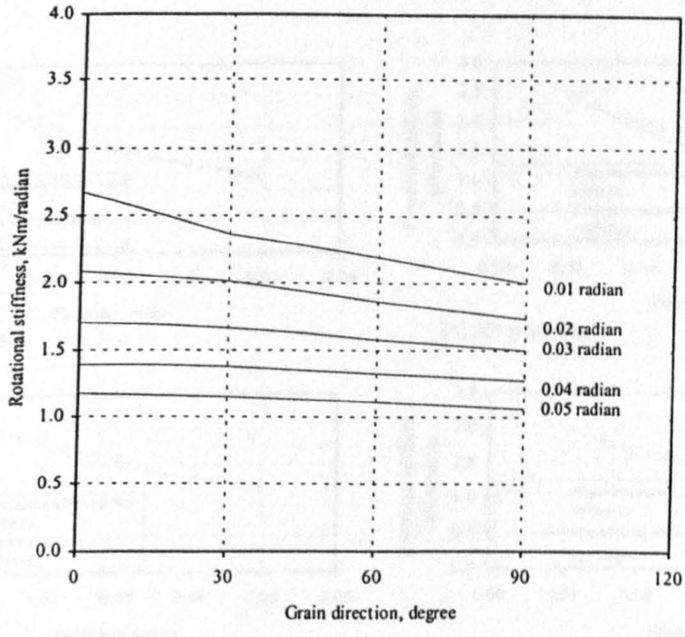


Figure 8.23 Rotational stiffness vs grain direction in the joints.

It is clear that the rotational stiffness were dependent on the grain direction in the joints. Increasing the angle of the grain will decrease the rotational stiffness of the joints. The rate of decreasing in rotational stiffness increase as the grain direction increased up to approximately angle of 60° in a joint tested. At low rotation level, the rotational stiffness was high comparing with high rotation levels. The rate of increasing in the rotational stiffness was reduced as the rotation levels were increased.

In Figure 8.24, a comparison of rotational stiffness versus rotation curves between experimental and empirical (i.e. equation 8.7) results for various joints with different grain direction are represented. The agreement between the empirical model and experimental observation was good.

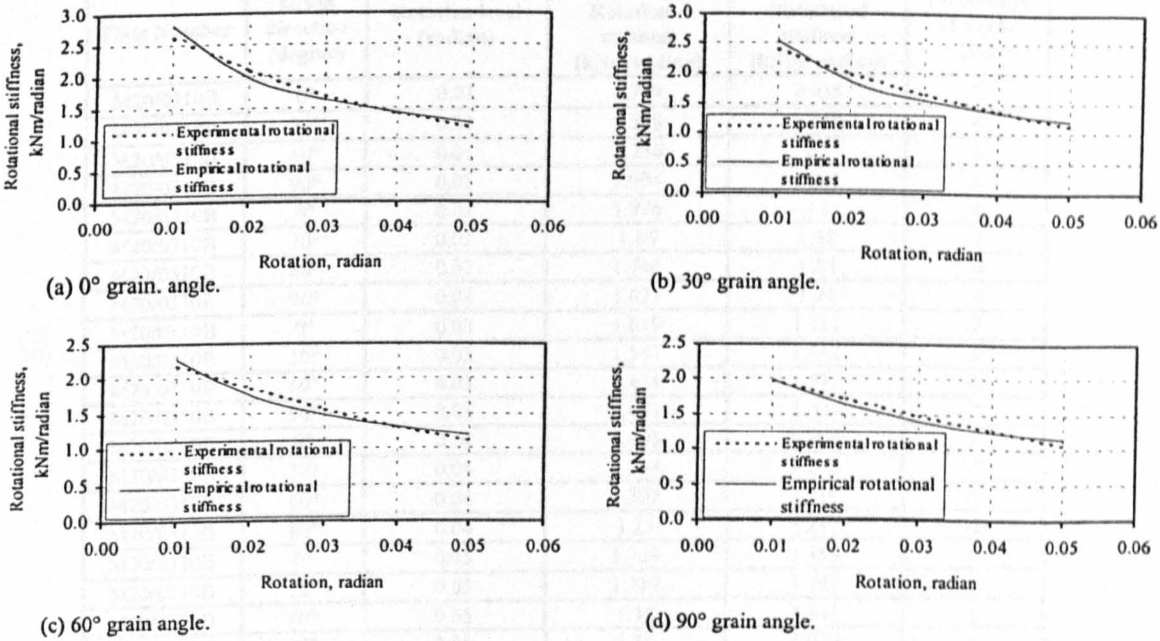


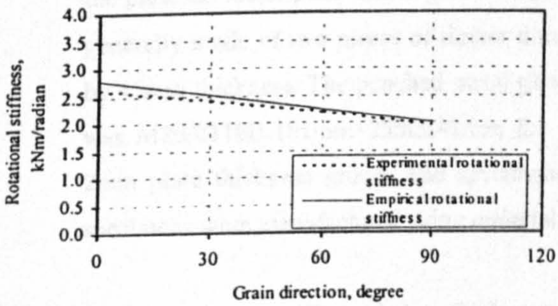
Figure 8.24 Comparison of rotational stiffness vs rotation curve between experimental and empirical (i.e. equation 8.7) results.

In Table 8.13 Comparison between the experimental and empirical (i.e. equation 8.7) rotation stiffness at various rotation levels 0.01 to 0.05 radian for the various grain direction in the joints are shown.

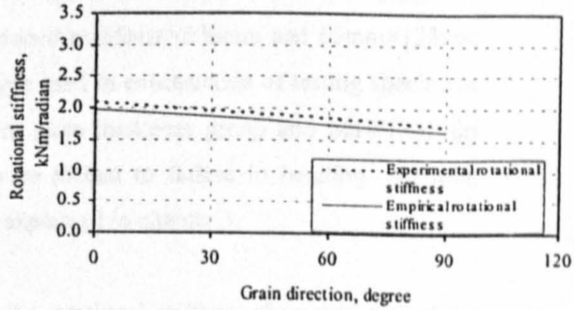
Plate Number	Grain direction (degree)	Rotation level (radian)	Empirical Rotational stiffness (kNm/radian)	Experimental Rotational stiffness (kNm/ radian)	Percentage of Error (%)
M20/0310B	0°	0.01	2.779	2.638	5
M20/0310B	30°	0.01	2.518	2.419	4
M20/0310B	60°	0.01	2.256	2.2	3
M20/0310B	90°	0.01	1.994	1.981	1
M20/0310B	0°	0.02	1.976	2.1	-6
M20/0310B	30°	0.02	1.86	1.98	-6
M20/0310B	60°	0.02	1.744	1.86	-6
M20/0310B	90°	0.02	1.627	1.74	-6
M20/0310B	0°	0.03	1.619	1.711	-5
M20/0310B	30°	0.03	1.547	1.642	-6
M20/0310B	60°	0.03	1.474	1.573	-6
M20/0310B	90°	0.03	1.402	1.504	-7
M20/0310B	0°	0.04	1.405	1.403	0
M20/0310B	30°	0.04	1.354	1.361	-1
M20/0310B	60°	0.04	1.302	1.319	-1
M20/0310B	90°	0.04	1.25	1.277	-2
M20/0310B	0°	0.05	1.259	1.183	6
M20/0310B	30°	0.05	1.219	1.147	6
M20/0310B	60°	0.05	1.18	1.111	6
M20/0310B	90°	0.05	1.14	1.075	6

Table 8.13 Comparison between empirical and experimental rotational stiffness at rotation levels of 0.01 to 0.05 radian for various grain direction in the joints.

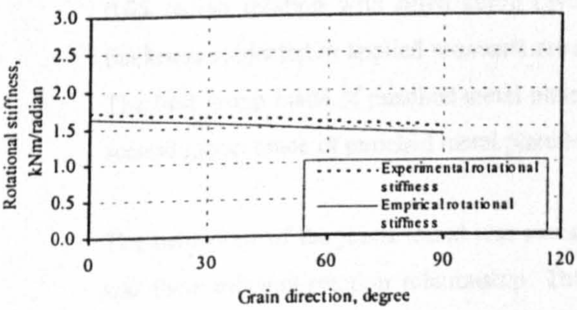
In Figure 8.25, a comparison of rotational stiffness versus grain direction curves between experimental and empirical (i.e. equation 8.7) results for various joints with different grain direction at rotation levels 0.01 radian to 0.05 radian are represented. There was a good agreement between the empirical model and experimental results.



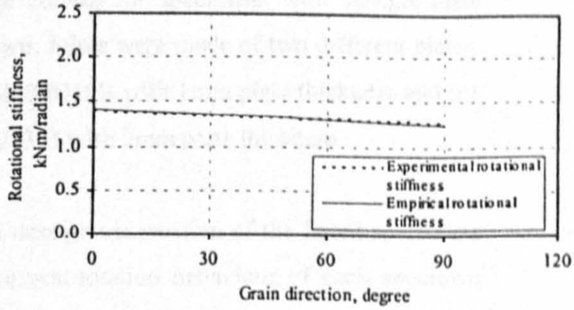
(a) Characteristics at 0.01 radian.



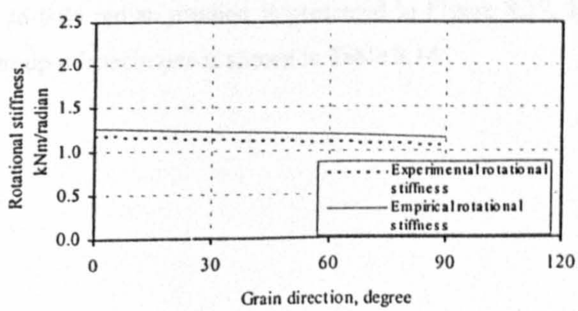
(b) Characteristics at 0.02 radian.



(c) Characteristics at 0.03 radian.



(d) Characteristics at 0.04 radian.



(e) Characteristics at 0.05 radian.

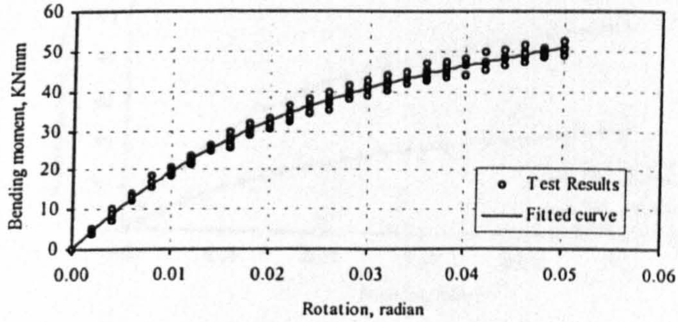
Figure 8.25 Comparison of rotational stiffness vs grain direction between experimental and empirical (i.e. equation 8.7) results.

8.4.4 Effects of plate thickness

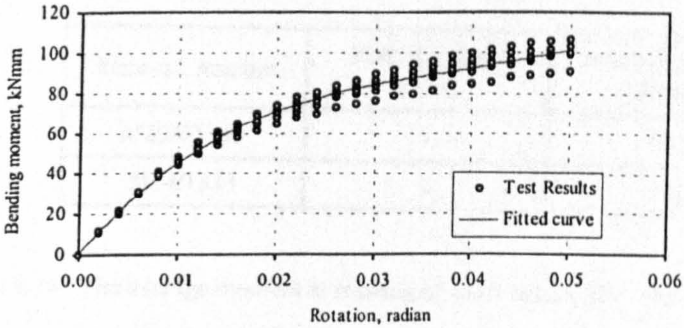
Tests were carried out to determine the influences of plate thickness on the performance of the punched metal plate timber joints subjected to applied moments. The test samples were generally made of two pieces of timber dimensioned as 65mm×300mm and 65mm×133mm by 45mm thickness. The punched metal plate type used in construction of testing specimens was M20/0310B-101mm×25mm×1mm for 1mm plate thickness group and M14/1333 for 2mm plate thickness group. The specimens were loaded to failure in bending. All joint specimens were manufactured using material as explained in chapter 3.

In this section the effect of plate thickness on the rotational stiffness characteristics of the joints were analysed in detail. In Figure 8.26 typical non-linear moment-rotation curves up to 0.05 radian rotation with fitted curve (average curves) for specimens with various plate thickness subjected to applied moments are shown. Joints were made of two different plates. The first group made of punched metal plates M20/0310B with 1mm plate thickness and the second group made of punched metal plate M14/1333 with 2mm plate thickness.

The behaviour of the joints tested was assessed through observation of the failed specimens and their moment-rotation relationship. The moment-rotation behaviour of each specimen was examined and third order polynomial equation was fitted to define the curve. A comparison of joints performance and their moment-rotation relationships in relation to the plate thickness up to 0.05 radian rotation is presented in Figure 8.27. The average induced moment for each group of specimens is shown in Table 8.14.



(a) 1mm plate thickness.



(b) 2mm plate thickness.

Figure 8.26 Moment-rotation behaviour of joints with various plates thickness subjected to applied moments.

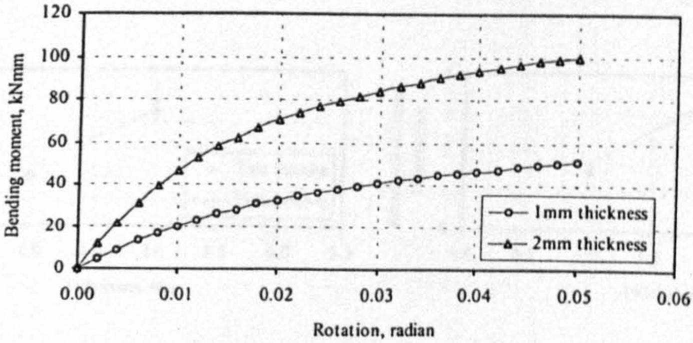


Figure 8.27 A comparison of joints performance in relation to plate thickness tested.

Plate ref. number	Plate thickness (mm)	Average moment (kNmm)
M20/0310B	1	50.8
M14/1333	2	100

Table 8.14 The average moment at rotation of 0.05 radian for various plate thickness.

It was observed that the plate thickness had significant effects on the performance of the joints. All joints studied behaved in similar manner. They showed a non-linear response from beginning up to the failure load.

8.4.4.1 Rotational stiffness characteristics of the joints

Similar method of analysis used for the number of bites was applied to the plate thickness. The equations obtained are tabulated and presented in Table 8.15. These equations was solved and empirical model (i.e. equation 8.8) describing the rotational stiffness of punched metal plate timber connections with different plate thickness was developed. Figure 8.28 represents results of rotational stiffness versus plate thickness in the joints at rotation levels of 0.01 to 0.05 radian.

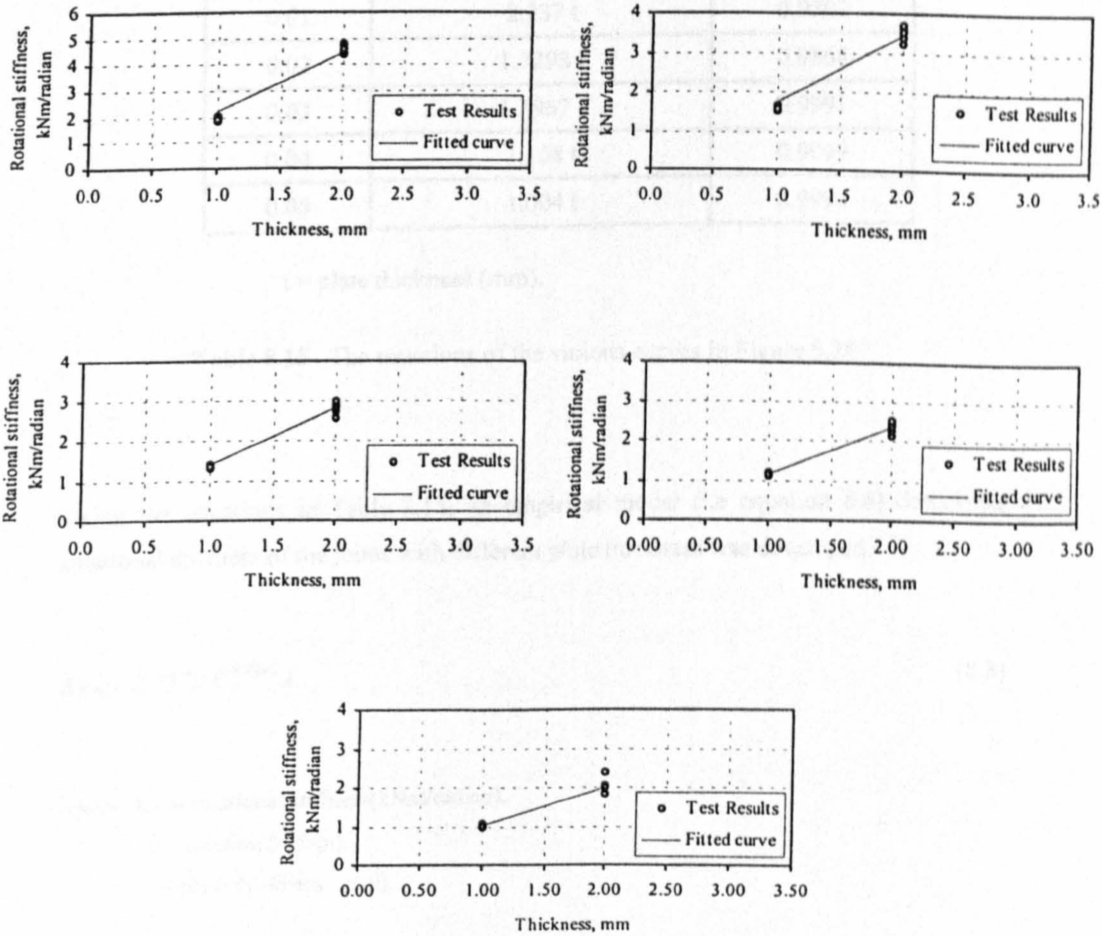


Figure 8.28 Rotational stiffness sustained in the joint versus thickness of plate.

Rotation, θ (radian)	Rotational stiffness (kNm/radian)	Coefficient of correlation, R^2
0.01	2.237 t	0.9702
0.02	1.7298 t	0.9868
0.03	1.3967 t	0.9991
0.04	1.168 t	0.9999
0.05	1.004 t	0.9993

t = plate thickness (mm).

Table 8.15 The equations of the various curves in Figure 8.28

Using the equations in Table 8.15, an empirical model (i.e equation 8.8) describing the rotational stiffness of the joints with different plate thickness was developed.

$$K_\theta = 0.2379\,\theta^{-0.4949}\,t \qquad (8.8)$$

where K_θ = rotational stiffness(kNm/radian).

θ = rotation (radian).

t = plate thickness (mm).

In Figure 8.29, the effect of plate thickness on the performance of the connections with respect to the rotational stiffness sustained by them at rotation levels of 0.01 to 0.05 radian are shown.

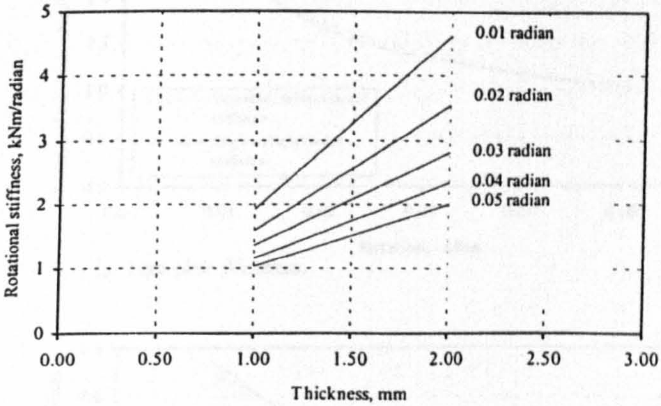
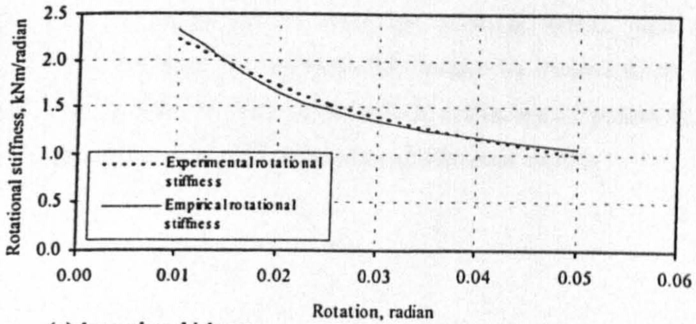


Figure 8.29 Rotational stiffness vs plate thickness in the joints.

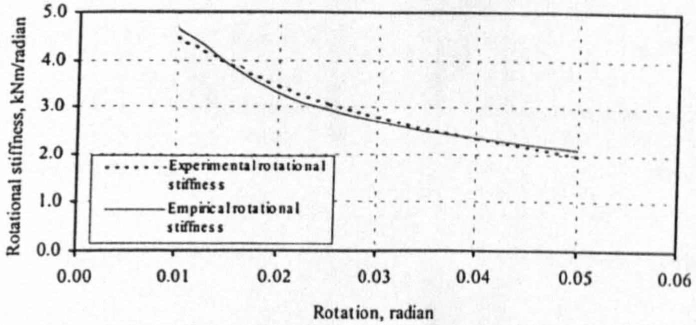
It is clear that the rotational stiffness were dependent on the plate thickness in the joints. Increasing the thickness of the plate will increase the rotational stiffness of the joints. The rate of increasing in rotational stiffness is approximately linear. At low rotation level, the rotational stiffness was high comparing with high rotation level. The rate of increasing in the rotational stiffness was reduced as the rotation levels were increased.

In Figure 8.30, a comparison of rotational stiffness versus rotation curves between experimental and empirical (i.e. equation 8.8) results for various joints with different plate thickness are represented. The agreement between the empirical model and experimental observation was good.

In Table 8.16 Comparison between the experimental and empirical (i.e. equation 8.8) rotation stiffness at various rotation levels 0.01 to 0.05 radian for the various plate thickness in the joints are shown.



(a) 1mm plate thickness.



(b) 2mm plate thickness.

Figure 8.30 Comparison of rotational stiffness vs rotation curve between experimental and empirical (i.e. equation 8.8) results.

Plate Number	Plate thickness (mm)	Rotation level (radian)	Empirical Rotational stiffness (kNm/radian)	Experimental Rotational stiffness (kNm/ radian)	Percentage of Error (%)
M20/0310B	1	0.01	2.324	2.237	4
M14/1333	2	0.01	4.648	4.474	4
M20/0310B	1	0.02	1.649	1.73	-5
M14/1333	2	0.02	3.298	3.46	-5
M20/0310B	1	0.03	1.349	1.397	-3
M14/1333	2	0.03	2.698	2.793	-3
M20/0310B	1	0.04	1.17	1.168	0
M14/1333	2	0.04	2.34	2.336	0
M20/0310B	1	0.05	1.048	1.004	4
M14/1333	2	0.05	2.096	2.008	4

Table 8.16 Comparison between empirical and experimental rotational stiffness at rotation levels of 0.01 to 0.05 radian for various plate thickness in the joints.

In Figure 8.31, a comparison of rotational stiffness versus plate thickness between experimental and empirical (i.e. equation 8.8) results for various joints with different plate thickness at rotation levels of 0.01 radian to 0.05 radian were represented. There was a good agreement between the empirical model and experimental results.

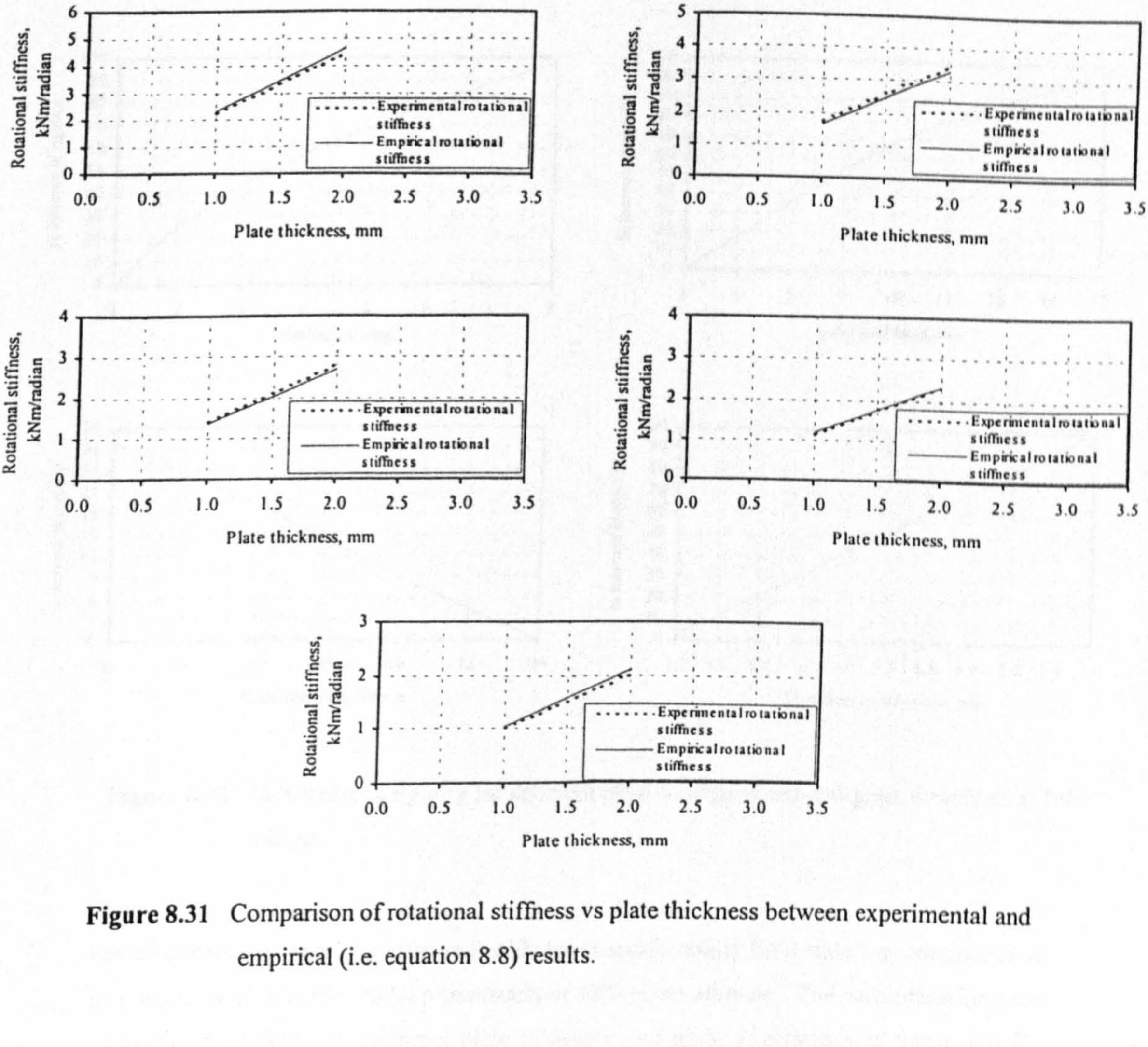


Figure 8.31 Comparison of rotational stiffness vs plate thickness between experimental and empirical (i.e. equation 8.8) results.

8.5 THE ROTATIONAL RIGIDITY OF THE JOINTS

In Figure 8.32 the percentage change in rotational rigidity of punched metal plate joints with different configurations and grain directions at rotation of 0.01 radian are shown. Joints with the largest number of bites (i.e. 8 bites) and largest length of bites (i.e. 15mm) were assumed to provide 100% rigidity for the joints considered, for comparison purposes.

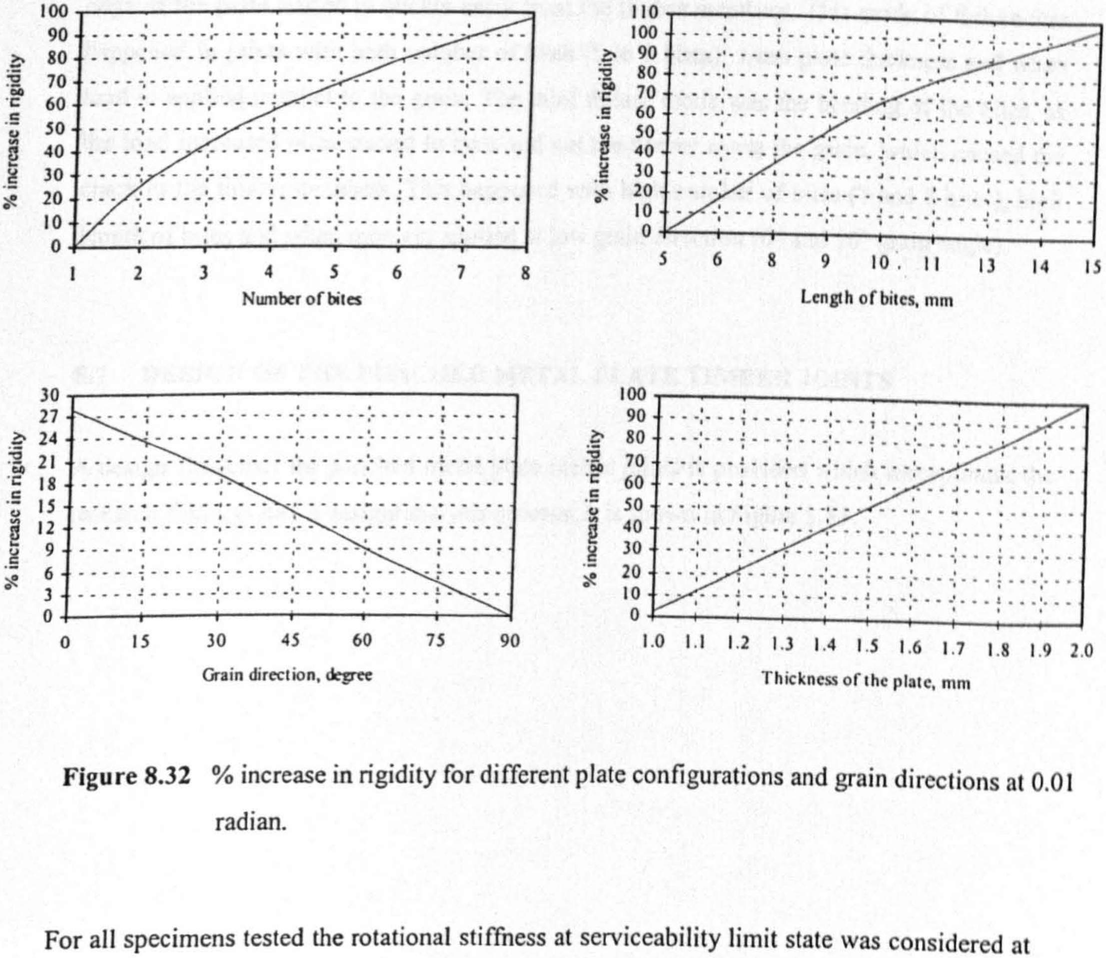


Figure 8.32 % increase in rigidity for different plate configurations and grain directions at 0.01 radian.

For all specimens tested the rotational stiffness at serviceability limit state was considered at rotation level of 0.01 radians (approximately at 40% of the ultimate). The percentage increase in rotational stiffness for different plate thickness and grain directions was linear and for number and length of bites was non-linear. For the number and length of bites the rate of increases in stiffness decreased with increase in the number and length of bites.

8.6 FAILURE MODES

The failure of joints was characterized as ductile, a considerable amount of ductility was generally observed prior to failure. There were three modes of failure. The most common mode of failure was anchorage failure (teeth withdrawal); as the load increased the toothed-plates started to peel away from the timber members. This mode of failure was common in joints made with low number of bites (1 to 4 bites), low bites length (5mm and 10mm), 1mm plate thickness. The second failure mode was plate buckling; as the load increased the top edge of the plate started to buckle away from the timber members. This mode of failure was happened in joints with high number of bites (5 to 8 bites), 1mm plate thickness and when load is applied parallel to the grain. The third failure mode was the bending of the bites, as the load increased bites started to bent and cut the timber along the grain, which caused the crack in the timber members. This happened with high number of bites (7 and 8 bites), high length of bites and when moment applied at low grain direction (0° and 30° grain angle).

8.7 DESIGN OF THE PUNCHED METAL PLATE TIMBER JOINTS

A design flowchart for punched metal plate timber joints is provided which incorporates the research findings into a design/analysis process. It is shown in Figure 8.33.

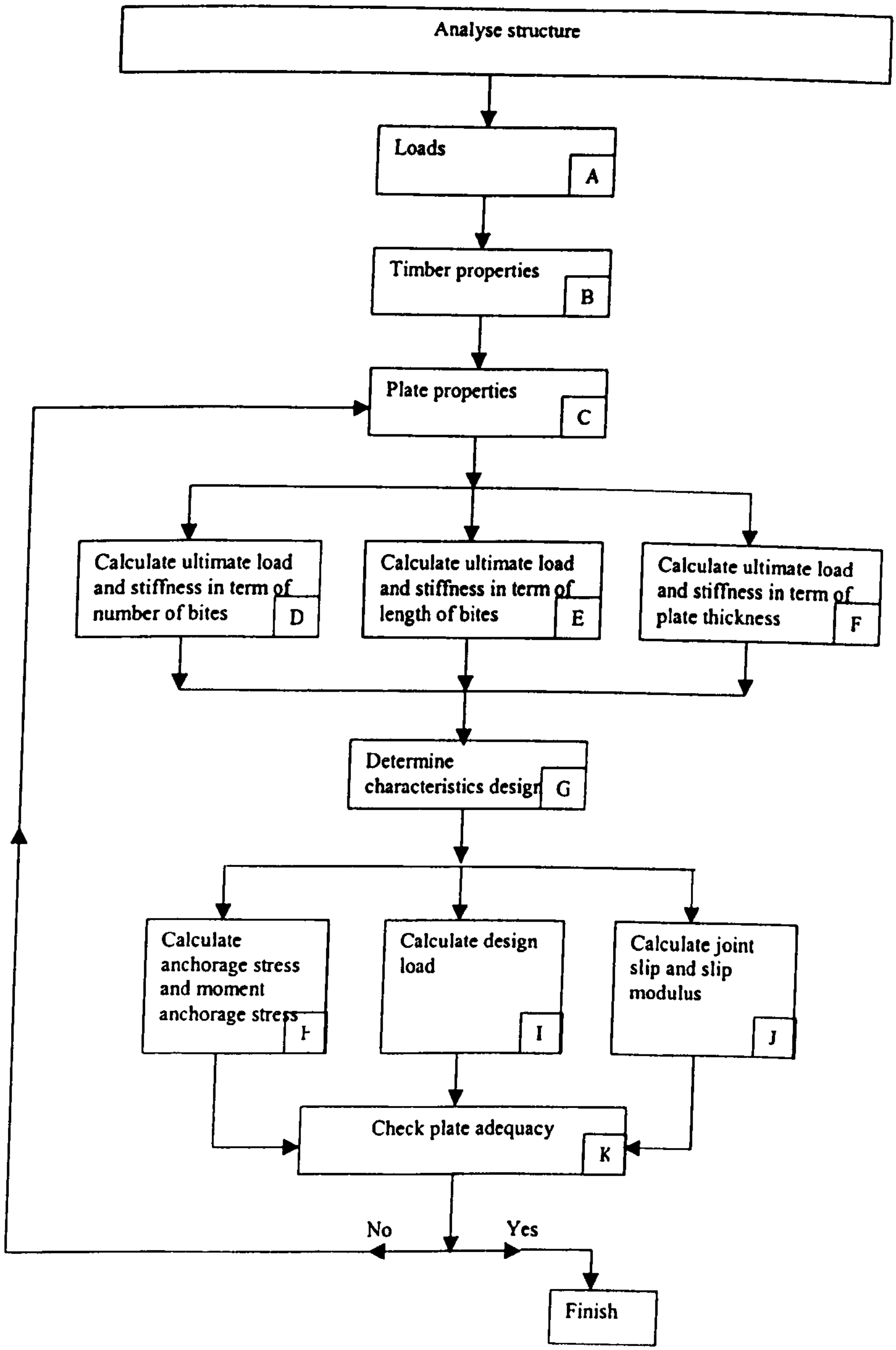


Figure 8.33 Design flowchart for punched metal plate timber joints.

In Figure 8.33, Block (A) is concerned with the loading properties such as type of load (tension, compression or moment load), direction of the load to the grain of the timber, duration of the load, load and deformation rates. Block (B) is concerned with timber properties such as timber species, geometry of the timber, grain direction, moisture content, and density of the timber. Block (C) is concerned with the selection of the appropriate plate size.

The calculation of the ultimate load and stiffness of the joints with different parameters takes place at Blocks (D), (E), and (F). The purpose of block (G) is to calculate the characteristic loads. The characteristic load is calculated using the minimum value of ultimate loads from Blocks (D), (E), and (F) using equations in chapter 5 and 6.

The characteristic design load calculation takes place at Block (I) with the application of the safety factor. The calculation of anchorage stress and moment anchorage stress takes place at Block (H) and joint slip takes place at Block (J). If the plate size is not satisfactory then the process is repeated from Block (C).

8.8 SUMMARY

In this chapter, details of experimental work carried out to study the moment-rotation characteristics of the punched metal plate timber connections, using joints with different parameters such as number of bites, length of bites, grain direction and thickness of the plate. The specimens tested were subjected to applied moment force up to failure.

From the results obtained, it was found that the number of bites, length of bites, the grain direction and the plate thickness in the joints have a significant effects on the moment-rotation characteristics of the joints. Increasing number of bites, length of bites, thickness of plate and decreasing angle of grain direction would increase the moment capacity and rotational stiffness of the joints. The percentage increase in rotational stiffness at serviceability limit state for different plate thickness and grain directions was linear and for number and length of bites was non-linear. For the number and length of bites the rate of increases in stiffness decreased with increase in the number and length of bites.

The failure of joints was characterised as ductile, a considerable amount of ductility was generally observed prior to failure. There were three modes of failure, the most common mode of failure was anchorage failure (teeth withdrawal); as the load increased the toothed-plates started to peel away from the timber members. The second failure mode was plate buckling, as the load increased the top edge of the plate started to buckle away from the timber members. The third failure modes was the bending of the bites, as the load increased bites started to bent and cut the timber along the grain.

Empirical models describing rotational stiffness characteristics of joints with different parameters (number of bites, length of bites, grain direction, and plate thickness) and moment anchorage stress of the joints with different number of bites subjected to applied moment were developed and compared well with the experimental results.

CHAPTER NINE

CONCLUSION AND RECOMMENDATIONS FOR FUTURE WORK

9. CONCLUSION AND RECOMMENDATIONS FOR FUTURE WORK

9.1 Conclusions

Most failures in timber structures occur at joints. The deformations of the joints are responsible for the overall deformation of most timber structures. The serviceability and the durability of a structural system depends mainly on the performance of the joints connecting the elements.

This research was conducted to study the behaviour of punched metal plate timber connections and to examine some of the main factors affecting the connection performance. It details experimental and analytical work investigating the load-displacement and moment-rotation characteristics of the punched metal plate timber connections in which the effects of factors such as number of bites, length of bites, plate thickness and orientation and timber grain directions were studied. Based on the analysis of the results and observation of the strength and stiffness characteristics and failure modes of the connections, the following conclusions are drawn:

1. In terms of transferring axial and shear forces and moments between the connected members, It is feasible to use punched metal plates at the joints of timber structures. These joints are capable of acting as tension, compression and moment resisting members.

2. Although it is time and money consuming, empirical destructive tests such as tension, compression and moment are necessary for determination of strength and stiffness characteristics of the punched metal plate timber joints. Simple but effective test methods were derived in this research.

3. The load-displacement and moment-rotational characteristics of the joints tested were non-linear.

4. The shape of the load-displacement is influenced by factors such as; number of bites, length of bites, thickness of the plate, plate direction, grain direction and loading and

deformation rates. Hence, all these factors have significant effects on the load-displacement characteristics of the joints.

5. Failure in the timber structure is generally of two types. The failure in the plated joints is in general ductile with significant plastic deformation, whilst the failure mode of the timber itself is brittle. Therefore, having a timber structure designed with connected joints that permits flexibility, to a certain degree, is very important in order to maintain safety and avoid sudden failure.

6. Failure modes :

(1) For joints subjected to compression loading 4 modes of failures were observed;

a. The most common mode of failure was anchorage failure (teeth withdrawal). As the load increased, plate started to peel away from the timber members at their lower ends. This peeling progressed upward until the plate withdrew completely. This mode of failure was common in joints made with low number of bites (1 to 5 bites), low bites length (5mm and 10mm), 1mm plate thickness and when load was applied at low grain direction (0° and 30°).

b. The second failure mode was plate buckling, as the load increased the middle of the plate started to buckle. This mode of failure occurred in joints with high number of bites (7and 8 bites) and in joints where the load was applied parallel to the grain.

c. The third failure mode was the closure of the gap between the connected members. This mode of failure happened in joints with high number of bites (6 to 8 bites), high bites length (15mm and 20mm), 2mm plate thickness and when load was applied at low grain direction (0° and 30°).

d. The fourth failure mode was timber failure. This mode of failure occurred in joints with high stiffness i.e. with high number of bites (7and 8 bites), high bites length (15mm and 20mm), 2mm plate thickness and when load is applied perpendicular to the grain.

(2) In the case of joints subjected to tensile load, the most common failure mode was anchorage failure (teeth withdrawal), whatever the configuration of the plate or the grain direction.

(3) For joints subjected to applied moment 3 modes of failure were observed;

a. The most common mode of failure was anchorage failure (teeth withdrawal); as the load increased the toothed-plates started to peel away from the timber members. This mode of failure was common in joints made with low number of bites (1 to 4 bites), low bites length (5mm and 10mm), 1mm plate thickness.

b. The second failure mode was plate buckling; as the load increased the top edge of the plate started to buckle away from the timber members. This mode of failure happened in joints with high number of bites (5 to 8 bites), 1mm plate thickness and when load is applied parallel to the grain.

c. The third failure mode was the bending of the bites, as the load increased bites started to bent and cut the timber along the grain, which caused the crack in the timber members. this happened with high number of bites (7 and 8 bites), high length of bites and when moment applied at low grain direction (0° and 30° grain angle).

7. Under short duration loading, the load rate and deformation rate have similar effect on the punched metal plate timber joints, especially in the case of compression. The strength and stiffness of the joint increased with increase in the load rate or deformation rate.

8. The stiffness of the joint under both compression and tensile loading was increased with increasing in the number of bites, bites length and thickness of plate and was decreased with increasing the plate and the grain directions to the applied load.

9. The rate of increase in the stiffness of the joints was increased with increase in the number and/or length of the bites and with decreasing the grain and/or plate orientations. With increasing the number of bites, the rate of increase in the stiffness of the joints was

approximately linear under tensile loading and non-linear under compression loading. The stiffness of the joints almost doubled when the thickness of the plates was doubled.

10. The punched metal plate timber joints provide partial rotational resistance when subjected to applied moments. The moment capacity and rotational stiffness of the joints increased with increases in the plate stiffness such as number of the bites, length of the bites, and plate thickness and decreased with increases in the grain directions. The percentage of increase in the rotational stiffness at serviceability limit state was linear with increases in the plate thickness and with decreases in the grain directions, and was non-linear with increases in the number and/or the length of the bites. For the number and the length of bites the rate of increases in stiffness decreased with increase in the number and length of bites.

11. The number of bites is one of the most important parameter affecting the performance of the joints. Specially, when joints were subjected to compressive loading. Increasing the number of bites in the joints was more effective than increasing the length of the bites under both tension or compression loadings.

12. The grain direction has a large effect on the performance of the joints under tensile loading than under compression loading.

13. The effectiveness of the grain direction at low displacement levels under tensile loading was low compared with the number of bites. As the displacement levels increased, the effectiveness of the grain direction was increased. At high displacement levels, the grain direction importance was more than the number of bites importance.

14. Empirical models were developed to calculate the load carrying capacity of the joints subjected to various deformation rates.

15. Empirical models were developed to calculate the stiffness of the joint based on load-displacement behaviour. Different models were developed to simulate the effects of the grain direction or plate parameters (number of bites, length of bites, thickness of plate or teeth direction).

16. Empirical models were also developed to simulate, the moment-rotation behaviour and moment anchorage stress values of the punched metal plate connected timber joints with good accuracy.

17. The developed empirical models can be used by other researchers for comparison and the test results can be used as a database for future research.

9.2 RECOMMENDATIONS FOR FUTURE WORK

Although timber has been used as a structural material for many years, a number of problems that are related to the behaviour and strength of timber structures and their components remain to be solved. The future of the timber engineering industry will depend not on the timber but on its method of connection. Research must be carried out to find new methods of connection to enable the basic material to be used more efficiently. The object of this section is to outline the areas for research and information needed on the characteristics, performance, and design of punched metal plate timber joints.

1. Testing of a range of full-scale trusses made with punched metal plate timber fasteners to determine their structural characteristics and failure modes for comparison with the tested joints.

2. Determination of the dynamic behaviour of the punched metal plate timber joints under cyclic loading conditions.

3. To investigate the behaviour of punched metal plate joints subjected to various loads under medium-term and/or long-term loadings.

4. To examine the effect of timber thickness in the joints. More research is needed to verify if timber members of different thickness would show similar results on the behaviour of the joints with different parameter examined.

5. Further research is needed to include environmental effects on the behaviour of punched metal plate timber joints.

6. To examine the effects of various parameters using different species of timber and/or different plates.

7. To investigate the behaviour of the joints subjected to other loading, such as combined loading and/or torsion.

8. To carry out an economical viability analysis on the implementation of semi-rigid characteristics in the design-analysis process.

9. To examine the effects of the gap between the connected members on the behaviour of the punched metal plate timber joints.

10. To determine the influence of the position of the bites on the behaviour of the joints.

11. Further research should be conducted into the improvement of connection stiffness, which could involve various parameters and plate configurations.

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