Geometric Non-Linear Behaviour of Single Shear Bolted Joints

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Summary

Findings are presented of the first stage of an investigation of second-order effects that influence the resistance and stiffness of single shear bolted joints. These effects develop as a result of joint deformation and the rotation of all, or part, of the bolt. A two-dimensional finite element model incorporating these effects is introduced and predicted behaviour compared to laboratory test results of pre-tensioned M16 single shear joints. The model is shown to accurately predict the load-slip curve, giving better predictions of resistance than the present Eurocode design equations indicating potentially underutilised strength reserve. Furthermore, the model allows the individual components of the second order effects to be quantified separately.

1. Introduction

Second order effects in bolted timber connections, namely the ‘rope effect’ (axial force in the fastener), rotational constraint (due to washer, head and nut) and friction between adjoining timber surfaces, represent a significant load resistance reserve over and above that calculated by Johansen theory. Some of these effects have now been incorporated into Eurocode 5 (EN 1995-1-1) design equations, but there may still remain better ways to utilise this strength reserve for design. Furthermore, their influence on joint slip behaviour has not yet been rigorously researched.

A two-dimensional finite element model has been used to study these effects and the predictions compared to laboratory test results using properties obtained from fastener embedment and washer embedment tests. The investigation represents the preliminary work of a wider study: the model and the findings will serve in the development of a complete three-dimensional model of timber joints with multiple bolts that is able to account for these second order non-linear effects and their interaction with fracture as the limiting factor of joint resistance. Such a model will be useful, when validated and calibrated against laboratory data, to research joint behaviour in more detail without the need for extensive testing programmes.

To take into account these effects, a geometric non-linear analysis (large deformation, contact and material non-linearity) has to be performed. With this the equilibrium forces and moments are calculated for the deformed system. Plasticity in the bolt is also modelled, but shall not be further considered in this paper. Similar models have been presented by Nishiyama and Ando (2003) and Sawata and Yasumura (2003). A geometric nonlinear analysis considering the rope effect and rotational constraint in dowel type joints was also performed by Erki (1991).

2. The Beam and Spring Model

The commercial package ANSYS was used to create the two dimensional model, which is capable of performing geometric as well as material non-linear analysis. The general configuration is shown in Fig 1. The bold lines show the fastener, nut and washer and shaded areas represent the two adjoining timber members, which are actually modelled with timber embedment springs (shown by the saw-tooth lines). The components are:

a) Fastener

The fastener is represented by regular beam elements with circular cross section, which allow for elastic-plastic bending, axial tension, stress stiffening effects and large deformation analysis. The tension yield strength is determined by tension tests of bolts, but for the results presented here the elastic limits were not exceeded and an elastic modulus of 210 kN/mm^2 has been assumed.

b) Washer, head and nut

The washer, head and nut are modelled with infinitely stiff beam elements, which ensure no flexure occurs. This behaviour is assumed for simplicity of model formulation. Although slight bending was observed in tests, it is not expected that this will have significant influence on overall joint behaviour. The washer is linked with the bolt shaft in the global Y-direction, allowing it to rotate independently to the head and nut. Therefore the rotational constraint of the fastener results from the moment that is applied through the nut to the washer.

c) Timber embedment for fastener

The timber embedment for the fastener has been modelled with two pairs of elastic-perfectly plastic springs arranged below and above the fastener. Properties are calculated from the results of embedment test data, from which the embedment strength and initial foundation modulus are taken. One of the pairs represents timber deformation in the global Y-direction and the other in the global X-direction. Contact elements have been used to model the interaction between the deformed fastener and the timber-embedment spring nodes (filled circles in *fig 1*). Therefore it is possible to take into account both an oversized bolt hole and a slack washer.

d) Timber embedment for washer

The same applies for the embedment underneath the washers. The behaviour of the springs is described by bi-linear load-slip curves according to the compressed area that they are representing underneath the washer. To guarantee that each washer embedment spring moves with the washer, they are coupled with the global vertical displacement of the washer.

The Newton-Raphson method was used to perform the non-linear analysis and the whole model is displacement controlled. A fixed displacement is assigned to the springs' end nodes on the right hand side timber to simulate the overall joint displacement (hollow circles). For each time step, load is calculated from the summation of forces in the vertical springs on the right hand side timber.

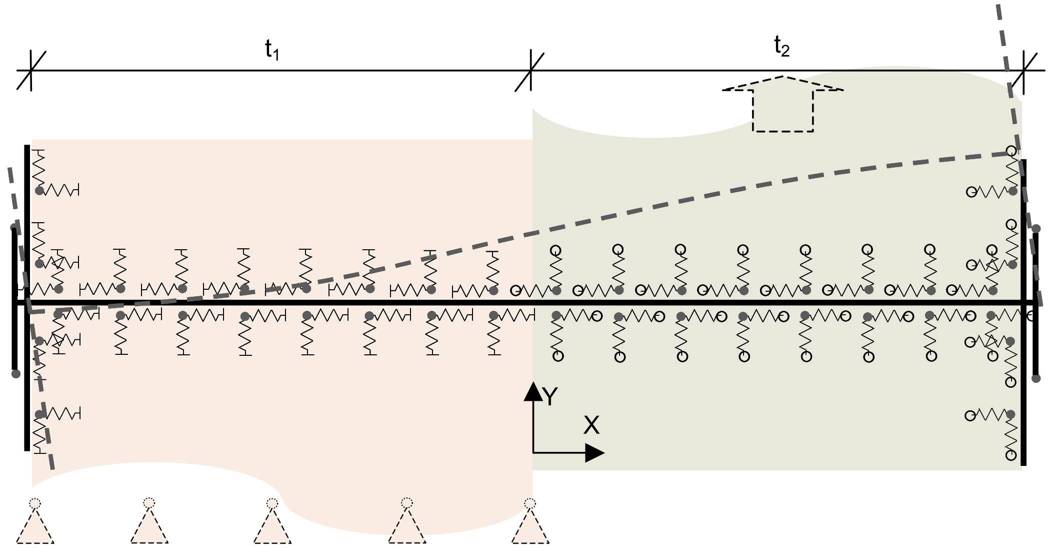

Fig 1 Schematic of model configuration

The model is set with the following parameters: bolt diameter (d), timber thicknesses (t_1 , t_2), bolt hole oversize, washer inner and outer diameter, possibility of slack washer, bolt preload, together with material parameters obtained from:

a) Fastener embedment tests according to BS EN 383:1993 (embedment strength and foundation modulus – values w_{02} and w_{04} are used)

b) Washer embedment tests (embedment yield strength, foundation modulus and post-yield hardening gradient)

Model outputs are obtained in accordance with EN26891:1991 (initial joint stiffness determined from the modified initial slip) and EN 26891:1991 (resistance at a displacement of 15 mm).

3. Laboratory Tests

For the laboratory tests presented in this paper, M16 (d = 15.6 mm) joints were manufactured with an edge-distance of 55 mm ($>3d$) and an end distance of 128 mm ($>7d$) to prevent splitting of the specimens. Eccentricity of the applied load was minimized by using notched steel plates joining the timbers to the test machine. It was attempted to minimise friction between the timbers by the use of graphite powder on the sliding surfaces. The timber used was C16 Sitka Spruce.

An inserted strain gauge was used to measure the axial force in the centre of the bolt, having been previously calibrated against know direct tension loads. Testing the bolt under in bending load confirmed that the gauge measurement was negligibly sensitive to flexure of the bolt. For these tests, the faster was preloaded by tightening the bolt to 250 N. During the tests, the global rotation of the bolt was calculated from the measurement of two displacement transducers arranged vertically under a rigid lever fixed to the bolt's end.

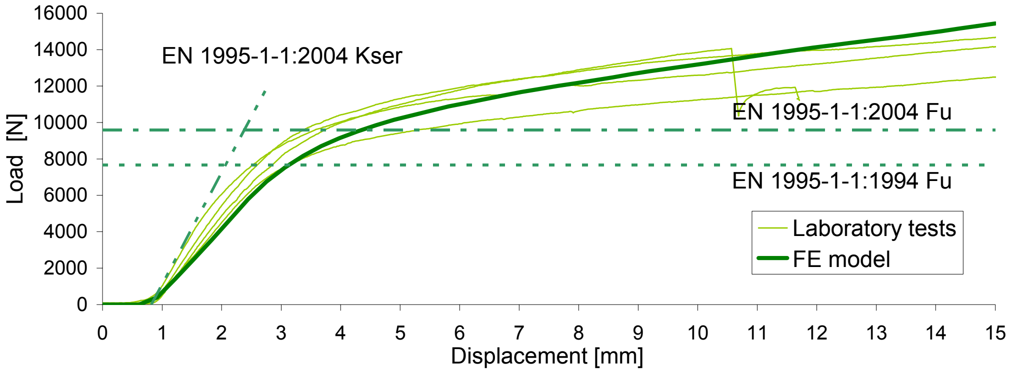

Fig 2 Laboratory measurements and finite element model prediction (load-slip)

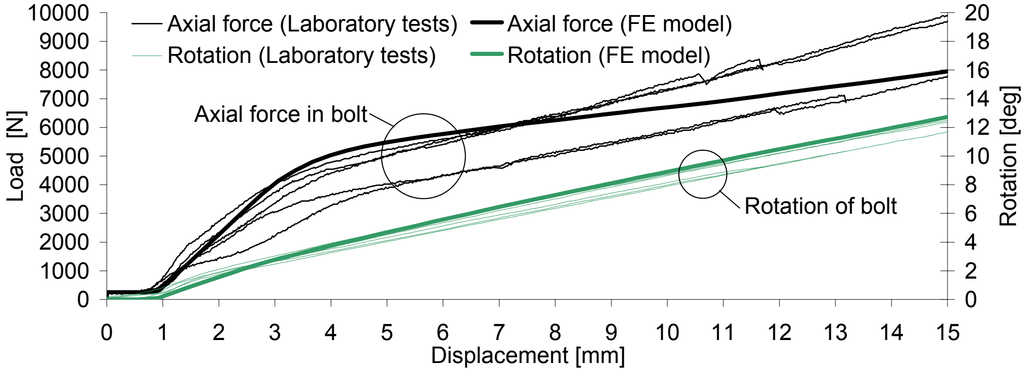

Fig 3 Laboratory measurements and finite element model predictions (bolt load and rotation)

Fig 2 shows the load-slip relationship for five replicate tests in comparison to mean values from Eurocode 5 prediction. Measurements of bolt axial force and bolt rotation are shown in *fig 3*. To compensate for variation in exact bolt hole oversize and starting position the test series curves have been shifted to the same value of initial slip.

The results confirm that the improvement made in the published Eurocode 5 to take into account the 'rope effect' compared to the 1994 draft results in better prediction of the joint resistance. However, the resistance still appears very conservative. This stems from the fact that the strength reserve is not only caused by the 'rope effect' but also by the increasing effective embedment length of the fastener, which results from the rotational constraint.

4. Discussion and Conclusion

The graphs also show the predictions of the finite model for comparison. In this case, the model does not include calculation of friction between the timbers. The effect of rotational constraint is included which results in a good prediction of the actual load-slip behaviour and joint resistance. In accounting for bolt strength reserve the present code does not consider any influence from unequal timber thicknesses. The strength reserve might be even more pronounced for the unsymmetrical case. Better equations might be found to take into account the rotational constraint in the calculation of the load carrying capacity of bolted joints.

In terms of the joint stiffness, in this case, the Eurocode overestimated the real stiffness while the model underestimated it. This could stem from the neglected friction in the model, as the measures used to remove friction from the laboratory tests might not have been successful.

The rotation of the bolt is predicted accurately by the model, with a slightly steeper gradient in the pre-yield range than afterwards. Agreement between the prediction and measurement of axial force in the bolt was less good, with the model predicting a lower gradient in the post-yield range than observed in the tests.

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