

# DYNAMIC RESPONSE OF TIMBER FLOORS

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**ABSTRACT:** Developments in composite timber construction have been widely used for forming relatively large-span floors. This has also resulted in undue floor vibrations, causing inconvenience to the occupants and requiring the vibrational response of the structure to be considered in more detail during the design process. The problems associated with vibration of floors are not adequately addressed in the current British Standards. The UK National Annex to Eurocode 5 considers the fundamental natural frequency of the floor, the deflection under a unit point load and the unit impulse velocity response. These design criteria have been analysed in this paper and parameters influencing the vibrational behaviour of the flooring system have been investigated by performing parametric studies on floors built with solid timber joists and engineered I-joists. Regarding fundamental natural frequency and deflection, the results show that the floor span and beam height are the critical parameters and the floors built with I-joists have a poorer vibrational performance.

**Key words:** Dynamic response, engineered joists, serviceability, timber floor.

## 1. INTRODUCTION

Structures tend to vibrate when excited. Since the invention of new light timber beam elements (such as I-Joists or parallel-chord trusses) for constructing larger floors, and offering more space for residence, floor vibrations in particular increasingly cause more inconvenience to the occupants. For decades, investigations have been made to evaluate vibrational performance of buildings or structural components and control its effects through appropriate modification of the structural system. The current available design criteria cannot satisfactorily provide adequate solutions in many cases.

The Eurocodes are generally sub-divided into two main categories, the ultimate limit states (ULS) and the serviceability limit states (SLS). The former are associated with the stability and load capacity of structures. The latter have been established to avoid impairment of the buildings, which can lead to excessive deflections or vibrations of the structure, even though non-compliance of the SLS may not cause collapse of the structure.

The vibration of timber floors is regulated by the SLS requirements in Eurocode 5 (EC5) "Design of timber structures". The vibrational performance of the floor is controlled by assuring the fundamental natural frequency to be greater than 8 Hz, and limiting the deflection under unit point load and the unit impulse velocity response. These three requirements are influenced, to different degrees, by several parameters. Investigation is needed to analyse the relevant formulas by performing parametric studies and to identify which parameters contribute more to vibrational performance of floors than the others. This helps to identify what parts of a flooring system need to be modified to eventually improve the dynamic response.

## 2. ANALYSIS OF THE EC5 VIBRATIONAL CRITERIA

The variation in parameters that significantly influence the vibrational criteria, i.e. fundamental natural frequency, deflection under unit point load and unit impulse velocity response, are identified and investigated for the floors built with solid timber joists and engineered I-joists. This study aims to provide information on the difference in vibrational performance between the solid timber joists and I-joists, and on the parameters which influence their response, which can be eventually utilised for the design of timber flooring systems.

The parametric analysis (although at its early stage) is focused on the most commonly used flooring systems in the UK, namely the floors with solid timber joists and engineered I-joists. Geometrical properties are the main difference between solid timber and I-joists. Each parameter in an appropriate formula is gradually increased, while the remaining parameters are kept constant. This procedure is repeated for all the parameters. Three floor dimensions are adopted here by increasing the original dimensions of  $3 \times 4$  m by 15% and 30%, respectively. The floors which are simply supported and one-way spanned have been initially designed according to the appropriate Eurocodes [EC0, EC1-1-1, EC5-1-1, EN 12369-1, EN 338] whereas only the initial width of the solid timber beam has been adjusted for easy comparison with I-beams. All the floors are assumed to be built with solid timber joists or I-joists of  $45 \times 195$  mm, spaced at 400 mm, and 19 mm particleboard for decking. The dead load or the mass per unit area is assumed to be  $51 \text{ kg/m}^2$  or  $0.5 \text{ kN/m}^2$ .

### 2.1 Fundamental Natural Frequency

A higher frequency is basically considered to be positive compared to a lower frequency [Trada Technology]. The fundamental natural frequency is calculated as follows [EC5-1-1]:

$$f_1 = \frac{\pi}{2L^2} \sqrt{\frac{EI_\ell}{m}} \quad [\text{Hz}] \quad (1)$$

where

$EI_\ell$	= Equivalent bending stiffness of the floor about the major axis y-y and $EI_\ell = E_{0,\text{mean}} I_y / s$ [ $\text{Nm}^2/\text{m}$ ];
$E_{0,\text{mean}}$	= Mean characteristic elastic modulus, parallel to the grain [ $\text{N/m}^2$ ];
$I_y$	= Second moment of area about the major axis y-y and $I_y = bh^3/12$ [ $\text{m}^4$ ];
$L$	= Floor span [ $\text{m}$ ];
$b, h, s$	= Breadth, depth and spacing of timber joists [ $\text{m}$ ];
$m$	= Mass per unit area [ $\text{kg/m}^2$ ].

Including all parameters into Eq. (1) yields:

$$f_1 = \frac{\pi}{4\sqrt{3} L^2} \sqrt{\frac{E_{0,\text{mean}} b h^3}{m s}} \quad [\text{Hz}] \quad (2)$$

Figure 1 shows the fundamental natural frequency  $f_1$  monotonically increasing with the increase in  $h$  and  $b$  but decreasing with the increase in  $s$  for the floors built with both solid joists and I-joists. Larger slopes of  $f_1$ - $h$  curves indicate that increasing  $h$  is more effective than increasing  $b$ . The present parametric study also shows a better performance of the floors built with solid timber joists than with I-joists for the same height, width or spacing of the joists. It can also be seen that in all six figures, the floors with longer spans will significantly decrease the frequency  $f_1$ , even below the design limit of 8 Hz. The floor width  $B$  has been considered and increased in all the calculations but is irrelevant to the frequency.

In general, a small percentage change in the floor span  $L$  affects the frequency  $f_1$  more than any other parameters. The height of the joist has the second highest impact. To increase the frequency, the floor span, the mass or the joist spacing need to be decreased, or the modulus of elasticity, the beam width or the height need to be increased.

## 2.2 Deflection Under Unit Point Load

The deflection under unit point load is calculated as follows [NA to EC5-1-1]:

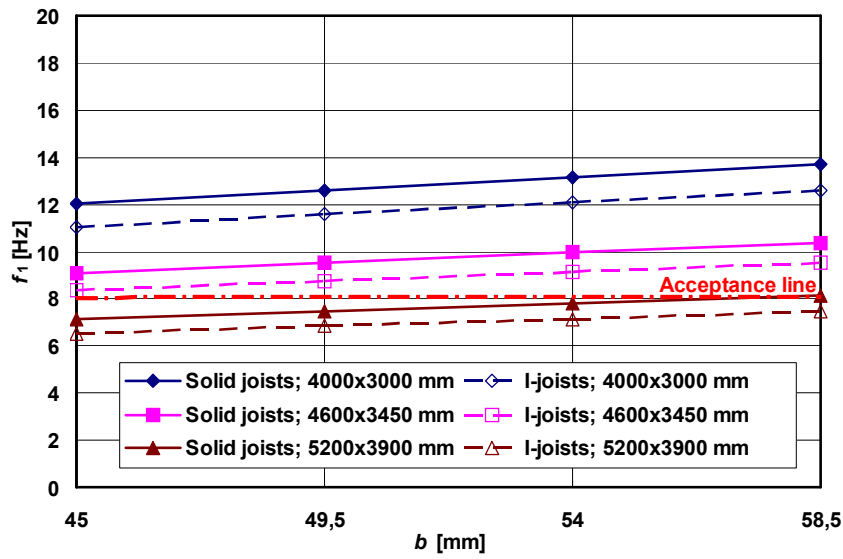
$$a = \frac{k_{\text{dist}} 1000 L_{\text{eq}}^3 k_{\text{shear}}}{48 k_{\text{comp}} EI_{\text{joist}}} \quad [\text{mm/kN}] \quad (3)$$

where

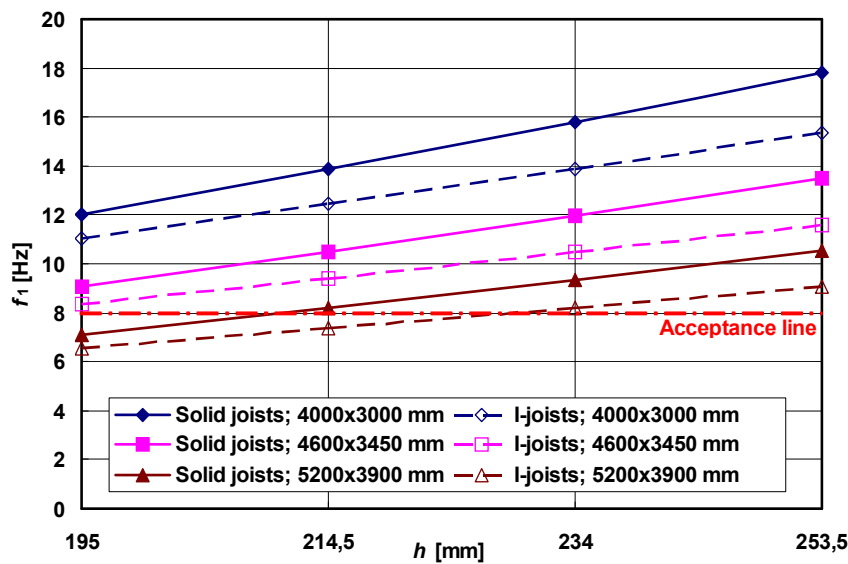
- $k_{\text{dist}}$  = Factor to account for proportion of point load distributed to adjacent joists by floor decking and  
 $k_{\text{dist}} = \max\{[0.42 - 0.09 \ln(14 E_b / s^4)], 0.35\}$ ;
- $E_b$  = Equivalent plate bending stiffness of the floor about the axis x-x parallel to the beam and  $E_b = E_{0,\text{mean,deck}} t^3/12$  [Nmm<sup>2</sup>/m];
- $E_{0,\text{mean,dec}}$  = Mean characteristic elastic modulus of the chosen decking [N/mm<sup>2</sup>];
- $t$  = Thickness of the floor decking [mm];
- $L_{\text{eq}}$  = Equivalent floor span, see EC5, [mm];
- $k_{\text{shear}}$  = Amplification factor to account for shear deflections, see EC5;
- $k_{\text{comp}}$  = Factor to account for composite action between the joists and floor decking, see EC5;
- $EI_{\text{joist}}$  = Equivalent plate bending stiffness of the floor about the major axis y-y and  $EI_{\text{joist}} = E_{0,\text{mean}} I_y$  [Nmm<sup>2</sup>].

Eq. (3) can also be re-written and expanded as far as possible to include more parameters by noticing that  $k_{\text{dist}}$  is often larger than 0.35:

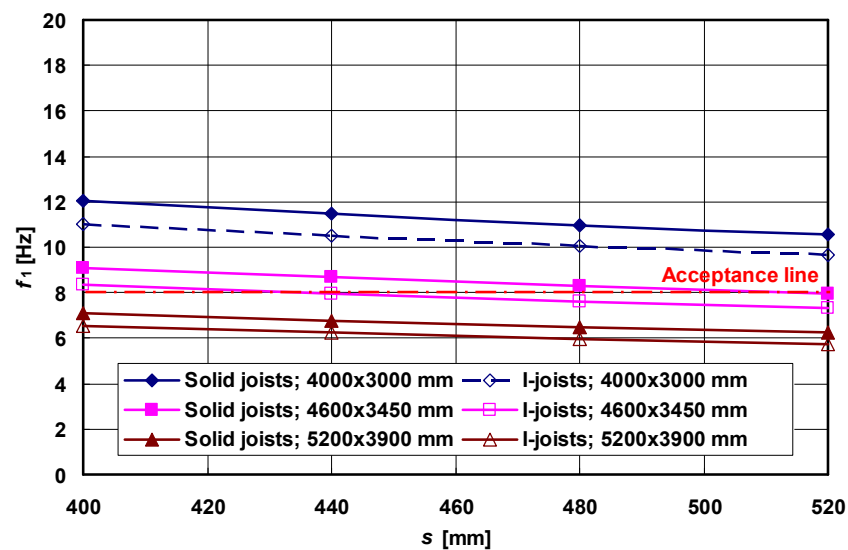
$$a = \underbrace{\left[ 0.42 - 0.09 \ln \left( \frac{7 E_{0,\text{mean,deck}} t^3}{6 s^4} \right) \right]}_{k_{\text{dist}}} \frac{250 L_{\text{eq}}^3 k_{\text{shear}}}{k_{\text{comp}} E_{0,\text{mean}} b h^3} \quad [\text{mm/kN}] \quad (4)$$



a) Relationship between  $f_1$  and  $b$



b) Relationship between  $f_1$  and  $h$



c) Relationship between  $f_1$  and  $s$

**Figure 1:** Fundamental natural frequency for solid timber joists and I-joists with varied  $L$ ,  $B$ ,  $b$ ,  $h$  and  $s$

The results of the parametric study show a better performance of the floors built with solid timber beams compared to the floors built with I-joists; as shown in Figure 2. An increase in the beam width or in particular the beam height will cause a decrease in deflection. An increase in the spacing or especially in the floor size, however, will lead to a higher deflection. A decreased deflection can also be expected by increasing the (equivalent) modulus of elasticity of the beams, or the modulus of elasticity and the thickness of the floor decking. In actual fact, an increase in the thickness of the decking will generally decrease the modulus of elasticity of the decking and this has been considered in this study (due to the use of particleboards) [EN 12369-1]. The most influential parameters on the deflection are, however, the equivalent span of the floor and the height of the beam. The impact of  $E_{0,\text{mean}}$  and  $b$  is the same if both are changed by an equal percentage but is much less pronounced than that of  $h$  and  $L_{\text{eq}}$ .

The deflection has to be smaller than its design value, which is not investigated further in this study since it has a fixed value of 1.75 mm for  $L \leq 4.5$  m and is only dependent on the equivalent floor span in the other cases (§7.3.3 in EC5).

### 2.3 Unit Impulse Velocity Response

The unit impulse velocity response of the floor,  $v$ , should not be larger than its design limit  $v_d$ . The response  $v$  for a floor with overall dimensions of  $L \times B$ , simply supported along all four edges is calculated as (see §7.3.3 in EC5):

$$v = \frac{4(0.4 + 0.6n_{40})}{mLB + 200} \quad [\text{m}/(\text{Ns}^2)] \quad (5)$$

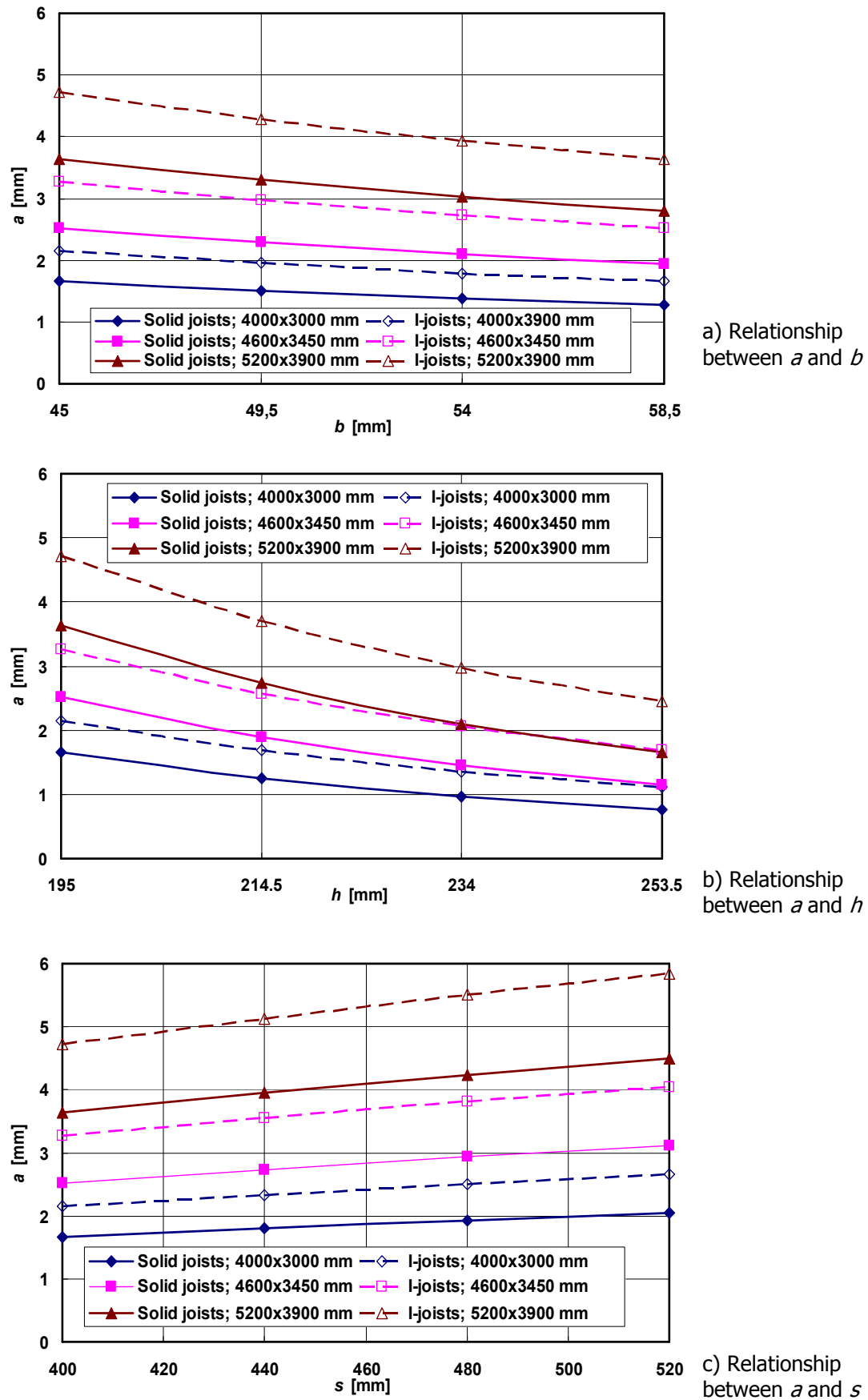
where:

$n_{40}$  = Number of first-order modes with natural frequencies up to 40 Hz and

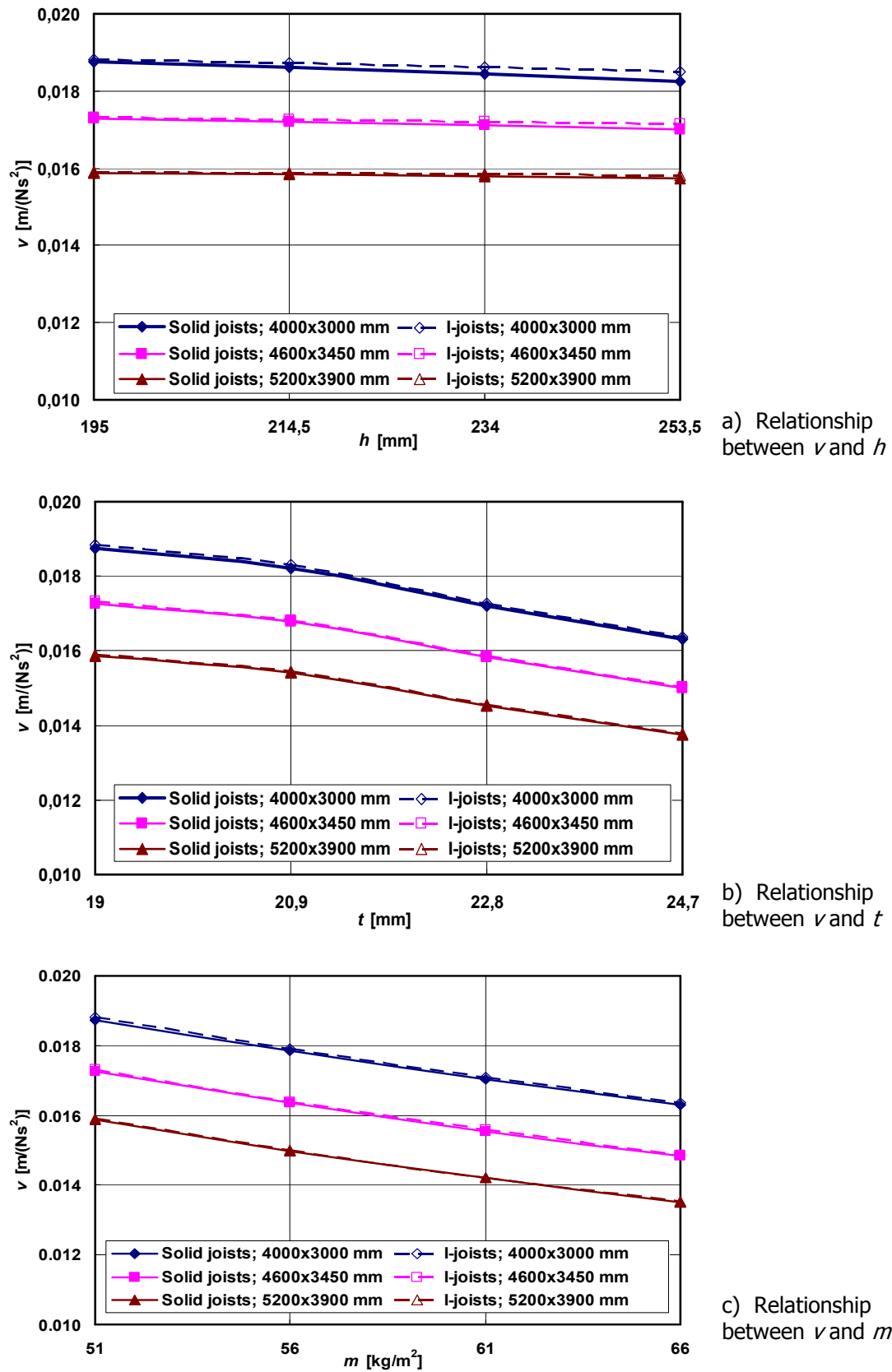
$$n_{40} = \left\{ \left[ \left( \frac{40}{f_1} \right)^2 - 1 \right] \left( \frac{B}{L} \right)^4 \frac{(EI)_\ell}{(EI)_b} \right\}^{0.25} = \left[ \left( \frac{76800L^4 ms}{\pi^2 E_{0,\text{mean}} b h^3} - 1 \right) \frac{E_{0,\text{mean}} b h^3}{E_{0,\text{mean,deck}} t^3} \right]^{0.25} \left( \frac{B}{L} \right) \quad (6)$$

Figure 3 shows the relationships of the velocity response of the floor with some most influential parameters, including the thickness of the floor decking and the floor mass.

Increasing the beam height only slightly decreases the velocity response. An increase in the deck thickness is generally accompanied with a lower value of the modulus of elasticity, and again this has been considered in the calculations. In this example, the I-joists perform just slightly better than the solid timber beams.



**Figure 2:** Unit point load deflection for solid timber joists and I-joists with varied  $L$ ,  $B$ ,  $b$ ,  $h$  and  $s$



**Figure 3:** Unit impulse velocity response for solid timber joists and I-joists with varied  $L$ ,  $B$ ,  $h$ ,  $t$  and  $m$

## 2.4 Design Value of Unit Impulse Velocity Response

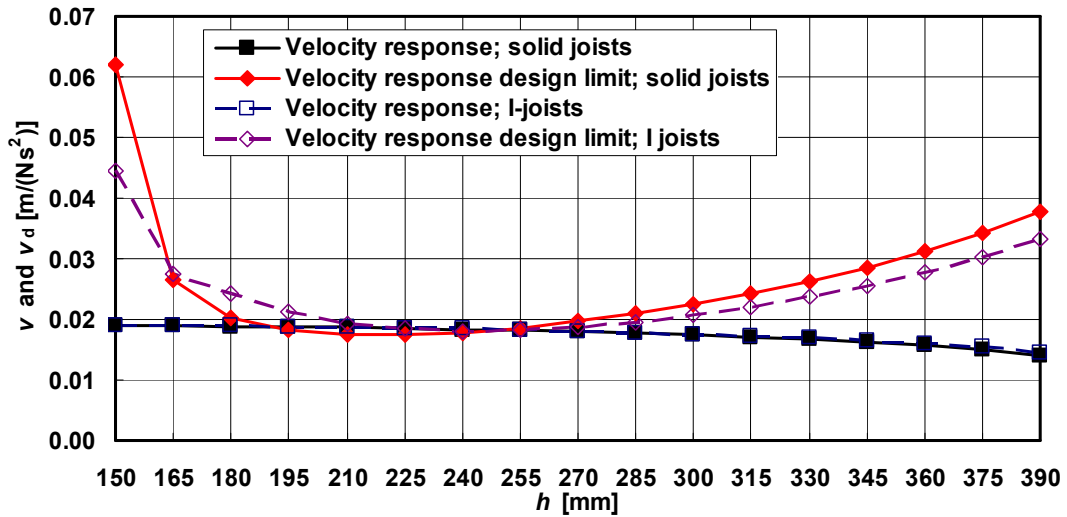
The design value of unit impulse velocity response  $v_d$  is calculated as [EC 5-1-1]:

$$v_d = b_f^{(f_1 \zeta - 1)} \quad (7)$$

where:

- $b_f$  = Parameter for calculating  $v_d$ , see §7.3.3 in EC5;  
 $\zeta$  = Modal damping ratio, which is taken as 0.01 (or 1 %).

The procedure used for this parametric study has also been applied to the equation for the design limit but provides uncertain results. Therefore, it is necessary to extend the investigated range concerning parameter adjustments. Figure 4 shows a plot of the velocity response and its design value versus the beam height. In this case the beam height was set to 150 mm and gradually increased to 390 mm, up by 160%.



**Figure 4:** Unit impulse velocity response and the design limit for solid timber joists and I-joists with varied  $h$

It can be seen that the design limit,  $v_d$ , first sharply decreases until it reaches the minimum of 0.0174 mm/(Ns<sup>2</sup>) corresponding to the height of 225 mm for the solid timber joists, and of 0.0181 mm/(Ns<sup>2</sup>) corresponding to the height of 240 mm for the I-joists. Thereafter, the curve gradually increases. Since the velocity response only slightly decreases, there is a reject zone where the velocity response is higher than its design limit and the design requirement is not satisfied. This parametric study also reveals that the variation of  $v_d$  is uncertain with other parameters, e.g. the beam width.

## 3. DISCUSSION OF RESULTS

The effects of increasing the geometrical properties or the dead load on the fundamental natural frequency, the deflection under unit point load, the unit impulse velocity response and the design limit of unit impulse velocity response are shown in Table 1. The table is also valid for the effects of decreasing the geometrical properties or the dead load. Varying  $E_{0,mean}$ ,  $b$ ,  $h$  or  $s$  will affect  $f_1$ ,  $a$  and  $v$  in a similar way. A



decrease of the floor span is favourable for  $f_1$  and  $a$ , but unfavourable for  $v$ . An increase of  $E_{0,\text{mean,deck}}$  or  $t$  will be favourable for  $a$  and  $v$  but unfavourable for  $f_1$ . Even though an increase in the mass per unit area is unfavourable for the frequency and irrelevant to the deflection, it is advantageous for the velocity response. The width of the floor only influences  $v$ .

**Table 1:** Variation of  $f_1$ ,  $a$ ,  $v$  and  $v_d$  with increasing individual parameters

Parameter	Criteria	$f_1$	$a$	$v$	$v_d$
$E_{0,\text{mean}}$		+	+	+	$\pm$
$E_{0,\text{mean,deck}}$		/	+	+	- or /
$B$		+	+	+	$\pm$
$H$		+	+	+	$\pm$
$T$		/	+	+	- or /
$S$		-	-	-	$\pm$
$L$		-	-	+	$\pm$
$M$		-	/	+	-
$B$		/	/	-	/

**Note:** “+” = positive effect, “-” = negative effect, “ $\pm$ ” = uncertain, “/” = no effect.

The effects on the design value of the velocity response can be exactly contrary to those on  $f_1$ ,  $a$  and  $v$  with regard to parametric changes. The increase of the beam height, for example, favourably affects the fundamental natural frequency and the deflection under unit point load but significantly lowers the design value for the unit impulse velocity response. Although the unit impulse velocity response is decreased, the requirement concerning the velocity response may not be fulfilled because of a higher decrease rate of the design limit (Figure 4). Hence, clear, distinct conclusions regarding the velocity response design limit cannot be drawn.

Comparison of the floors built with solid timber beams with those built with I-joists indicates that using solid timber beams is advantageous for the fundamental natural frequency and the deflection under unit point load since the vibrational performance of the floor corresponding to these two criteria is more satisfactory with the design limit criteria. As for the velocity response, there is little difference between the two types of construction. In practice, I-joists still stand great advantages for building large span floors.

## 4. CONCLUSIONS

The study to date has shown that it is difficult to make a general recommendation about a parameter change which can improve vibrational performance of a timber flooring system. This is due to the fact that no parameter change can have a definite positive or negative effect on all the serviceability criteria simultaneously. In particular, the design limit for the unit impulse velocity response is complex for evaluating whether a parameter change will be beneficial or not. Increasing the moduli of elasticity, the beam height and width, or the deck thickness will always positively affect the frequency, deflection and velocity. Increasing the spacing in general is unfavourable. Changes of the span length and the height of the beam have the largest impact on the frequency and deflection. The highest influence on the velocity is provided by adjusting the deck thickness, the mass and again the floor span. A change in the beam height only has a nominal effect on the velocity response.

The design values are important to fulfil the serviceability requirements and thus should be considered. The difficulty lies in that the design value of the velocity response,  $v_d$ , can be affected even more than  $v$  even though  $v$  is influenced in the same way as  $f_1$  and  $a$  in several cases with regard to individual parameter changes. This may cause serviceability criteria not to be completely fulfilled.

This study also indicates that simple predictions may still not be possible for assessing the improvement of the serviceability behaviour of timber flooring systems, and more comprehensive and understandable formulations for the design limit of the unit impulse velocity response are needed. Extensive experimental investigations are required as well.

At present experimental investigations are being carried out at Napier on the vibrational behaviour of a series of timber floors prefabricated with engineered I-joists according to the existing design rules of EC5 and construction practices for the ultimate and serviceability limit states. Adjustments are made to the tested floors to enhance their vibrational performance, including adding blockings between joists, altering nail spacing and joist spacing, varying dead load, etc. Parameters to be measured include natural frequencies, damping ratios, mode shapes, deflections, velocity responses, accelerations, etc. Theoretical predictions and numerical simulations using FEM software will be compared with the measured data, so as to provide valuable guidance for existing construction practices of timber floors and to further make useful recommendations to the design codes with respect to serviceability design criteria.

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