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A Comparison of Design, Construction and Dynamic Performance of Timber Floors in the UK and Finland

Scientific Report
by Jan Weckendorf

Short Term Scientific Mission
of
COST Action E55
-Modelling the performance of timber structures-

Proposer: Dr. Binsheng Zhang
Host: Dr. Tomi Toratti
Host Institution: VTT Technical Research Centre of Finland

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1. Introduction

A Short Term Scientific Mission (STSM) of COST Action E55 - Modelling the performance of timber structures - has been undertaken for exchanging knowledge and experiences about the dynamic performances of timber flooring structures. Humans in residential or office buildings can sense excessive floor vibrations, which produce a certain level of discomfort. Unsatisfying vibrational floor behaviours are serviceability issues. These issues are not satisfactorily addressed in the current design standards. Furthermore, although the establishment of the Eurocodes provides harmonisation of design criteria within the member countries, this harmonisation is not reached for floor vibration design in different countries such as Finland and UK. The EC5 design criteria are either partly modified (UK National Annex) or completely superseded (Finnish National Annex).

Research in the area of floor vibrations has been continuously carried out at Napier University in Edinburgh of Scotland and at VTT Technical Research Centre of Finland in Espoo, whereas different methods and techniques are used at the two institutes, which are focused on different aspects. The research that has already been undertaken at VTT includes investigating human discomfort due to vibrations of light-weight floors and classifying the structural floor performances. Fundamental natural frequency, acceleration, velocity and dynamic displacement of the flooring systems were the main parameters examined (Talja et al., 2002; Toratti et al., 2002, 2006). The research carried out at Napier University focuses on the effect of structural and non-structural modifications on the dynamic response of timber flooring systems. Natural frequencies, mode shapes, damping ratios and static deflections are the parameters of main interest (Weckendorf et al., 2006, 2007).

In brief, while the research at VTT is especially aimed to assess and classify the floor performances, the research at Napier aims to identify contribution of individual structural and non-structural components on variation in the dynamic response. This has formed a strong basis for the undertaken STSM, for exchanging and enhancing the expertise with respect to different measurement and analysis procedures, and design, construction and assessment methods.

1.1 Objectives

The Memorandum of Understanding (MoU) of COST Action E55 states that "*attributes such as high performance regarding reliability, serviceability and durability are generally not associated with timber as a building material*." One of the main objectives of the Action is to improve "*the knowledge concerning the behaviour of timber structural elements*". Excessive floor vibrations are serviceability issues. The described research projects will provide a better understanding of the problems and show the effect of structural modifications on dynamic floor performances. The MoU further states, "*However, whereas the codes and regulations for the design of concrete and steel have undergone a remarkable modernisation over the last two to three decades, codes and regulations for the design of timber structures are falling significantly behind*." In this STSM it is specifically concentrated on the different design, assessment and construction methods in Finland and the UK due to the fact that reconsideration of the design rules with regard to floor vibrations is required. Contribution to design criteria is continuously made by VTT and is aimed to be also made by Napier University in the near future.

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2. Design Guides for Controlling Floor Vibrations

The Eurocodes have been established to serve as pan-European standards in form of harmonised design criteria within the member countries to build a common basis for design, research and development. The design of timber structures is covered in Eurocode 5 (EC5). The criteria associated with timber floor vibrations are part of the serviceability limit states (SLS) in EC5. National Annexes to EC5 provide the modified or additional design criteria by considering local design aspects.

The design rules in EC5 to control timber floor vibrations are based on the research carried out by Ohlsson (Ohlsson, 1982, 1988). A floor having a fundamental frequency above 8 Hz is considered to be a high-frequency floor, where "*the resultant vibration is made up of a low-frequency semi-static component [...] and a number of resonance dominated components [...], which are of the same magnitude, or larger than, the semi-static component*" (Ohlsson, 1994). Limiting the unit point load deflection of the floor is believed to satisfy the floor performance regarding the semi-static component. The resonance dominated components are to be controlled by limiting the unit impulse velocity response.

Referring to the EC5 it is thus required that for floors with a fundamental natural frequency greater than 8 Hz the deflection under a unit point load and the unit impulse velocity response of the floor are limited. Equations for calculating the fundamental natural frequency, unit impulse velocity response and the velocity limit are provided. A limit for the unit point load deflection and a method for calculating the deflection are not given. The EC5 does not provide guidance for low-frequency floors.

2.1 Design in the UK and Finland

To design the floors with respect to its vibrational performance in the UK, the design rules of EC5 are adopted. Due to the lack of formula and limiting value regarding the deflection criterion in EC5, guidance for determining the deflection and its limit is introduced in the UK National Annex (UK NA to EC5-1-1). Furthermore, the damping ratio for calculating the design limit for the unit impulse velocity response in EC5 has been doubled in the UK NA.

In the Finnish National Annex (FI NA to EC5-1-1), completely new design criteria are established. After classifying the floors as low- or high-frequency floors at a threshold level of 9 Hz, only a deflection limit applies for high-frequency floors. Guidance for low-frequency floors is not given.

Table 1 provides a comparison of the design guidelines used in Finland and the UK. Table 2 shows the calculation methods to be used and Table 3 shows the limiting values. For details of the individual factors, see EC5, UK NA to EC5-1-1 and FI NA to EC5-1-1.

2.2 Summary regarding design criteria

There are certain limitations and uncertainties when floors are designed with respect to the EC5 criteria. First of all, it is distinguished between low-frequency floors and high-frequency floors. Whereas design criteria are provided for high-frequency floors, guidance for the design of low-frequency floors is not given. The design thus needs to assure a fundamental frequency that is above the given threshold for classification. For the design of high-frequency floors, unit point load deflection and its limit need to be determined. Formulae for the calculations of these and the

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corresponding limits are not included. The calculation methods for the velocity response and its limit are questionable since their validation is not easily proven (Hu, et al., 2001; Zhang, 2004).

Table 1: Comparison of floor classification and design guidance

Country	Low-frequency floor		High-frequency floor	
	Condition	Guidance	Condition	Guidance
UK (based on EC5)	$f_1 \leq 8$ Hz	N/A	$f_1 > 8$ Hz	1) Limiting unit point load deflection w 2) Limiting unit impulse velocity response v
FI (NA)	$f_1 < 9$ Hz	N/A	$f_1 \geq 9$ Hz	Limiting unit point load deflection δ

Table 2: Design equations for calculating frequency, deflection and velocity

Country	Fundamental frequency	Point load deflection	Velocity response
UK	"*For a rectangular floor [...], simply supported along all four edges [...]*" (EC5-1-1) $f_1 = \frac{\pi}{2\ell^2}\sqrt{\frac{(EI)_\ell}{m}}$	$w = \frac{k_{\text{dist}} 1000 L_{\text{eq}}^3 k_{\text{amp}}}{48(EI)_{\text{joist}}}$	$v = \frac{4(0.4 + 0.6 n_{40})}{m L B + 200}$
FI (NA)	for 2-side supported floors: $f_1 = \frac{\pi}{2\ell^2}\sqrt{\frac{(EI)_\ell}{m}}$ for 4-side supported floors: $f_1 = \frac{\pi}{2\ell^2}\sqrt{\frac{(EI)_\ell}{m}} \cdot \sqrt{1 + \left[2 \cdot \left(\frac{\ell}{b}\right)^2 + \left(\frac{\ell}{b}\right)^4\right] \cdot \frac{(EI)_b}{(EI)_\ell}}$	$\delta = \min\begin{cases} \frac{F\ell^2}{42 \cdot k_\delta \cdot (EI)_\ell} \\ \frac{F\ell^3}{48 \cdot s \cdot (EI)_\ell} \end{cases}$	N/A

Classification of the structures as low- and high-frequency floors and assessment of their dynamic performances differs in Finland and the UK as this can be easily seen from the design rules. There are two formulae provided in the FI NA to calculate the fundamental frequency. One is used for floors supported along two edges and the other for floors supported along four edges. The formula in the FI NA used for two-side supported floors is the one used in EC5 "*for a rectangular floor [...] simply supported along all four edges [...]*." This comment in the EC5 is irritating since it creates the impression that the formula is rather to be used for floors supported along four edges. However, this simplified formula may rather be valid for two side supported floors but is also used for floors with supports along four sides.

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It can be noted that the formulae for calculating the deflection are adopted from the general deflection equations for beams and plates but have been modified to account for factors such as load distribution in the UK NA. Also, detailed guidance on the design of more complex flooring structures is not given. The uncertainties of the formulations are more comprehensively shown in the following section where simple and complex structures from the UK and Finland are assessed by the available design criteria.

Table 3: Design limits for frequency, deflection and velocity

Country	Fundamental frequency	Point load deflection	Velocity response
UK (NA)	$f_1 > 8$ Hz	1.8 mm/kN for $l \leq 4000$ mm $16500/l^{1.1}$ mm/kN for $l > 4000$ mm	$v \leq b^{(f_1 \zeta - 1)}$ where $\zeta = 0.02$ (EC5: $\zeta = 0.01$)
FI (NA)	$f_1 \geq 9$ Hz	$0.5 \times \min \begin{cases} \sqrt[4]{\frac{(EI)_b}{(EI)_l}} \\ \frac{b}{l} \end{cases}$ mm/kN for $l \leq 6000$ mm 0.5 mm/kN for $l > 6000$ mm An additional 0.5 mm deflection can be allowed in case of floating and raised floors	N/A

3. Investigation of Finnish and British Flooring Systems

Before the STSM started, flooring structures had been built and tested in laboratory conditions at VTT and Napier University. A Finnish and a British timber flooring system have been selected for a detailed analysis using the classification and assessment methods of EC5 and the Finnish and UK National Annexes. The flooring structures are representing the typical construction styles in either country and are described below.

3.1 The Finnish floor

The Finnish test floor had dimensions of 6.0x4.3 m. LVL joists of 51x400 mm, spaced at 600 mm centres, were used for the structure. The ends were connected to LVL rim boards, which had the same dimensions as the joists. The floor was simply supported on timber walls along all 4 sides and decked with 18 mm thick plywood boards which were connected to the joists using glue and screws. A 60 mm concrete screed was added on top of a 30 mm thick hard mineral wool (ASL2) layer that was placed on the plywood deck. The concrete screed had no structural connection to the flooring structure. LVL blockings, staggered between the main LVL floor beams at the third points of the span and glued to the deck, and tension bars below the rows of blockings were used as transverse stiffeners. The plywood decking layer and the tension bars are the only continuous primary floor structural elements in the transverse direction. However, also the concrete screed helped to distribute the load in the direction perpendicular to the joist direction. Figure 1 shows a Finnish test floor in construction, before isolation and concrete layer were added, representing a typical Finnish flooring structure.

Figure 1: Typical Finnish floor, similar to the test floor described: constructed with main solid timber beams, blocking elements, tension bar and plywood deck

3.2 The British floor

The British test floor had dimensions of 3.5x2.44 m. I-joists with a depth of 220 mm were spaced at 400 mm centres. The ends were fixed to Glulam rim boards. The 19 mm thick chipboard decking layers were fixed to the joists using screws at a spacing of 300 mm. The floor was supported on timber beams along 2 edges, whereas the bottom flanges of the I-joists were connected to the supports using screws at the joist ends. Figure 2 shows the British test floor.

3.3 Summary of construction practices

In Finland LVL or solid timber beams are usually used for constructing flooring structures. Blockings as transverse stiffeners are recommended to be used. Furthermore, it is a standard procedure to use adhesives in addition to screws for fixing the plywood decking to the joists. A concrete screed is in some cases laid on top after hard mineral wool isolation has been added. In the UK, I-joists are used nowadays to form the flooring structures. Adhesives are only occasionally used for fixing the decking to the joists. Concrete screed is usually not utilised for timber floors in the UK.

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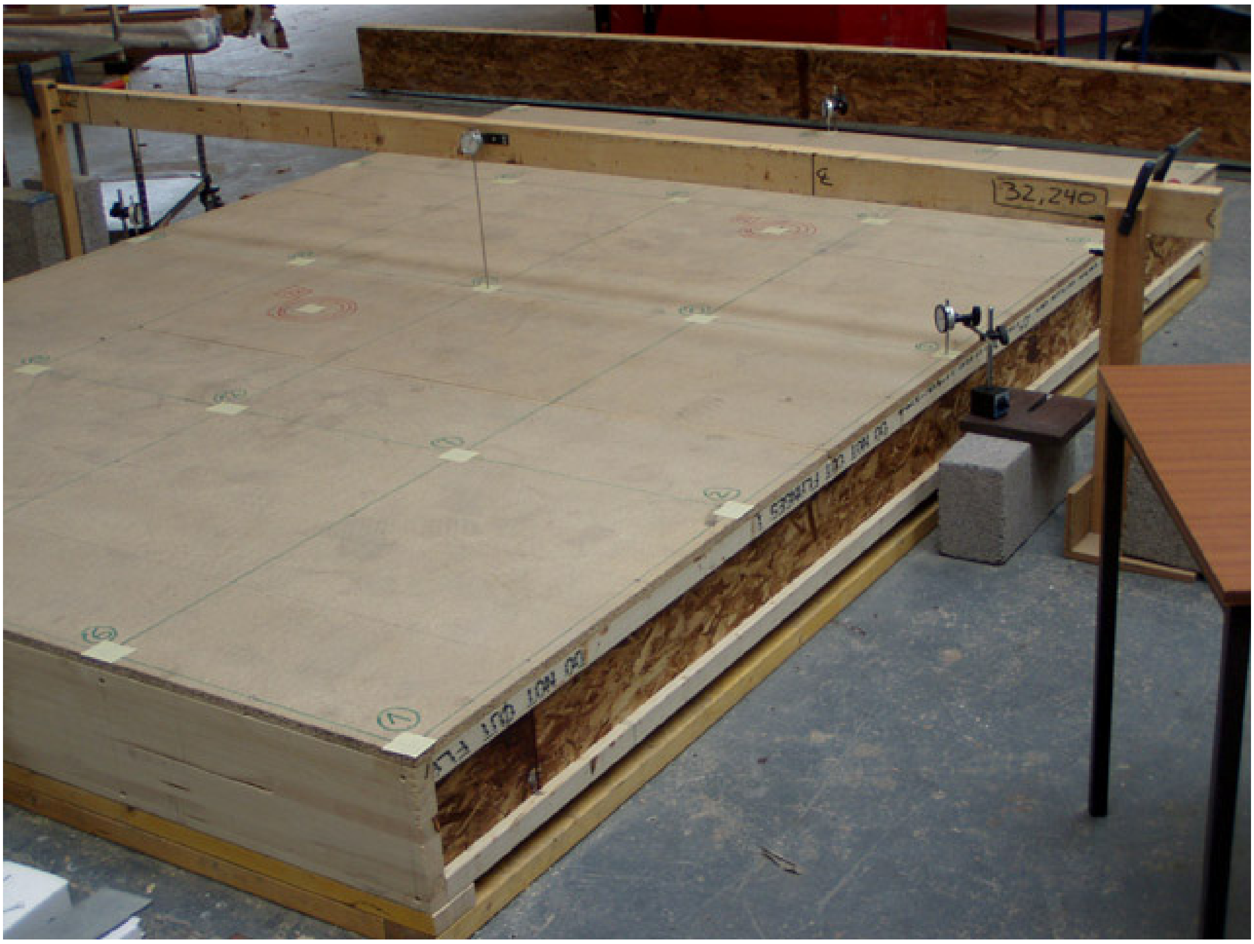

Figure 2: Typical British floor built with I-joists and chipboard deck for a deflection test

4. Investigation of Design Criteria

The Finnish and British flooring structures were examined with respect to the design rules of EC5 only, EC5 with the UK NA and the FI NA. Comparisons were made for the measured and calculated values including the limits and for the design to the nationally determined parameters (NDPs) and criteria.

4.1 Investigation of the Finnish flooring structure

The Finnish flooring structure has been assessed at two different construction stages: before and after the concrete screed was added to the flooring system. Due to the plywood layer being glued to the floor joists, full composite action of plywood deck and joists was assumed. Since the EC5 does not give any advice for consideration of composite action and this effect may sometimes be neglected for simplicity, the calculations for the fundamental natural frequencies have been repeated where composite action was not considered. For all other calculations composite action was included. To determine the stiffness in the transverse direction, composite and non-composite I-sections have been assumed to be effective at the position of the blocking and tension bar, where the tension bar acted as the bottom flange, the plywood deck as the top flange and the blockings as the web. For not overestimating the transverse stiffness, however, a width of 0 mm has been assumed for the web.

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From Figure 3, it can be seen that the predicted frequencies are significantly higher when full composite effect is considered. It can also be noted that the mass of the concrete drastically reduces the fundamental frequencies in a region that becomes critical for design. The predicted frequencies based on the design rule of the FI NA for floors supported along four edges and of the simplified design rule of EC5 are very close if only the timber structure is considered. In case of the floor with concrete screed, however, the calculations to the Finnish formula result in higher fundamental frequencies by up to 12% compared to the calculations to the EC5 formula. If the structure has no concrete screed, the fundamental frequency is well above the thresholds but over-predicted if full composite effect between the deck and joists is assumed (Figure 3(a)). For the flooring structure with concrete screed, the predicted frequencies are below the measured ones and thus on the safe side (Figure 3(b)).

From Figure 4 it can be noted that all the predicted deflection values are at least 83% larger than the measured values. It can also be clearly seen that the added concrete screed has halved the actual floor deflection in comparison with the floor without the concrete screed. In all cases, the floors would result in satisfactory performances if the UK design criteria are applied. In the case of the floor without concrete topping (Figure 4(a)), the floor would be rated as unacceptable with regard to the Finnish design rules, even though the actual measured value is below the limit and the floor thus misclassified. The predicted values with respect to the different design criteria are close. For the floor with concrete screed (Figure 4(b)), the deflection calculated using the UK design rule is 72% higher than that determined from the Finnish formula.

The velocity criterion is not part of the Finnish design guide but is included in EC5 and the UK NA. From Figure 5 it can be noted that the allowance with respect to the UK National Annex is much higher than the one to the EC5. The addition of the concrete screed considerably reduced the velocity response and the limits. However, the velocity response is not a critical criterion in this example.

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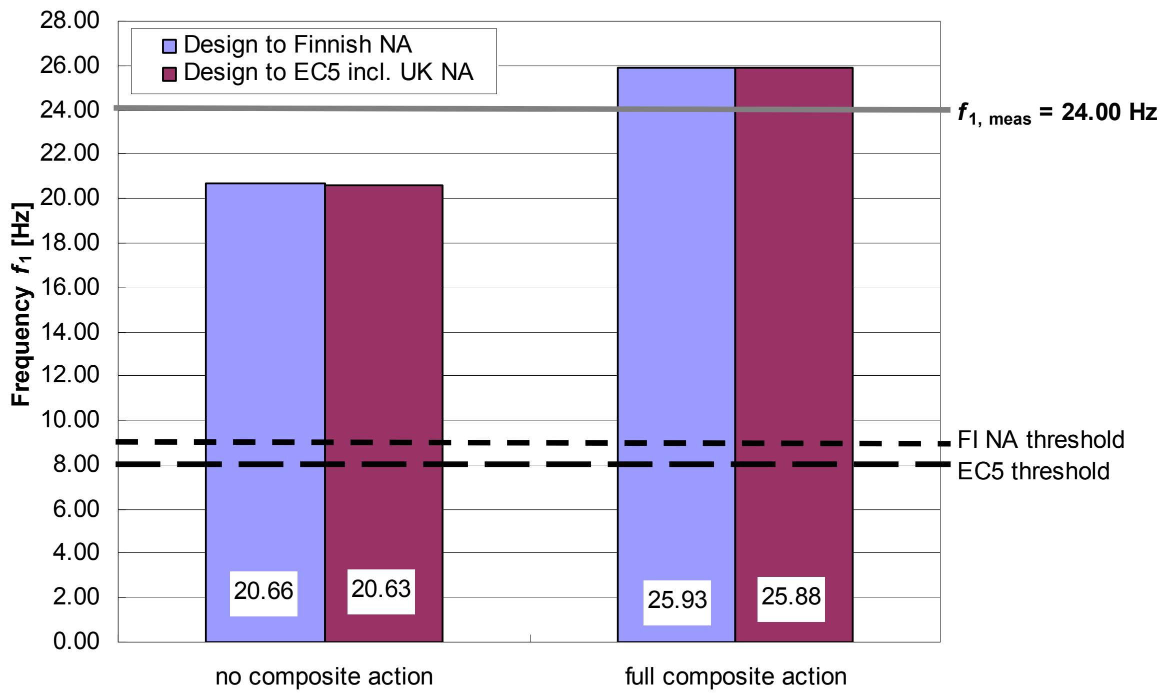
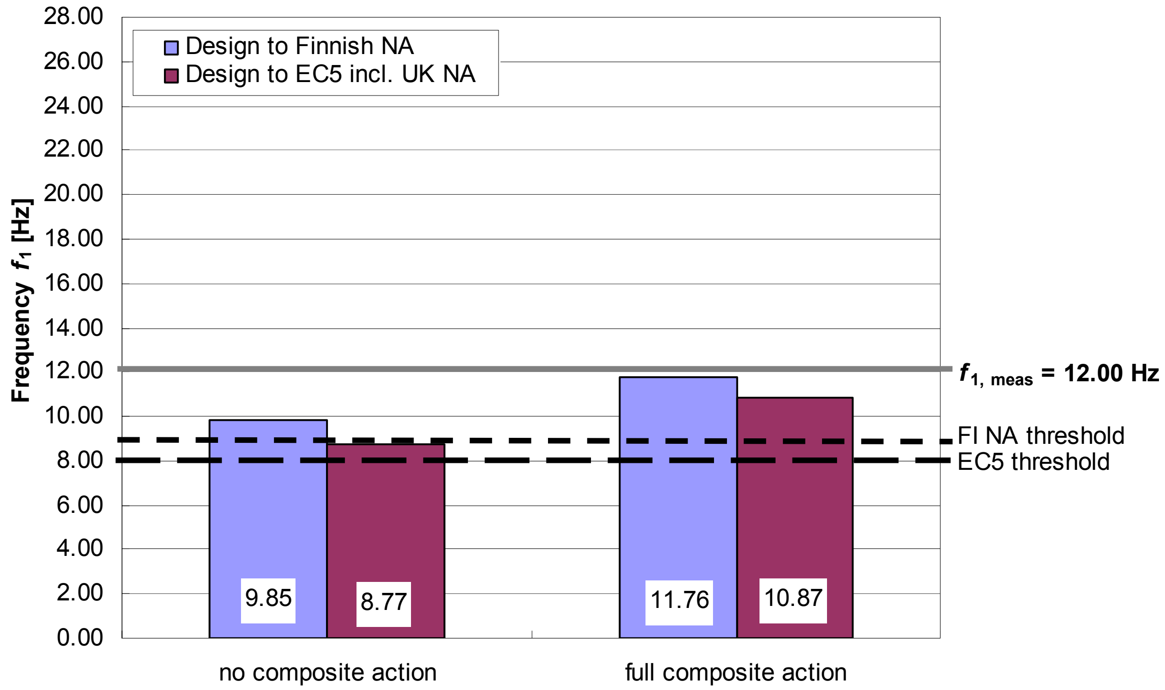
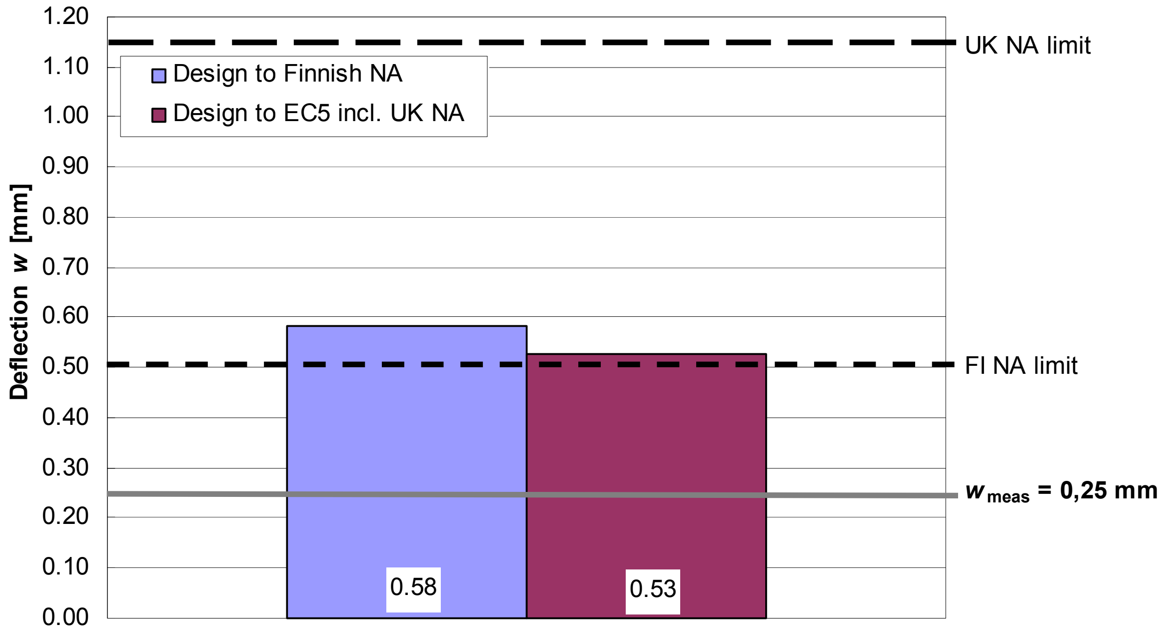


(a) Without concrete screed

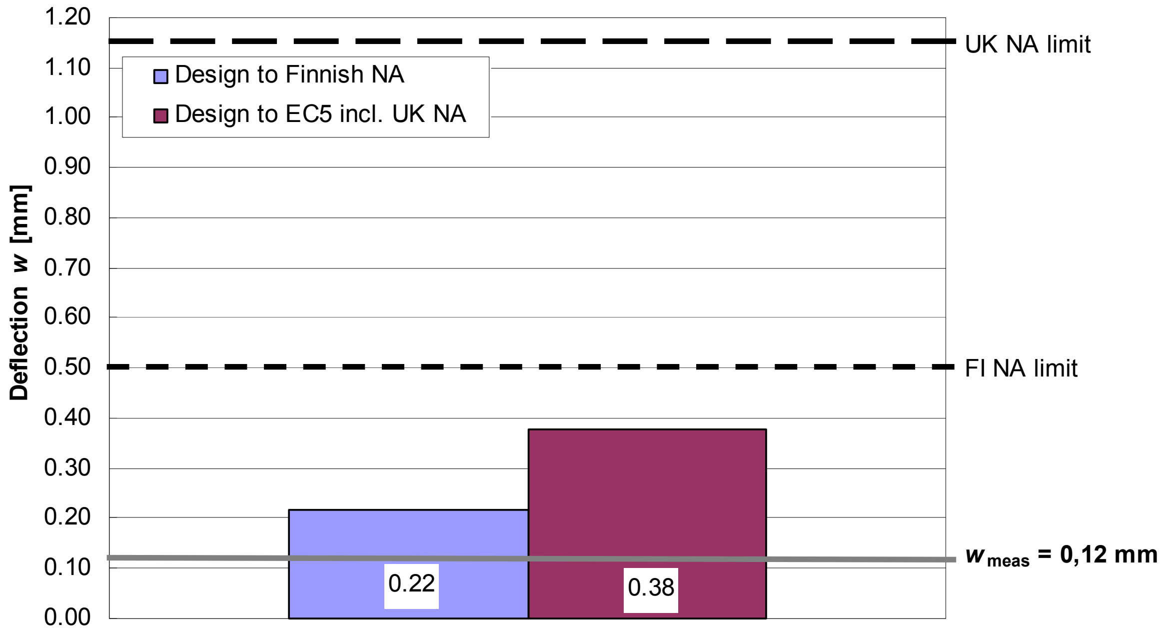


(b) With concrete screed

Figure 3: Measured and predicted fundamental frequencies with respect to the design thresholds in Finland and UK for the Finnish floor



(a) Without concrete screed



(b) With concrete screed

Figure 4: Measured and predicted point load deflections with respect to the design limits in Finland and the UK for the Finnish floor

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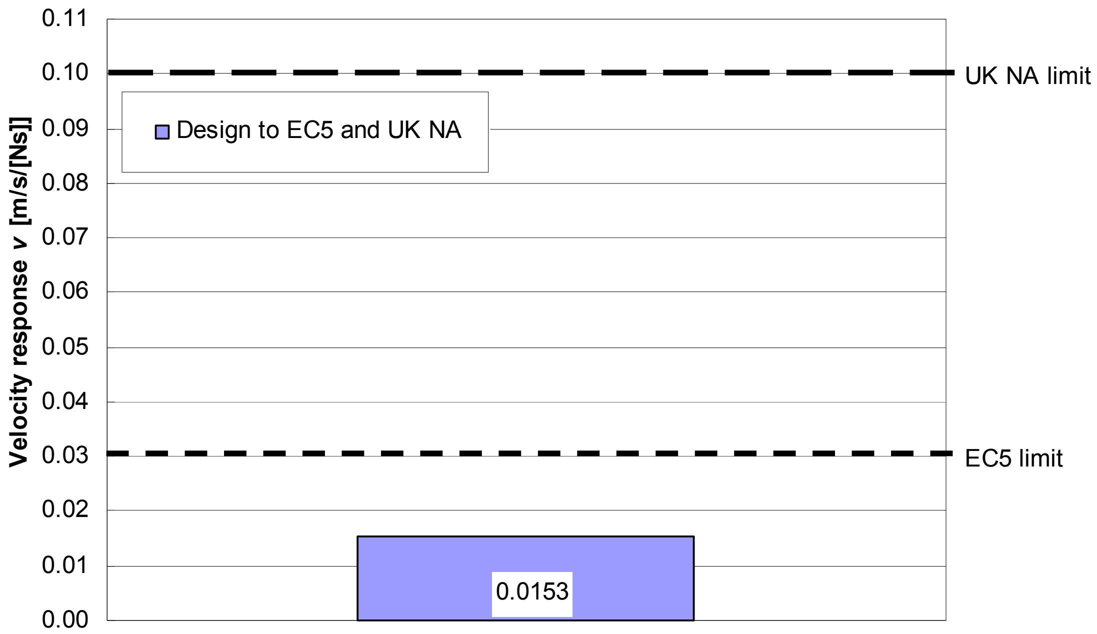
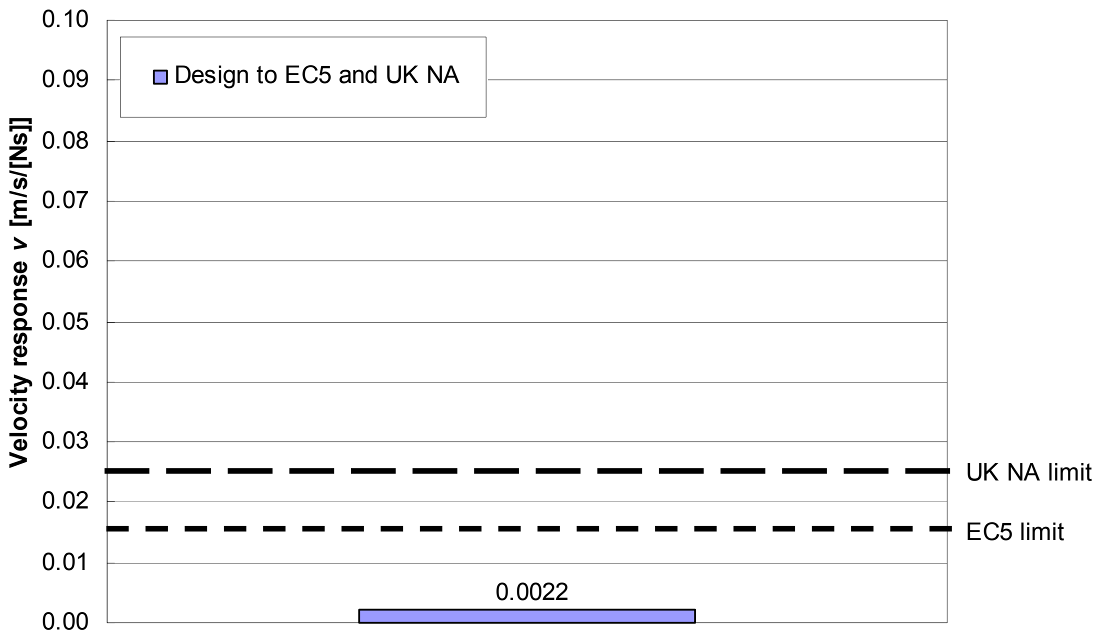


(a) Without concrete screed



(b) With concrete screed

Figure 5: Predicted velocity responses and limits with respect to EC5 and the UK NA for the Finnish floor

4.2 Investigation of the British flooring structure

The deck of the British flooring structure was fixed to the joists using screws, which means that a certain degree of composite action was achieved. The fundamental frequencies were calculated by assuming no composite action first and then an appropriate level of composite action due to the screw fixing. In all other calculations composite action was accounted for. The degree of composite action has been calculated using the guidelines in EC5 (§B.2 in EC5). The formulae for calculating the natural frequencies of the British floor were the same for Finland and the UK since this floor was supported along two edges only so that there are no differences in frequency predictions (see Table 2).

Figure 6 shows that all calculated natural frequencies lie well above the threshold levels, but it must be mentioned that the flooring structural elements were slightly oversized. However, no matter whether composite action was considered, the measured fundamental natural frequency was over-predicted by up to 20%.

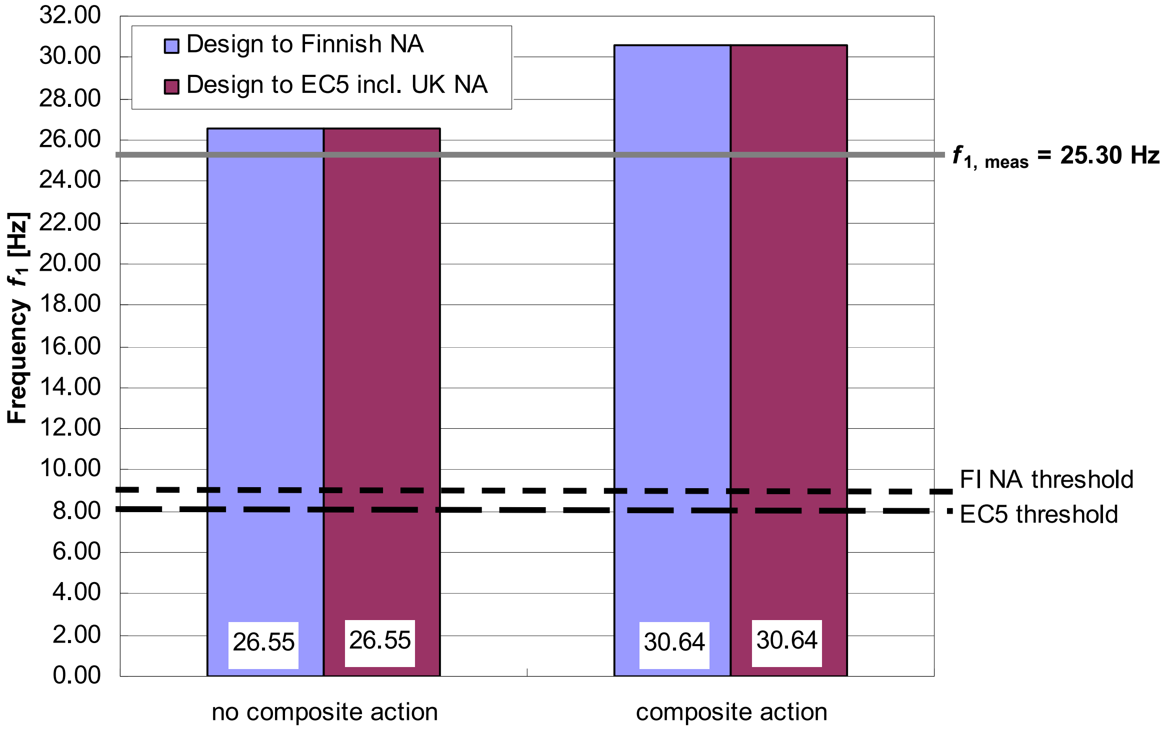


Figure 6: Measured and predicted fundamental frequencies with respect to the design thresholds in Finland and UK for the British Timber floor

From Figure 7 it can be seen that the design to the FI NA provides relatively accurate prediction of the unit point load deflection, the design to UK NA underestimates the actual floor deflection. Whereas the measured and predicted deflection values are well below the UK limit and would thus be regarded to be acceptable, they are well above the Finnish limit and thus regarded to be unacceptable in Finland.

Figure 8 shows that the velocity response is not critical for design in this example. However, it can be clearly noted that the corresponding limit to the UK NA is far more generous than the one to EC5.

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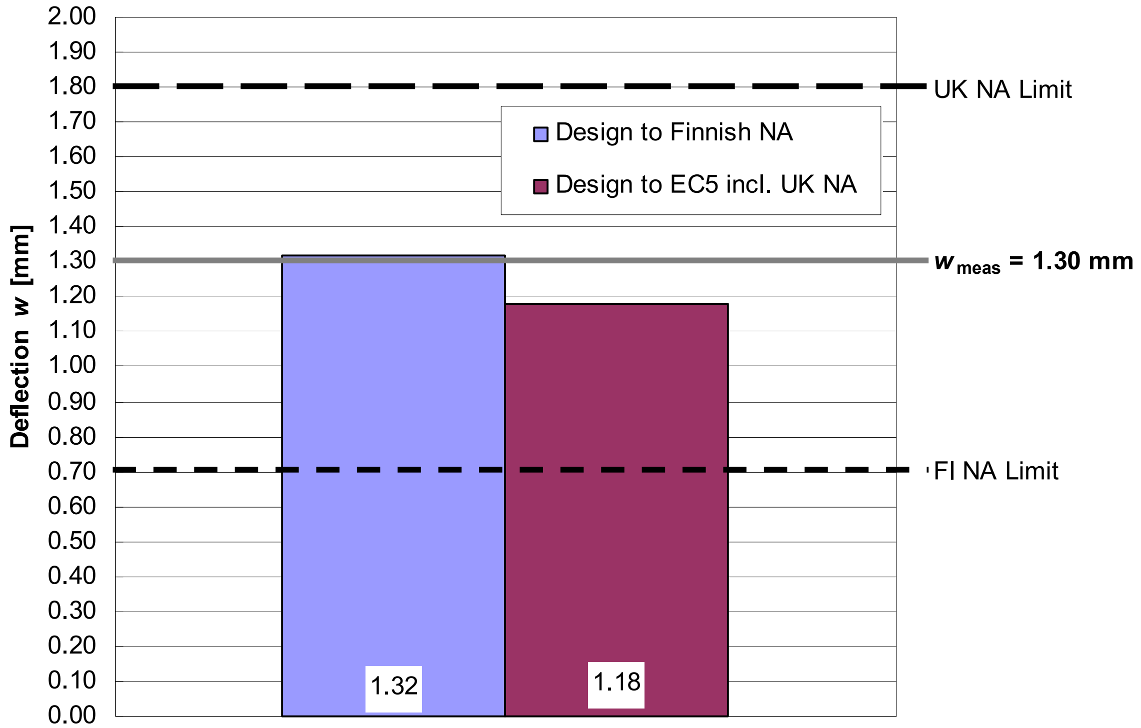

Figure 7: Measured and predicted point load deflections with respect to the design limits in Finland and the UK for the British timber floor

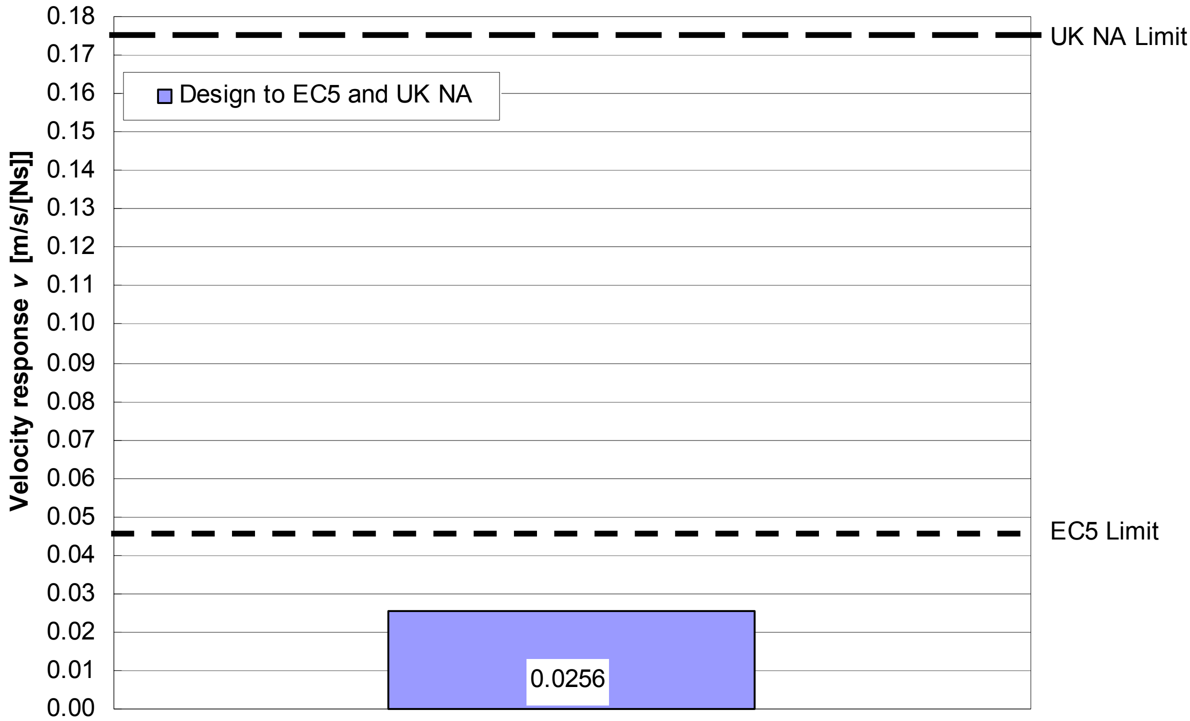

Figure 8: Predicted velocity responses and limits with respect to EC5 and the UK NA for the British timber floor

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4.3 Summary of investigations

For the classification of a flooring system as high frequency floor in Finland, the fundamental natural frequency needs to be above a threshold that is more than 12% above the EC5 (and thus UK) requirement. The design then relies on a static deflection criterion where the allowable deflection is usually below the UK limit. In the EC5 and the UK NA, a velocity response criterion is included additionally.

The simplified formula in EC5 for calculating the fundamental natural frequency for floors supported at four edges gives similar predictions as the precise formula of the FI NA for pure timber structures. However, it is recommended to use the Finnish formula if a concrete screed is used since it leads to more precise results, which can be considerably higher than those from the simplified formula. The deflection criteria overestimate the measured unit point load deflection of the two investigated Finnish flooring structures by at least 83%. The criteria yield predictions closer to the measurement for the UK timber floor, but the deflection is under-predicted to the UK NA and may thus not be on the safe side. The velocity limit to the UK NA is more generous than that to the EC5 and is 65 - 289% higher in the examples shown.

The obtained calculations reveal that it is a complex task to make accurate assumptions for determining the transverse stiffness if, beside the decking layers, transverse stiffening elements are used. Simple guidance for estimating the crosswise stiffness is neither provided in the Eurocode nor properly defined in the National Annexes of Finland and the UK. The examples also demonstrate that it is unclear whether composite action should be accounted for in the calculation of the fundamental natural frequency. Whereas consideration of composite action of boards and joists leads to reasonable predictions for the frequencies of the Finnish floor, frequencies are overestimated by more than 21 % for the British floor.

5. Conclusions and Recommendations for Future Work

The research undertaken for the STSM shows the differences in the design, construction and assessment methods in Finland and the UK. Overall it can be observed that the Finish design rules are stricter than those of the UK, the latter being even more generous than the criteria in EC5. Whereas all three flooring types investigated show satisfactory performances with regard to the UK design rules, two of the systems would be classified as unacceptable to the Finnish standards. Nevertheless, neither in UK nor in Finland can the dynamic parameters be predicted accurately in all cases, which can result in misclassification of flooring structures as confirmed by the NDPs.

Reconsideration of the design rules and guidance for more accurately determining the crosswise stiffness as well as recommendations regarding composite effects are needed. Future research is also needed to show whether different construction practices justify different design methods in different countries. The procedures for more accurately calculating the floor performances, thresholds and limits need to be further harmonised. Furthermore, parametric studies on the velocity response criterion as currently used in the UK are required to assess whether this design rule is redundant or needs modification due to a relatively high limiting value, which may satisfy this criterion easily in common cases. This may then need further reconsideration of the given set of design criteria regarding dynamic floor performances in the EC5 to produce appropriate guidance for the UK NA.

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