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COST-EFFECTIVENESS OF VIBRATION CRITERIA FOR WOODEN FLOORS

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ABSTRACT

The vibration serviceability requirements for wooden floors in accordance with Eurocode-5 (EC-5) as illustrated by Ohlsson [1] are rated using a combination of Value Analysis (VA) and the Checking Point Method (CPM) of the First-Order Reliability Procedure (FORP). The implied safety indices for the current requirements were first estimated and consequently the associated potential losses were deduced for varying design inputs considered as random variables with practical probability distributions. The preliminary results indicate the direction for enhancing the effective use of timber in flooring systems to withstand human-induced vibrations safely and economically.

Keywords: wooden floors, vibrations, design requirements, reliability, randomness, failure cost

1. INTRODUCTION

A design criterion is expected to ensure a low probability of getting an action value higher than the resistance of a member or section to be designed. However, it is often not easy to obtain a specific value of this low probability. According to Larsen [2] this is because there is always a conflict between simple but sometimes conservative models and the more complicated models that may better reflect the behaviour of a system though with a higher risk of making errors and overlooking failure modes. This is more serious during the periods of high economic activities when attention may be directed at the construction of new physical structures that are brought into use as rapidly as possible [3].

Structural quality is dependent on human intervention at every stage of a building process. Thus, the performance of risk assessment from the design stage rather than sitting back till failure occurs is necessary [4]. Wilkinson [5] remarked that once the nature and scope of the exposure to risk have been recognized the next step should be the determination and implementation of measures that will reduce the risk or reduce the effects of the loss or both at an economical cost. Eventually, the need for loss financing will be reduced in most instances and losses will be avoided or minimized.

According to Ditlevsen and Madsen [6] engineering judgment can be seen as the art of being

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able to decide whether results obtained from a structural analysis or design model is sufficiently realistic to justify the basis for practical decisions on the results. A mathematical model is often formulated not only to get a realistic description but also to have it operational in accordance with the intended solution. Thus, in modeling a balance between reality and functionality becomes an art.

Timber, in general, as a low density, cellular, polymeric composite does not fall into one class of materials but tends to overlap a number of classes. In many respects, timber as a structural material is similar to steel, although there are marked differences between both materials leading to different design problems as clearly itemized in [7].

A structure is rated serviceable as long as it fulfills all its intended functions in an appropriate fashion. In service conditions structural vibrations may constitute a state of reduced serviceability in many load-response situations. However, the major concern in design is to limit human discomfort. As reiterated by Ohlsson [1], EC-5 is concerned with the design of residential wood-based floors with respect to vibration serviceability, in which only footstep forces are considered. The vibration criteria examined apply only to floors with a fundamental frequency higher than 8 Hz.

It is a common practice to improve the vibration performance of timber floor structures by increasing the joist dimension and also by gluing the floorboard to the joist [8]. The most efficient measure according to [8] is to increase the bending stiffness perpendicular to the principal bearing direction. This may be done either by using a flooring material with higher stiffness or by strutting between the joists. Apart from material consumption, the limitation of the strutting method lies in the shrinkage and compression perpendicular to the grain in the joist.

This paper highlights the potential loss indices for a typical wooden floor subjected to human induced vibrations on the basis of the serviceability criteria proposed in EC-5 and illustrated by [1]. Uncertainties in all the key design variables are systematically considered and perturbed to simulate practical conditions through the use of one of the documented and applied methods of reliability concepts [9-12] whose applications have always been growing [e.g., 13-16].

2. CRITERIA FOR VIBRATIONAL SERVICEABILITY

Human activity and installed machinery have been regarded [1] as the two most important internal sources of vibration in timber-framed buildings. In this presentation, the dynamic influence from ordinary human activity is considered. Within this framework, the design criteria will be based on a floor with fundamental frequency higher than 8 Hz.

It is easy to show that the different eigen-frequencies of a rectangular floor simply supported along all four edges can be given by

$$f_n = f_0 \sqrt{1 + n^4 \left(\frac{L}{b}\right)^4 \frac{(EI)_b}{(EI)_L}} \tag{1}$$

where f_1 is approximately equal to the fundamental frequency for a corresponding beam member of unit width. That is,

$$f_1 = f_0 = \frac{\pi}{2L^2}\sqrt{\frac{(EI)_L}{m}} \tag{2}$$

In Eqs. (1) and (2), n = the mode number, m = mass per unit area, L = floor span, b = floor width and EI = equivalent plate bending rigidity per unit width with the indices L and b referring to perpendicular directions.

It was remarked in [1] that a fundamental frequency of at least 8 Hz is needful for human-induced vibration on floor surface. Thus, a resulting vibration velocity caused by an ideal unit impulse can be estimated from

$$v_{\max} = \frac{0.4 + 0.6n_{40}}{0.25mbL + 50} \tag{3}$$

in which

$$n_{40} = \left\{\left[\frac{1600}{f_1^2} - 1\right]\frac{b^4}{L^4}\frac{(EI)_L}{(EI)_b}\right\}^{0.25} \tag{4}$$

Apart from the fact that the resulting vertical deflection should not exceed 1.5 mm, the maximum vibration velocity is also limited by the damping quality of the floor. Consequently, the condition to be satisfied for human-induced floor vibration in EC-5 as illustrated by [1] is

$$v_{\max} \le 100^{(\xi f - 1)} \tag{5}$$

where f = f_1 divided by 1.0 Hz and ξ = damping ratio taken as 1% for ordinary wood-based floors. Eq. (5) is one of the conditions for probing probabilistically the cost-effectiveness of the vibration serviceability requirement of a wooden floor under human-induced excitation. For proper evaluation all the relevant parameters are treated as random with admissible probability distributions.

3. METHODOLOGY FOR POTENTIAL LOSS

Conditions in any code of practice rarely replicate the true states of a structural component or system. This reality is properly and widely accepted in engineering practices and for this reason the question of safety often arises. Consequently, standards and codes of practice invariably provide a means of computing safe loads or suggest a load factor by which load effects must be multiplied before the member sizes are proportioned. In this way, the factor of safety has been seen as inversely proportional to the factor of ignorance [17] that does not truly represent the margin against failure.

According to Anthony [18] no structure is free from the possibility of failure or damage, it is only required that the loads must be designed to fit the risk. This is why the serviceability criteria for wooden floor systems are evaluated and the concept for this purpose is briefly reviewed.

3.1CPM

In the evaluation of safety using probabilistic concepts it is often the practice to define a safety margin Z on the basis of the performance function $g(x_1,...,x_n)$ which relates the resistance of the component to the applied loading. That is,

$$Z = g(x_1,...,x_n) \tag{6}$$

Since the individual members of this function may be random quantities Z also must be a random variable which must satisfy the condition that Z > 0 at the internal points of the safe set, Z = 0 at the limit state, and Z < 0 at the internal points of the failure set. A generalized simple safety index can be formed if the random variables collected in the vector **X** are normalized and collected in another vector **Y** using a linear mapping of the kind $\mathbf{X} = L(\mathbf{Y})$ such that $\mathbf{Y} = L^{-1}(\mathbf{X})$. Therefore the corresponding space of points is then defined by the transformation

$$\mathbf{x} = L(\mathbf{y}), \qquad \mathbf{y} = L^{-1}(\mathbf{x}) \tag{7}$$

The consequence of this transformation maps eqn (1) at the limit state into

$$h(y_1,...,y_n) = 0 \tag{8}$$

in which

$$h(\mathbf{y}) = g(L(\mathbf{y})) \tag{9}$$

The mean value of **Y** occurs at the origin while the projection of **Y** on a straight line through the origin is a random variable with a unit standard deviation. The distance from the origin to the limit state surface in this normalized space becomes the geometric safety index. In other word,

$$\beta = \min\left\{\sqrt{\mathbf{y}'\mathbf{y}}\,\middle|\,h(\mathbf{y}) = 0\right\} \tag{10}$$

where the minimum of the distance β from the origin to **y** is obtained for varying **y** over the entire limit state surface. A point **y** on this limit surface that actually corresponds properly to the globally most central limit-state point [6] is the checkpoint corresponding to the sought probable failure point.

3.2VA

The expected total cost of a structural system may be mathematically expressed as follows.

$$T_c = I_c + P_c \tag{11}$$

in which T_c = the expected total cost, I_c = initial expected cost and P_c = risk cost. If we assume that the life-time failures are related to acceptable economic fluctuations, then eqn (11) can be rewritten in an expanded form as [19]:

$$T_c = I_c + \frac{R_f}{\psi}(1 - e^{-\psi})\sum_{i=1}^{N} P_{ci}\Phi(-\beta_i) \tag{12}$$

in which

$$\psi = (\eta_I - \eta_F)T_L \tag{13}$$

is a function which accounts for economic fluctuations and it depends on the interest rate η_I, inflation rate η_F, and the design life, T_L. In eqn (12), R_f is the life-time failure probability related to the probability $\Phi(-\beta_i)$ associated with the event due to cause i at level β estimated using eqn (10) out of N resulting into failure and P_{ci} denotes the potential loss in respect of failure cause i.

Dover and Bea [20] showed that

$$R_f = 1 - e^{-\Phi(-\beta)T_L} \tag{13}$$

where $\Phi(-\beta)$ is the probability of violating the serviceability limit state. Therefore in a dimensionless form eqn (12) becomes

$$T_c^* = 1 + R_c R_f P_f \left(\frac{1 - e^{-\psi}}{\psi}\right) \tag{14}$$

so that $T_c^* = T_c/I_c$. The second term of eqn (14) represents the risk cost index, C_{RI}, expressed as

$$C_{RI} = R_c R_f P_f \left(\frac{1 - e^{-\psi}}{\psi}\right) \tag{15}$$

where $R_c = P_c/I_c$. Hence, eqns (5), (10) and (15) are sufficient for appraising the potential loss associated with the violation of the serviceability limit state due to human-induced vibrations when all quantifiable uncertainties in material, loading and geometrical properties are considered.

4. THE TIMBER FLOOR EXAMPLE (ADOPTED FROM [1])

The assumed dimensions in plan are 3.9×4.8 m^2. The floor is constructed with 22 mm chipboard flooring supported by 45×220 mm^2 wood joists (with varying aspect ratio, ASR1) of grade C22 and spaced at 600 mm centres along the 3.9 m span. A 70×45 mm^2 spaced boarding (with assumed varying aspect ratio, ASR2) of grade C16 is fixed at 300 mm centers at the 4.8 m span while 11 mm plasterboard is placed.

All the variables related to material properties are considered log-normally distributed, the geometrical properties are assumed normally distributed while the unit impulse load is assumed Gumbel. The cost-effectiveness of the requirements of EC-5 as illustrated in [1] is now examined for a 10% difference between the interest and inflation rates, 50 years of the expected design life of the floor system and R_o = 50. Other values of these parameters may be chosen without loss of purpose.

In figures 1 and 2, the degeneracy of the safety of the floor for various geometrical considerations for the floor components is displayed. The floor safety drops as the floorboard slenderness augments in a very rapid manner. However, there are specific trends that can assist designers in decision-making. For instance, designers should pay particular attention to the proportioning of the various floor components to enhance the serviceability requirements. As the floor performance degenerates with increasing floor slenderness, it is advisable to increase the sizes of the joist and the spaced boarding. However, this should not be done indiscriminately as suggested by the information on figures 3 and 4.

Figures 3 and 4 show the trends of the potential losses associated with the vibration serviceability requirements using the example floor. Geometrical properties of the floor components influence the potential losses disproportionately. For instance, when the floor slenderness is 1.6 and ASR2 = 0.4, an 8.33% increase in ASR1 reduces the potential loss

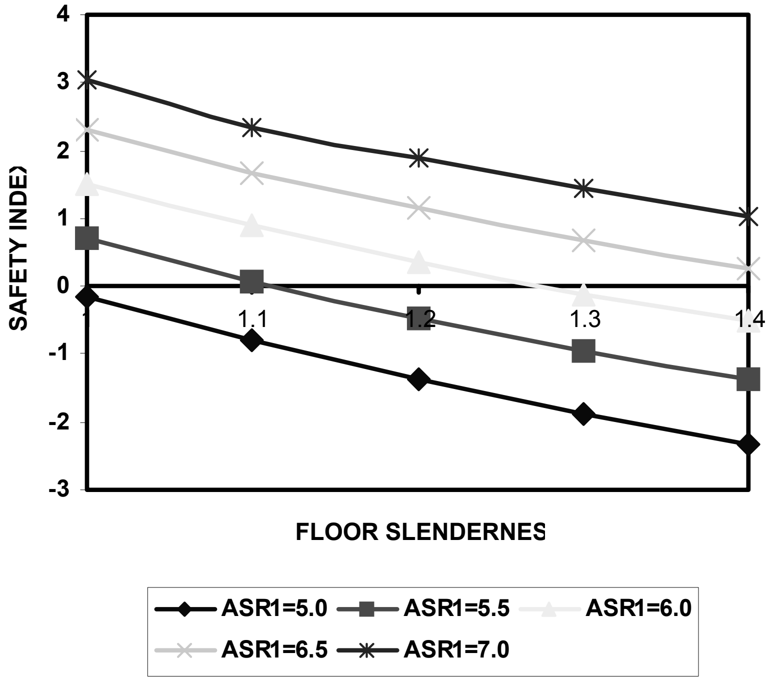

Figure 1 Safety indices against geometrical variation (ASR2 = 0.2)

index by 69.51%. On the other hand, if ASR2 is increased by 200% at the same floor slenderness and ASR1 = 5.5, the reduction in the potential loss index is about 88.17%. Thus, a problem of decision-making has arisen, one of which may affect aesthetics.

Design decisions are often taken in spite of imperfect knowledge about nature. In figures 5 to 7 the influence of variability in material properties of the floor components on potential loss is displayed while figure 8 shows the effect of variability in the unit impulse on the potential loss. These variabilities are not as significant as the geometry of the various components except for the joist (see figure 5).

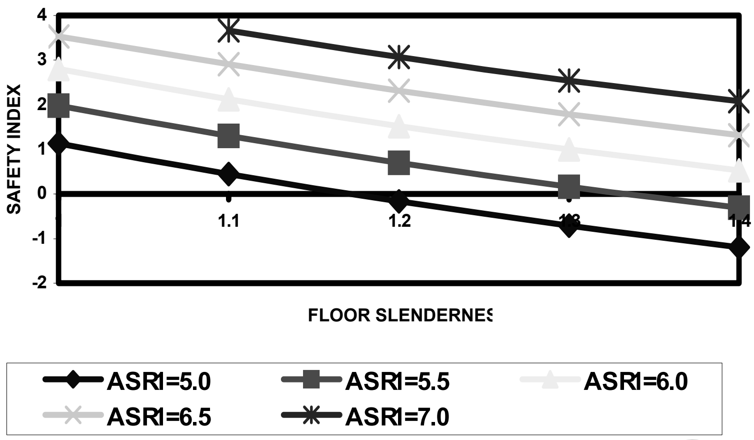

Figure 2 Safety indices against geometrical variation (ASR2 = 0.4)

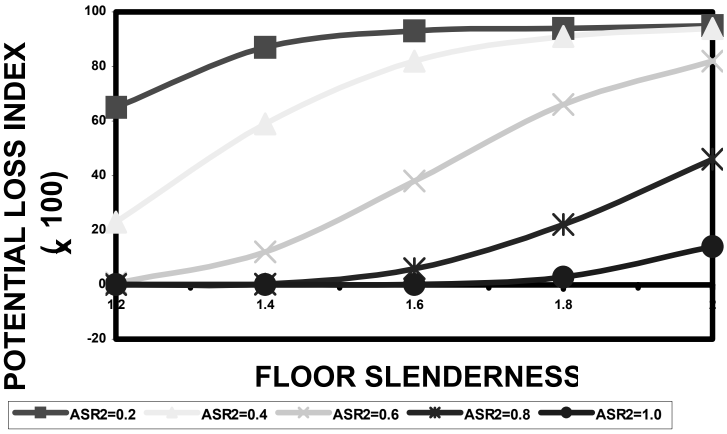

Figure 3 Variation of Potential Loss with Geometry (ASR1=5.5)

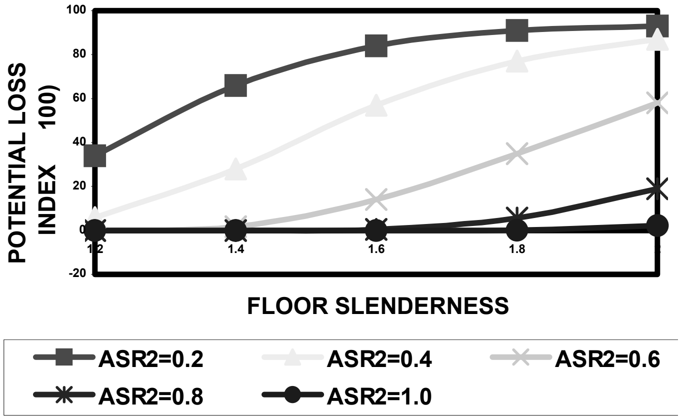

Figure 4 Variation of Potential Loss with Geometry (ASR1=6.0)

5. CONCLUSIONS

The cost-effectiveness of the vibration serviceability requirements for wooden floor systems given in EC-5 illustrated by [1] has been examined. It was assumed that the

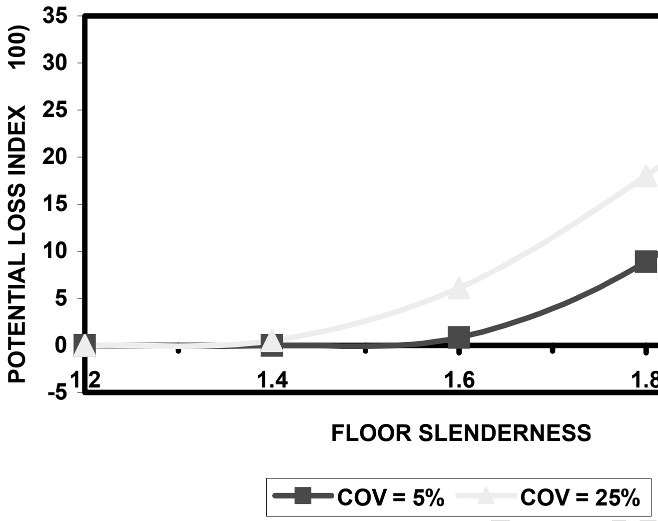

Figure 5 Effect of Material Variability on Potential Loss (Joist)

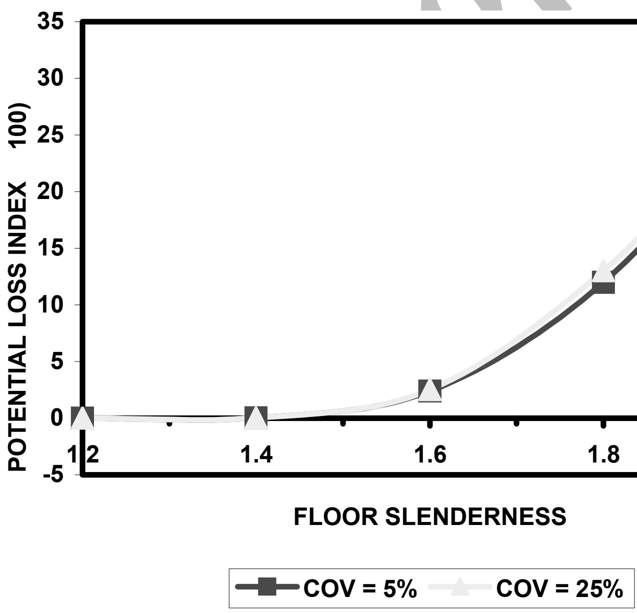

Figure 6 Effect of Material Variability on Potential Loss (chipboard)

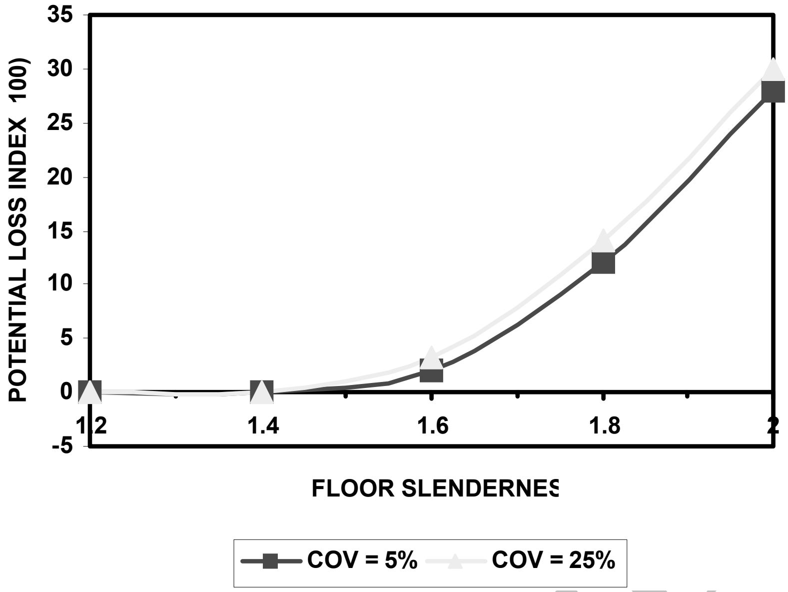

Figure 7 Effect of Material Variability on Potential Loss (spaced boarding)

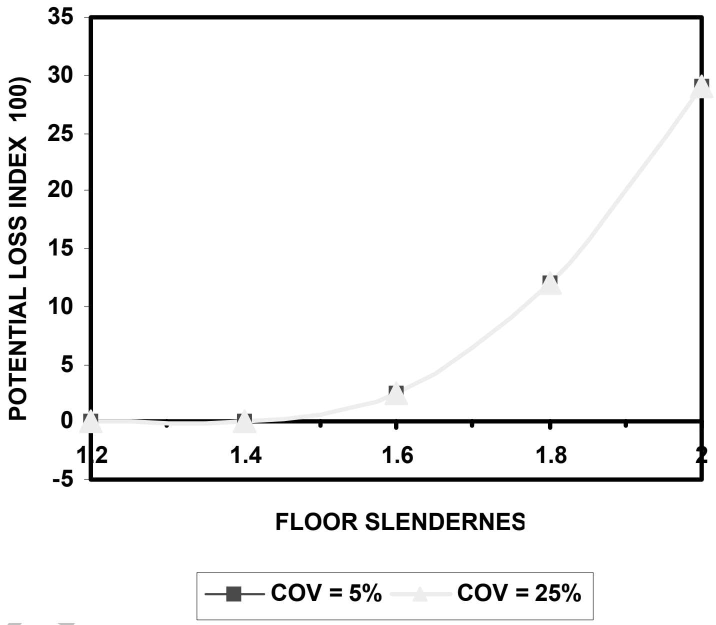

Figure 8 Effect of Unit Impulse Variability on Potential Loss

fundamental frequency of the floor was higher than 8 Hz and only human-induced vibrations were considered. For varying inputs related to the important design parameters, potential loss indices are plotted. The results of the evaluation have shown that the serviceability requirements lead to disproportional losses depending on the quality of material and dimensional quantities employed. To a great extent, the potential loss associated with the loss of structural integrity of a wooden floor depends on the quality of the materials of the joist more than that of the chipboard or the applied unit impulse. The results of this investigation can be used to a great advantage in the effective use of timber in floor systems. In addition, a designer is also placed on caution in the application of the serviceability criteria.

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