# Serviceability limit states - Vibration of wooden floors

STEP lecture A18
S. Ohlsson
Chalmers University
of Technology

## Objectives

To explain the mechanisms of serviceability reduction due to the disturbing vibration of wood floors and to explain the background and application of the dynamic methods specified in section 4.4 of EC5.

## Prerequisite

B3 Bending

## Summary

Service requirements based on human tolerance of vibration are described. Service loads from human footfall and from rotating machinery are surveyed. The design loads according to EC5 (unit impulse and static concentrated force) are described and the way in which they are believed to represent real dynamic loads is explained.

Static stiffness properties of timber floors related to concentrated vertical forces are described. Models and calculation methods are introduced.

Dynamic properties of plate-like structures are introduced. Dynamic properties of timber floors are explained in some detail, especially for one-span simply supported floors. In particular, eigenfrequencies, mode shapes, modal masses and modal damping are essential concepts.

The design method based on limitation of the impulse velocity response is explained. The background assumptions are surveyed, effects of various possible re-designs are illustrated, and limitations of the method are outlined. Effects from the general structural properties of the whole building and its mechanical system on the transfer of vibration are briefly explained.

## Serviceability requirements

A building is generally rated as serviceable as long as it fulfils all its intended functions in an appropriate fashion. All serviceability aspects which are strongly dependent on the structural system or on the structural components of a building are included in the term "structural serviceability". These aspects should be considered by the structural engineer during the design process.

Structural serviceability requirements are usually formulated in relation to a building or in relation to a fairly large portion of a building. Most serviceability criteria originate from the following objectives:

- Acceptable human comfort.
- Ensured functionality of building and installations.
- Acceptable visual building appearance.

These design objectives are referred to in EC5. Damage to surfacing materials or partitions may for instance represent a loss of building functionality (loss of water tightness of a bathroom floor) or an unacceptable appearance (cracked partition).

Serviceability requirements are to some extent different in nature when compared to classical requirements on safety. Some states of violated serviceability are reversible. This is for instance true for human discomfort caused by vibration. Another specific case can be illustrated by the visual appearance and the functionality of a floor. Both qualities are related to the deviation from a flat and horizontal condition. Consequently, the total deviation composed of initial deviation, deviations due to static load and deviations caused by climate factors, is relevant. In such cases it is possible to use pre-cambered components in order to limit the deviation. Consideration of such initial deviation (pre-camber) is permitted in EC5, where limiting values of deflection are given. This is not applicable in conjunction with dynamic problems.

In order to facilitate engineering design of timber structures, the most essential EC5 serviceability requirements have been transformed to design limiting values for deflections and vibrations respectively. The remaining part of this paper is focused on criteria for vibrations.

## Vibrational serviceability

In general there are many load-response cases where structural vibrations may constitute a state of reduced serviceability. The main concern, however, is with regard to human discomfort. People are in most cases the critical sensor of vibration. Among different dynamic actions, human activity and installed machinery are regarded as the two most important internal sources of vibration in timber-framed buildings. Human activity not only includes footfall from normal walking, but also childrens' jumping, etc. Two critical load response cases are finally identified:

- Human discomfort from footfall-induced vibrations.
- Human discomfort from machine-induced vibrations.

Human susceptibility to vibration is a complex matter. Griffin (1990) provides an extensive monograph on the subject, and ISO 2631-2 (1989) may be considered as a summarising document. The following basic statements are valid in most situations:

The human sensitivity to vibration is:

- related to vibration acceleration for frequencies < 8 *Hz*;
- related to vibration velocity for frequencies > 8 *Hz*;
- increased by the duration of vibration;
- decreased by proximity to and awareness about the source;
- decreased by physical activity.

In the light of these conclusions, two different design aims emerge. Firstly, the vibration levels in the vicinity of the dynamic action should be limited and secondly, the transfer of structural vibrations to adjacent building units (e.g. another apartment) should be avoided.

The first aim may be achieved by proper design of the local load-bearing floor, as described in the following sections. In order to attain the second aim, a suitable structural system must be chosen. The use of moment resisting frames incorporating both vertical and horizontal members can enable vertical vibration transfer to adjacent storeys and may not be the best choice in this context. Continuous floor construction between different apartments should be avoided. Partitions should preferably be located above each other and be vertically supported by the foundation. Location of a partition at floor midspan in just a single storey may structurally couple the two adjoining floors and they will experience almost the same vibration. This vibration may be acceptable on the floor where the dynamic load acts, but it may be intolerable on an adjacent floor where the neighbour is unaware of the source.

## Human-induced vibration

EC5 is concerned with the design of residential wood-based floors with respect to vibrational serviceability. Dynamic influence from ordinary human activity, i.e. footstep forces, is considered. More severe dynamic loads, which can be anticipated from dancing and rhythmic exercises call for other design methods, Allen (1990).

The design criteria presented here apply to floors with a fundamental frequency $f_1$ higher than 8 $Hz$. Floors having a lower fundamental frequency will experience more severe dynamic resonant response from people in motion. Such floors must be designed due to principles not covered by this lecture. Eriksson (1994) discusses design principles for such floors, which usually have larger spans than are common for wooden floors.

The different eigenfrequencies of a rectangular floor simply supported along all four edges may be calculated according to the approximate Equation (1).

$$f_n = f_0 \sqrt{1 + n^4 \left(\frac{l}{b}\right)^4 \frac{(EI)_b}{(EI)_l}} \qquad (1)$$

where $f_1$ is approximately equal to the fundamental frequency for a corresponding beam member of unit width, $f_0$, which is given by Equation (2):

$$f_0 = \frac{\pi}{2l^2} \sqrt{\frac{(EI)_l}{m}} \qquad (2)$$

The parameters used are as follows:

- $n$ is the mode number (only first order modes are considered, that is only modes with a mode shape corresponding to a half sine wave in the direction parallel to the span direction are incorporated).
- $m$ is the mass per unit area ($kg/m^2$).
- $l$ is the floor span ($m$), $b$ is the floor width ($m$).
- $EI$ is the equivalent plate bending rigidity per unit width ($Nm^2/m$), index $l$ and $b$ refer to perpendicular directions and $l$ represents bending in the stiffer direction.

It may be observed from Equation (1) that the difference between consecutive resonances is dependent on the ratio between the bending rigidity in two perpendicular directions. Most wood floors will have a high degree of anisotropy, that is the quotient between such bending rigidities will be low. As a consequence, typical wooden floors will have a high number of closely spaced resonance frequencies within the frequency band of interest with respect to serviceability.

The criteria and corresponding methods for calculation are based on the proposal presented by Ohlsson (1988). The scientific background is documented by Ohlsson (1982). A summary of the background is presented here.

The dynamic footfall contact force from ordinary walking has been experimentally verified. A case representing a person treading in place will create a forcing function like the one in Figure 1. In residential premises the transient short-time response will be governing. The force is composed of two different component types:

- Low-frequency components (0 - 8 *Hz*) which originate from the step frequency and its harmonics.

- High-frequency components (8 - 40 *Hz*) which mainly originate from impacts when the heel contacts the floor surface.

Since the fundamental frequency of the floor is supposed to be higher than 8 *Hz*, the low-frequency components will generate vibrations which are semi-static in the sense that their amplitudes are governed by the structural stiffness, while the mass of the floor is rather insignificant. Since this assumption is important, EC5 requires that the fundamental frequency is calculated and shown to be at least 8 *Hz*, or higher.

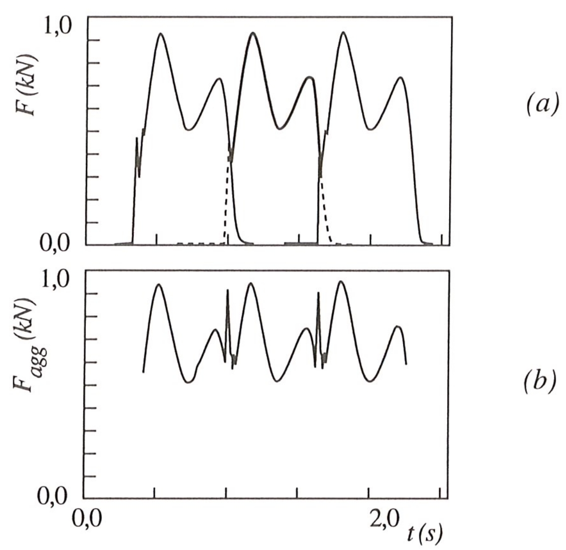


*Figure 1* *Successive footstep contact forces F from ordinary walking person (a) and corresponding aggregated resultant force $F_{agg}$ acting on the floor (b). Ohlsson (1988).*

As a consequence, the corresponding design action is taken as a static concentrated vertical force of 1,0 *kN*, see Figure 2. The resulting vertical deflection *u* is limited to 1,5 *mm*. It should be pointed out that the calculation may be based on a model reflecting the real two-way action of a floor.

The high-frequency impulsive force components are represented by a unit impulse of 1,0 *Ns* as the design action. The resulting vibration velocity *v* caused by such an ideal impulse is a property of the structure.

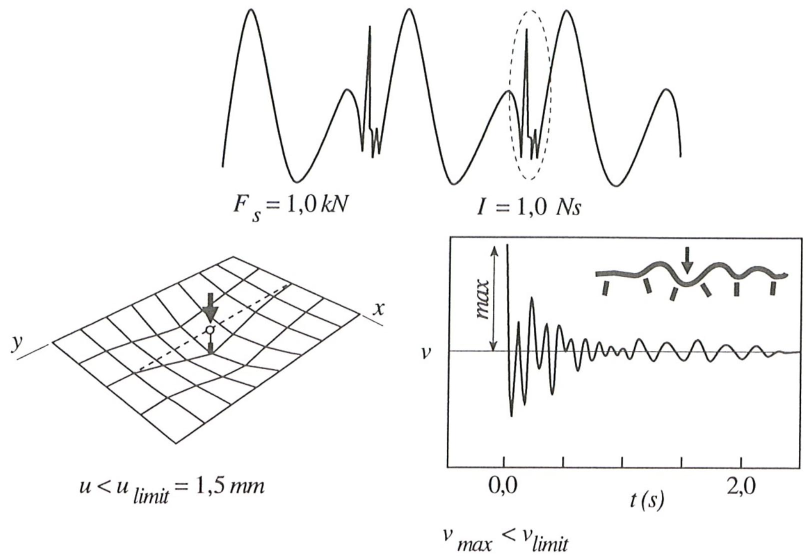


*Figure 2* *Typical resultant force-time history from ordinary walking, illustration of corresponding idealised design actions consisting of a static force $F_s$ and a unit impulse I (top), resulting deflection u (bottom left) and vibration velocity v(t) (bottom right) and limiting criteria for design calculations $u_{max}$ and $v_{max}$.*

It may be recalled that if the floor had been a free rigid body with a concentrated mass *M*, a unit impulse would have resulted in a velocity of the mass equal to *1/M*. For a practical floor with distributed stiffness and mass, the initial maximum velocity may be calculated using Equation (3):

$$v_{max} = \sum \frac{\Phi_n^2}{m_n} \qquad (m/s)/(Ns) \tag{3}$$

where the summation is taken over all different modes of vibration *n*. $\Phi_n$ is the mode shape function for mode *n*, which is normalized for unit maximum modal displacement and $m_n$ is the modal mass (sometimes referred to as the generalized mass) for mode *n*. Two modifications of Equation (3) are now undertaken. The first one concerns the summation of contributions from different modes of vibration *n*. Experimental work has shown (Ohlsson, 1982) that the frequency content of impulsive forces induced by footfall is essentially confined to the frequency range below 40 *Hz*. Consequently, the summation may be restricted to all modes with eigenfrequencies lower than 40 *Hz*. The second modification concerns the mass which should be included in the calculations. It is difficult to state assumptions here, which are on the safe side. With regard to many timber floors, however, it will be conservative to assume a low value for the distributed mass. It is thus stated that calculations shall be carried out based on the distributed mass of the floor only. The second modification is that the modal properties (eigenfrequencies, mode shapes, and modal masses) are calculated for this "bare" floor, but a standard addition of 50 *kg* to each modal mass $m_n$ is allowed when calculating the velocity response. This addition represents a notional vibrating portion of the body of the person which is supposed to be disturbed by the vibration.

It has been found that Equation (3) can be significantly simplified for the ordinary case of a rectangular floor which is simply supported along all four edges, Ohlsson (1988). Assuming floor dimensions $b \times l\ m^2$ and a mass of a unit area floor $m\ kg/m^2$, Equation (3) may be approximated by Equation (4), which corresponds to the formula given in EC5.

$$v_{max} = \frac{4\ (0{,}4 + 0{,}6\ n_{40})}{m\ b\ l + 200} \qquad (4)$$

The parameter $n_{40}$ represents the number of eigenmodes with eigenfrequencies lower than 40 *Hz* and *mbl* is the floor mass. The additional 50 *kg* of modal mass in the denominator is represented by the quotient 4/200 in Equation (4). The number $n_{40}$ can be calculated from Equation (5), which is an approximate expression.

$$n_{40} = \left( \left( \left( \frac{40}{f_1} \right)^2 - 1 \right) \left( \frac{b}{l} \right)^4 \frac{(EI)_l}{(EI)_b} \right)^{0,25} \qquad (5)$$

An effective way is established of calculating the maximum vibration velocity due to an ideal unit impulse. The favourable effect of a short vibration duration must also be taken into account. This is achieved by making the limiting value dependent on the damping of the floor. The most relevant damping parameter in this context is the damping coefficient $\sigma_0$. This parameter represents the decay rate expressed with respect to time rather than with respect to the number of oscillations. The damping coefficient is defined as:

$$\sigma_0 = f\ \zeta \qquad (6)$$

where $f$ may be taken as equal to the fundamental frequency $f_1$ and the modal damping ratio $\zeta_n$ may be taken as 0,01 (1%) for ordinary wood-based floors. Damping is a parameter which shows large scatter and an expected value may be around 1,5% to 2%, Chui (1988) and Ohlsson (1982). If a value higher than 1% is to be used for calculations, duration ought to be verified. In fact, it should be shown that such a higher damping value will be valid for the entire expected service life of the structure. The limiting value is expressed as a function of the damping coefficient in accordance with the procedure suggested by Ohlsson (1988):

$$v_{vel,max} \leq 100^{(f\ \zeta\ -\ 1)} \qquad (7)$$

where $f$ is taken as equal to the fundamental frequency $f_1$ divided by 1,0 *Hz* in order to achieve a dimensionless exponent.

## Example

A floor in a private dwellinghouse with the following properties is to be checked.

The dimensions in plan $l$ x $b$ are equal to 3,9 x 4,8 $m^2$. All four sides are simply supported. The floor is constructed with:

- 22 *mm* chipboard flooring in accordance with prEN 312-4 supported by 45 x 220 $mm^2$ wood joists of grade C22 according to prEN 338 and spaced at 600 *mm* centres (span = 3,9 *m*).
- 70 x 45 $mm^2$ spaced boarding of grade C16 according to prEN 338 which is fixed at 300 *mm* centres (length = 4,8 *m*).
- 11 *mm* plasterboard.

Characteristic values for the different materials according to EN 112.406 and prEN 338:1991 are as follows:

Floor chipboard $E_{0,mean} = 2650\ N/mm^2$.
Wood joists $E_{0,mean} = 10000\ N/mm^2$.
Spaced boarding $E_{0,mean} = 8000\ N/mm^2$.

The mass per unit area $m$ equals 35 $kg/m^2$.
Equivalent bending rigidities are calculated:

$$(EI)_l = \frac{10000 \cdot 45 \cdot 220^3}{12 \cdot 0{,}6} = 6{,}66 \cdot 10^5\ \frac{N\ m^2}{m}$$

$$(EI)_b = \frac{2650 \cdot 1000 \cdot 22^3}{12} + \frac{8000 \cdot 70 \cdot 45^3}{12 \cdot 0{,}3} = 16{,}5 \cdot 10^3\ \frac{N\ m^2}{m}$$

The static deflection $u$ from a static concentrated force $F$ of 1,0 $kN$ is calculated using a grillage model and the computer program BLAG (1991). The resulting vertical deflection $u$ is found to be 1,3 $mm$. This value is lower than the limiting value of 1,5 $mm$. A diagram based method like the one illustrated by Pham & Gianarakis (1980) may be used instead.

The fundamental frequency $f_1$ should be larger than 8 $Hz$. Since $f_1$ is approximately equal to $f_0$, Equation (2) can be used:

$$f_1 = f_0 = \frac{\pi}{2 \cdot 3{,}9^2} \sqrt{\frac{6{,}66 \cdot 10^5}{35}} = 14{,}2\ Hz$$

The fundamental frequency is found to be higher than 8 $Hz$ and the design methods are thus applicable. The number of contributing modes is calculated according to Equation (5):

$$n_{40} = \left( \left( \left( \frac{40}{14{,}2} \right)^2 - 1 \right) \left( \frac{4{,}8}{3{,}9} \right)^4 \frac{6{,}66 \cdot 10^5}{16{,}5 \cdot 10^3} \right)^{0,25} = 5{,}0$$

The value of the impulse velocity response is calculated according to Equation (4):

$$v_{max} = \frac{4\ (0{,}4 + 0{,}6 \cdot 5)}{35 \cdot 4{,}8 \cdot 3{,}9 + 200} = 0{,}016\ (m/s)/(Ns)$$

The limiting value is calculated according to Equation (7):

$$v_{max,limit} = 100^{(0,142-1)} = 0{,}019\ (m/s)/(Ns)$$

The floor is thus found to comply with the criteria for human-induced floor vibration in EC5.

## Machine-induced vibration

Structural vibrations caused by installed machinery should be limited. The human sensitivity to steady vibration from such sources is estimated according to Griffin (1990). Acceptable levels of vibration may be taken from Table 2 and Figure 5a in annex A to ISO 2631-2 (1989). Calculation of steady vibration should be based on expected unfavourable combinations of permanent load and variable load as stated in clause 4.4.2 of EC5. The variation of the corresponding effective mass will consequently be rather high. Since many wood-based structural components have closely spaced eigenfrequencies, the frequency bands where an eigenfrequency must be expected to occur will be rather wide. Vibration isolation or separate structural supports for installed machinery may be the best solution in many cases.

## Concluding summary

Serviceability is a matter of quality and performance in relation to cost. The limiting values corresponding to criteria for human-induced floor vibrations presented here should be regarded as minimum requirements. It is essential to stimulate active customer decisions about desired levels of functional quality at the design stage of a construction project.

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