Vibration performance of a glued stressed skin LVL balcony element

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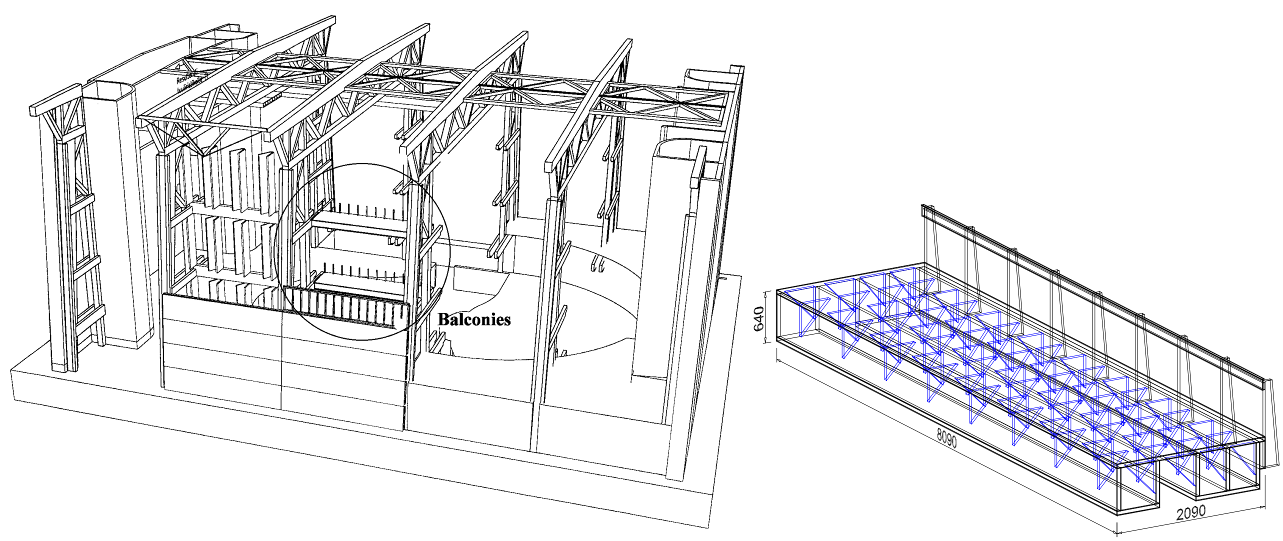
ABSTRACT

The balconies of the wooden concert hall of Lahti are made of glued stressed skin laminated veneer lumber (LVL) elements. These elements are light and because their spans are relatively long (8.1 m), their vibration performance under human-induced excitations were studied. In different standards and instructions the floor vibrations are controlled by limiting the static deflection under a serviceability limit state load (≤L/200–L/360) or under a 1 kN point load (≤0.6mm–2mm), by the lowest natural frequency (≥8 Hz) and by the vibration magnitudes. The vibration performance of the balcony structure was estimated with simplified calculation methods and finite element method models and tested with a 1:1 scale test element. The maximum static deflection under a 1kN point load was 0.12-0.36 mm, the lowest natural frequency was 8.1Hz or 17.4Hz depending on the support conditions and the human-induced vibration magnitudes were smaller than the limit values of different instructions. According to subjective tests the floor vibrations were also acceptable when the support of the balconies was properly arranged.

INTRODUCTION

A wooden concert hall, the Sibelius House, has been built in Lahti, Finland and it has new kind of balcony structures (Figure 1). The balconies are made of glued stressed skin laminated veneer lumber (LVL) elements which utilize the composite action of ribs and skin boards. These elements are light and because their spans are relatively long (8.1 m), a question rose about their vibration performance under human-induced excitations. A possible disturbing situation could arise for example from a person coming late to his or her seat when a concert has already started, because a persons walking may induce vibrations which disturb other people's concentration on the concert.



(a) (b)

Figure 1: (a) Perspective drawing of the structures of the wooden concert hall, the Sibelius House, in Lahti Finland. Samples of the balconies are shown in a circle in the middle of the drawing. (b) Dimensions and structure of a balcony element. Ribs of the element are made of 51 mm thick KERTO S -LVL and skin boards are made of 51 mm thick KERTO Q -LVL. The ribs and the boards are joined together with screws and polyurethane glue.

The objective of this research was to find out what kind of criteria and recommendations of vibrations and deflections do the standards and instructions of different countries have for this kind of structures and do these balconies fulfil them.

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Another objective was to find the critical properties of the structure and how they can be improved. At first a literature study was made. It concerned character of different excitations, human reactions to vibrations, standards, instructions and evaluation methods of floor vibrations and influences of various structural solutions on the vibration performance of floors. Then the vibration performance of the balcony structure was evaluated by dynamic calculations based on simplified calculation methods and finite element method (FEM) models. There is no fully satisfactory ready-to-use calculation method for this complicated structure, so it was necessary to build a FEM model for the vibration analysis and to verify its accuracy. Further, because the manufacturing technology of these glued stressed skin elements is new, it is also reasonable to produce and examine a 1:1 scale test element before building the real structures of the concert hall. The vibration performance of the test element was tested by deflection tests, human induced vibration tests, mode analysis and subjective tests. This way the proper performance of the real structure was ensured and the building authorities became convinced about the adequacy of the structures. This study was made in short-term time class and indoor climate conditions.

STANDARDS AND INSTRUCTIONS OF FLOOR VIBRATIONS

Measured or calculated vibration magnitudes i.e. accelerations, velocities and displacements need to be evaluated to find out whether the effects of vibration can be tolerated or not. In only a few cases the acceptance criteria represent more or less agreed bounds; much more often they indicate a practicable order or magnitude with a certain scatter. Acceptance criteria for vibration are set according to the use of the structure. In floor or balcony structures it is very rare that vibrations cause damages, but they can disturb the serviceability of a structure.

Finnish Building Regulations: Wooden Structures B 10

In Finnish regulations it is stated that the loads which can appear during the use of a structure must not do any harm to the structure or to the users. Serviceability of floor structures is regulated by limiting the static deflection under serviceability limit state load to L/200-L/300 depending on the use and the location of the structure. From the vibrations point of view this is not enough, because the behaviours of the structure under static and dynamic loads are different.

ISO 2631: Evaluation of Human Exposure to Whole-body Vibration

Standard ISO 2631 part 1: Evaluation of Human Exposure to Whole-body Vibration covers all effects on people from periodic or transient vibrations in the frequency range of 1 to 80 Hz. Three different levels of human discomfort are distinguished: "*reduced comfort boundary*", "*fatigue-decreased proficiency boundary*" and "*exposure limit*". The acceleration limits are given as a function of frequency and exposure time. The limits also depend on the direction of the vibration, people are more sensitive to horizontal vibration that to vertical vibration when the frequency is lower than 2 Hz. When the vibration frequency is higher than 2 Hz, vertical vibration becomes more disturbing. Revision of ISO 2631-1.2 introduces different calculation methods and weighting factors for various vibrations. Unfortunately there are still very few reference values available for these calculations methods.

Standard ISO 2631 part 2 has instructions for continuous and shock-induced vibration in buildings. Acceptability of structural vibrations in buildings can be evaluated by comparing to the base curves defined in ISO 2631-2. The base curves represent magnitudes of approximately equal human response with respect to human annoyance. The acceptable vibration levels depending on the place and duration of the vibration are obtained by multiplying factors. The highest measured acceleration and velocity at one-third octave band centre frequency determines the value which is to be compared with the acceptable level. Tolerable vibrations in residential buildings vary a lot. This shows how subjective a matter the sensitivity to vibration is and how difficult it is to set any accurate limit value for vibrations. However, Eurocode 5 part 2: Bridges (1995) gives an accurate multiplying factor of 60 for pedestrian bridges. The most suitable reference value in the case of concert hall balconies is the residential, daytime, transient vibration excitation which gives the magnification factor 30 to 90.

Standard DIN 4150, Part 2 (1975)

DIN 4150 deals with the effects of vibrations from mostly external sources on people in residential buildings and it considers the frequencies from 1 to 80 Hz. DIN 4150 defines an empirically derived intensity of perception called "KB value":

$$KB = u * \frac{0,8 * f^2}{\sqrt{1 + 0,032 * f^2}} \tag{1}$$

in which: u = displacement amplitude [mm] and f = vibration frequency [Hz]. The KB value of the measured vibration calculated in this way is to be compared with a reference value in the standard according to the use of the building, frequency of occurrence, duration of effects and time of day of occurrence. The most suitable reference value in the case of concert hall balconies is the residential, daytime, infrequent which gives the acceptable KB intensity of 4.

Eurocode 5: Design of Timber Structures (ENV 1995-1-1)

Eurocode 5 gives vibration criteria only for floors. In other structures it refers to ISO 2631. According to EC5 the floor of a wooden residential building is acceptable, when

- The lowest natural frequency f_1 is higher than 8 Hz.
- Maximum deflection under a 1.0 kN point load must be smaller than 1.5 mm
- Vibration velocity $v_{vel,max}$ caused by high-frequency impulsive force components of up to 40 Hz must be lower than $v_{max,limit}$. The equation for $v_{max,limit}$ is:

$$v_{max,limit} = 100^{(f\gamma-1)}\ [(m/s)/(Ns)] \tag{2}$$

in which f = fundamental frequency ≥ 8 Hz and γ = modal damping ratio which may be taken as 0.01 (1%) for ordinary wood-based floors unless other values are proved to be more appropriate. In the calculations the floor is unloaded. In other words only the self-weight of the floor is taken into consideration. To estimate the lowest natural frequency, an equation of a beam simply supported from its ends can be used.

$$f_0 = \frac{\pi}{2L^2}\sqrt{\frac{(EI)_l}{m}} \tag{3}$$

in which L = span of the floor [m], m = mass per unit area [kg/m^2] and $(EI)_l$ = equivalent plate bending rigidity per unit width in direction of the span [Nm^2/m]

North American Instructions for Vibrations

Chui (1988) has tested wooden floors with heel-drop impact test. The impact is produced by the observer dropping his heels rapidly through a distance of about 65 mm According to his experimental work on both laboratory and in-situ floors, a suitable limit for domestic floor structures is a_{rms} < 0.45 m/s^2. This refers to motion experienced by a human observer, standing in the centre of the floor when he himself produces the heel-drop impact.

In USA Dolan, Murray, Johnsson, Runte and Shue (1999) have proposed that the lowest natural frequency of unoccupied lightweight floors should be greater than 15 Hz and greater than 14 Hz in occupied conditions. When calculating the predicted natural frequency, composite action between the subflooring and joists is to be neglected as well as effects of damping since damping cannot be controlled at design stage. This is a simple criterion and it is based on vibration tests of 126 floors in unoccupied conditions and 54 floors in occupied conditions. It eliminates all rated unacceptable floors, but it is quite conservative, because it also eliminates many acceptable floor structures.

Canadian, Danish and Norwegian Instructions for Maximum Deflection under a 1.0 kN Point Load

In Canada Onysko (1998) has proposed that vibration of wooden floors should be controlled by limiting the vertical deflection u under a static 1.0 kN point load according to the equation:

$$u_{max} = 0.6 + 2.5 * \exp[-0.6 * (L-2)] \leq 2mm \tag{4}$$

in which L = span length. This criterion is much stricter than the 1.5 mm criterion given in EC5. Especially with longer spans it considers the possibility of resonance caused by several impulses in row along the span. By shorter spans this is not a problem and therefore bigger deflections are allowed. According to Pynnönen and Laavola (1990), Denmark and Norway have limited the deflection under a 1 kN point load to 0.9 mm which is a rather strict requirement. According to the acceptable acceleration values for domestic and office building floors given in ISO 2631-2 the maximum deflection under a 1 kN concentrated load should be less than 0.8 mm. When it is expressed in this way it can be seen that the requirements of ISO standard is also strict. In the case of the Lahti concert hall, the span length is 8.1 meters which means that Onysko's criterion will set the hardest requirements for this structure.

EXPERIMENTAL ARRANGEMENTS

The vibration tests were made in the experiment hall of the Technical Research Centre of Finland (VTT) on a massive reinforced concrete base floor. The floor is so massive and stiff that it does not affect the results of vibration tests. The aim of the experiments was to find out the significance of human induced vibrations. The experiments were done according to a test procedure developed at the Technical Research Centre of Finland. It included the following stages:

a) Measuring the static deflection under a1 kN point load and comparing the results with design criteria.
b) Measuring the human motion induced vibrations. Excitation was in the first phase a 75kg man walking on the element in a frequency of 2 Hz and in the second phase a 75 kg man making heel-drop impacts by dropping his heels rapidly through a distance of about 65 mm.
c) Measuring the natural frequencies, natural modes and viscous damping of the balcony element.
d) Subjective observation of the intensity and acceptability of human induced vibrations.

The test element was tested in two different primary support conditions and in one additional support condition. In the first series (test 1) the element was supported from its ends on two 183*540 mm^2 LVL cantilever beams which were glued together from three KERTO S lamellas. These cantilever beams simulated the 215*540 mm^2 cantilever beams of the gluelam frame of the concert hall. The width of the LVL beams is smaller than the width of the gluelam beams, because LVL has higher bending stiffness than gluelam. The aim of the first series was to examine the interaction behaviour of the element and the gluelam frame, because bending of the cantilever beams can have a significant effect on the dynamic performance of the balcony. The arrangement of the test series 1 is described in figure 2.

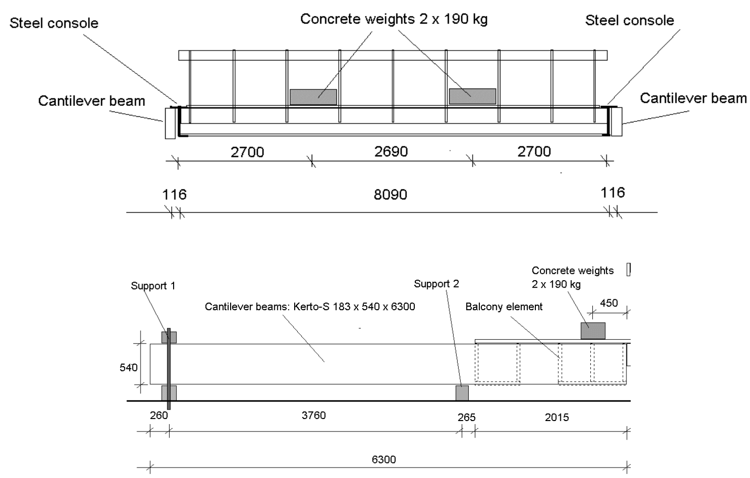

Figure 2: Experiment arrangement and dimensions in test series 1 which simulate the support condition of the balconies in the concert hall. In test series 2 the balcony element was supported from its both ends on a solid concrete floor. Two 190 kg concrete weights on the element represented the weight of the floor surface materials and the seats of the balcony.

In test series 2 the element was supported from its ends on solid steel beams which lie on the concrete floor. The aim in series 2 was to examine the vibration performance of the element itself and compare the results with the results of FEM modelling. Because in the tests of the first series (test 1) it was noticed that the horizontal movements were disturbingly strong, a third additional test arrangement was done. There the balcony element was set on cantilever beams and the whole system was wedged between two heavy concrete cubes to prevent the horizontal movements.

RESULTS AND DISCUSSION

Maximum Deflection Under a 1 kN Point Load

When the element was supported from its ends on a solid base in test series 2, the deflection under a 1 kN point load in the middle of the span was 0.12 mm. In test series 1 where the element was set on cantilever beams, the deflection in the midpoint increased to 0.21 mm because of a bending of the beams. Largest deflection 0.36 mm was measured at the end of the cantilever beam when the 1 kN point load was also at the end of the cantilever beam. In the real structure, two

cantilever beams will be bound together which reduces the deflection at the ends of the beams. This means that the maximum deflection will be in the middle of the balcony element. The measured deflections are considerably lower than the limit values given in all standards and instructions, see figure 3.

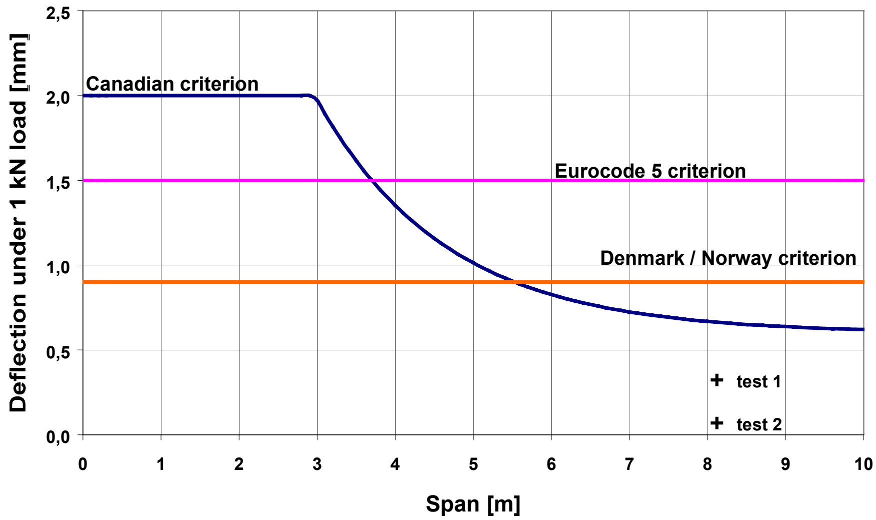

Figure 3: Measured deflection under a 1 kN point load compared to limit values of the Canadian criterion, the Eurocode 5 and the Scandinavian criterion. Test 1 is the element set on cantilever beams. Test 2 is the element set on a solid base. The test results are marked with (+) -signs to the graph.

Human Induced Vibrations

Excitation in human-induced vibration tests was in the first phase a 75kg man walking on the element in a frequency of 2 Hz and in the second phase a 75 kg man making heel-drop impacts by dropping his heels rapidly through a distance of about 65 mm. The test results are shown in tables 1 and 2.

Table 1: Key values of walking induced vibrations. Series 1 is the balcony element set on cantilever beams, series 2 is the balcony supported from its ends on a solid base. In test a the motion transducer box was across the span direction of the balcony element and in test b it was parallel to the span direction. 1-hor means horizontal movement in the support condition of test 1. All the other figures are values of vertical vibrations.

Test	$\|a_{max}\|$ m/s^2	$\|v_{max}\|$ mm/s	$\|u_{max}\|$ mm	a_{rms} m/s^2	$a_{w,max}$ m/s^2	F Hz	ISO-Factor	a_w m/s^2	KB Value
1a	0,23	4	0,10	0,09	0,067	8	13	0,09	2.9
1b	0,27	4	0,13	0,09	0,071	8	14	0,09	3.8
2a	0,38	4	0,05	0,16	0,11	16	23	0,16	3.4
2b	0,34	3	0,05	0,12	0,08	16	17	0,12	3.4
1-hor	0,26	9	0,33	0,12	0,11	5	22	0,12	4.9

The effective acceleration results $a_{w,max}$ can be compared directly to the base value 0.005 m/s^2 presented in ISO 2631-2 (1989). This comparison is usually done by calculating the ratio between the effective acceleration and the base value. For this relation, which can be called the ISO-factor, only suggestive reference values have been given. For residential buildings this factor is allowed to be 30-90 during the day and 1.4-20 during the night when the transient vibration excitation occurs several times a day. A reference value 60 has been given for pedestrian bridges in EC5, part 2 (1995). According to the test made with lightweight steel floor by Kullaa & Talja 1999, floors which had the ISO factor smaller than 15 were normally considered acceptable by test persons. Only the test 2a has notably higher ISO factor (23) for vertical vibrations.

Horizontal vibrations in the test 1-hor are, according to the accelerations, about as strong as the vertical vibrations. To be able to compare the vibrations accurately, the results of horizontal vibrations should be weighted with the weighting function W_d instead of W_k of ISO 2631-1.2 (1995) as it has been done here. In the determining frequency range of 5 Hz,

the weighting function W_k is, however, only 25 % too large which means that the ISO factor of horizontal vibrations can be compared directly with the ISO-factor of vertical vibrations.

Unfortunately there are no common reference values for the square sum of the weighted acceleration a_w. According to the light-weight steel floor tests of Kullaa & Talja (1999), floors which had walking induced acceleration a_w smaller than 0.1 m/s^2 were generally regarded acceptable. Acceleration values a_w of the balcony element are of about this magnitude or even a bit higher, but as told before there are no official reference values for a_w. Kullaa & Talja noticed in steel floor tests that walking induced dynamic displacement u_{max} described the acceptability of a floor better than acceleration. When u_{max} was smaller than 0.15 mm, the floors were generally regarded acceptable. All measured vertical displacements u_{max} of the balcony element were smaller than 0.15 mm. The horizontal displacement 0.33 mm in support arrangement 1 was more than two times larger. This explains for the most part the disturbance in the test series 1.

The determining frequency of vertical vibrations was 16 Hz for the element supported from its ends on a solid base and 8 Hz when the element was set on cantilever beams. The frequency of horizontal vibrations was 5 Hz for the element set on cantilever beams. These can be presumed to be close to the frequencies of the lowest natural modes of the structure.
KB values of the German standard DIN 4150 were calculated using the equation (1). KB values of vertical vibration varied between 2.9 and 3.4. The most suitable reference value is the residential, daytime, infrequent vibration which gives the acceptable KB intensity of 4. So, the vertical KB values were smaller. Horizontal KB value 4.9 is bigger than recommended.

Table 2: Key values of heel-drop induced vibrations. Series 1 is the balcony element set on cantilever beams, series 2 is the balcony supported from its ends on a solid base. In test a the motion transducer box was across the span direction of balcony element and in test b it was parallel to the span direction. 1-hor means horizontal movement in the support condition of test 1. All the other figures are values of vertical vibrations.

Test	$\|a_{max}\|$ m/s^2	$\|v_{max}\|$ mm/s	$\|u_{max}\|$ mm	a_{rms} m/s^2	$a_{w,max}$ m/s^2	f Hz	ISO-Factor	a_w m/s^2	KB Value
1a	0,86	15	0,32	0,30	0,26	8	53	0,29	9.4
1b	1,20	18	0,39	0,41	0,36	8	73	0,39	11.4
2a	1,20	11	0,19	0,41	0,28	16	55	0,31	12.8
2b	1,17	12	0,24	0,40	0,27	16	54	0,30	16.2
1-hor	0,13	3	0,09	0,05	0,035	5	7	0,04	1.3

Smith & Chui (1988) have suggested that a floor having the lowest natural frequency higher than 8 Hz, should have the effective acceleration a_{rms} of 1-second measurement period smaller than 0.45 m/s^2, when the floor is loaded by heel-drop impact. According to this criterion all the results are acceptable. Unfortunately no reference values have been presented for the other key values of table 2.

The results also show that the horizontal vibrations caused by heel-drop are smaller than the walking induced vibrations (1-hor). One reason for this is that heel-drop is an impulse load and it does not create resonance in the structure like periodic load walking does. Another reason is that the horizontal components of heel-drop load are much smaller than the horizontal components of walking.

Natural Modes and Damping

The lowest measured vertical natural frequency was 17.4 Hz for the element supported from its ends on a solid base and 8.1 Hz for the element set on cantilever beams. Both values are higher than the minimum of 8 Hz normally set for lightweight floors (Eurocode 5 and Smith & Chui 1988). On cantilever beams, the fundamental natural frequency is only half of the natural frequency of the solid base supported case. Also the damping values are smaller when the element is set on cantilever beams which means that the internal damping of the cantilever beams is smaller than the damping of the element. The measured damping values of 0.57 % and 0.85% for the fundamental natural frequencies are very small. Normal values of damping given in literature are between 1 and 3 % (Ohlsson 1988, Smith & Chui 1988, Kullaa & Talja 1999). This means that the glued joints of the stressed skin LVL balcony element are rigid and the structure acts as a static unit.

Table 3: Four lowest natural frequencies and their corresponding damping values.

Test 1			Test 2		
Natural mode	Frequency (Hz)	Damping (%)	Natural mode	Frequency (Hz)	Damping (%)
1	8.1	0.57	1	17.4	0.85
2	17.3	1.20	2	23.5	1.96
3	19.4	1.05	3	26.5	2.48
4	36.7	1.36	4	39.4	1.40

The lowest natural frequency measured in test series 2 is about 19% lower than the lowest natural frequency of the FEM analysis and 26 % lower that the result of simplified calculations. Higher natural frequencies of the test 2 and the FEM analysis are quite close to each other. FEM models generally tend to describe structures a bit more stiff than they are in reality, which makes the natural frequencies higher. Another reason for the difference can be that in the FEM model the surface load is a uniform load and in the test arrangement the surface load is described with two concrete weights on the element. In manual calculations the balcony element was simplified to a one-dimensional beam in which the shear deformations were ignored. One reason for the lower value of the measured lowest natural frequency could be a flexibility of the support conditions. Although the element was supported on a solid base, the contact between the supports and the ends of the element had some flexibility because of the work tolerances.

Table 4: Natural frequencies according to the measurements, FEM analysis and simplified calculations

Mode number	Measured frequencies	Results of FEM analysis	Result of simplified calculations
1	17.4 Hz	21.4 Hz	23.5 Hz
2	23.5 Hz	25.7 Hz	-
3	26.5 Hz	28.3 Hz	-
4	39.4 Hz	38.5 Hz	-

The mode shapes of the FEM analysis shown in figure 4 and the measured mode shapes shown in figure 5 fit quite well together, except two peaks in the measured mode shapes. Those peaks are caused by the concrete weights on the test element. The first mode is clearly the natural vibration of the whole structure in span direction. In the second and fourth modes the box beams are vibrating in slightly different rhythms and the mode shape is not as clear as for the first one. The third vibration mode is vibration across the span direction. In FEM analysis the second and third mode shapes were vibrations of the box beams in different rhythms and the fourth mode was vibration across span direction. Because the across span vibration appeared in a lower frequency in the measured modes, the stiffness of the element across the span direction is a bit smaller than in the FEM model.

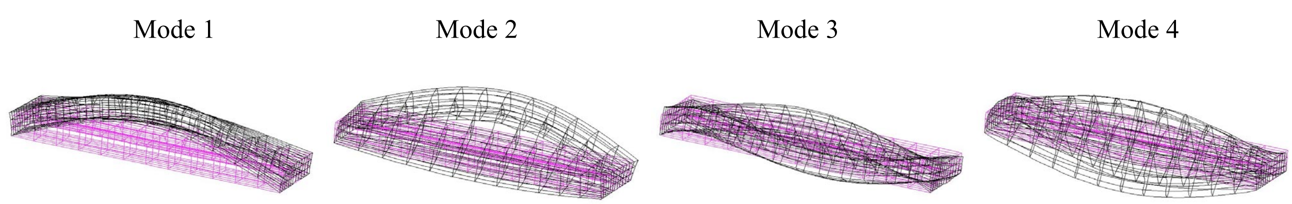

Figure 4: Four lowest natural modes of the LVL balcony element

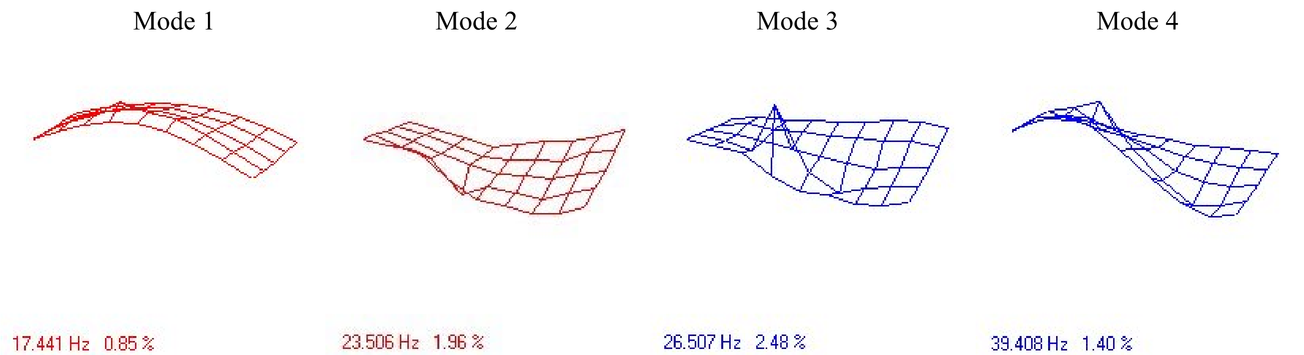

Figure 5: Four lowest natural modes of the element supported from its ends directly on a massive concrete floor (test 2).

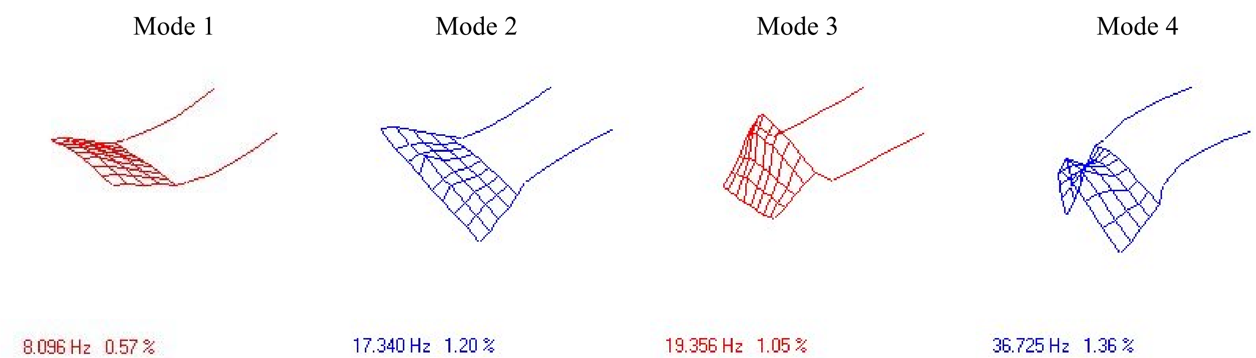

Figure 6: Four lowest natural modes of the element set on cantilever beams (test 1)

From the natural modes it can be seen that the lowest natural modes strongly depend on the deflection of the cantilever beams. In the first mode both beams are bending to the same direction with a frequency of 8.1 Hz and in the second mode they are bending to opposite directions with a frequency of 17.3 Hz. In the natural mode corresponding to the frequency of 19.4 Hz it can be seen that the element dips on the cantilever beams. Horizontal natural modes were not determined with the mode analysis, but according to walking and heel-drop tests, the lowest natural frequency of the system is about 5 Hz. This is considerably lower than 8 Hz which is the minimum requirement for vertical vibrations.

Subjective Tests

In developing criteria for a subjective vibration test, the Technical Research Centre of Finland has normally used the test of body perception of walking induced vibrations. Because in test situations people are more critical than in normal circumstances, it has been proposed as a criterion that when more than half of the test persons accept the vibrations, the floor is acceptable (Talja & Kullaa 1998, Talja 1999). According to this criterion the floor element set on cantilever beams in test 1 was not acceptable, but the element supported from its ends on solid a base in test 2 was acceptable. Because during the test it was noticed that horizontal vibrations in test 1 may have an influence on the results, the test persons were asked to state their opinions on the test arrangement where horizontal movements were prevented. According to the opinions of test persons, the performance of the floor element in this support condition was close to the performance of the element supported from its ends on a solid base. According to the body perception the vibrations in test 1 were clearly or strongly perceptible. In test 2 they were barely or clearly perceptible.

CONCLUSIONS

The vibration performance of the glued stressed skin LVL balcony structures was analysed theoretically and experimentally. Theoretical analysis corresponded to the test results with good accuracy. The FEM model developed in this study can be used for evaluating the vibration performances of other glued stressed skin LVL structures.

Floor vibrations are controlled by limiting the static deflection under a serviceability limit state load (≤ L/200 – L/360) or under a 1 kN point load (≤ 0.6 mm – 2 mm), by the lowest natural frequency (≥ 8 Hz) and by the vibration magnitudes of displacement, velocity and acceleration. The acceptance criteria for floor vibrations given in different standards and instructions vary a lot. This describes how complex the vibration matters are and how difficult it is to set any accurate limit values, because people react to vibrations in different ways depending on people themselves and the situations in which the possible disturbing vibrations occur. Adequate instructions for high frequency floor vibrations are given in standards ISO 2631, DIN 4150, Eurocode 5 and in some North American instructions.

The vibration tests showed that the properties of the glued stressed skin LVL element are adequate for the balcony structures of the Lahti concert hall. The maximum static deflection of the test element under a 1 kN point load was 0.21 mm in the middle of the element which is clearly smaller than the limit values of standards. The human induced vibrations were also smaller than the permissible values of vertical vibrations, but horizontal vibrations when the element was set on cantilever beams were larger. The lowest natural frequency of the element supported from its ends on a solid base was 17.4 Hz and when it was supported on cantilever beams the frequency was 8.1 Hz. According to subjective tests, the vibrations of the test element were perceptible in both support conditions. The vibrations were regarded acceptable for a concert hall balcony, when the element was supported from its ends on a solid base. When the element was set on cantilever beams, the vibrations were regarded unacceptable, but when horizontal movements of the cantilever beams were prevented, the vibration performance of the structure was regarded almost as good as when the element was supported on a solid base.

Although the research group was conscious about problems which might occur with the cantilever beams, the influence of horizontal movements was still underestimated. Structural designers of the Lahti concert hall were informed about this weakness of the balcony structure and they developed the final structure so that cantilever beams on both sides of the gluelam frames are tightened together with blocks and steel bars. Further, the steel consoles which connect the balcony elements to the cantilever beams are much more robust than the consoles used in the vibration tests. The balcony elements are also wedged tightly between the cantilever beams so that whole balcony rows will function together. These actions improve the horizontal stiffness of the structure.

ACKOWLEDGEMENTS

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