inter.noise 2010
noise and sustainability
13-16 June 2010 . Lisbon . Portugal
www.internoise2010.org

Vibration properties of a timber floor assessed in laboratory and during building construction

Jarnerö K.; Brandt A.; Olsson A.

Technical Research Institute of Sweden, SP Trätek, Växjö, Sweden
{kirsi.jarnero@sp.se}
Department of Industrial and Civil Engineering, University of Southern Denmark
{abra@ib.sdu.dk}
School of Engineering, Linnaeus University, Växjö, Sweden
{anders.olsson@lnu.se}

Abstract
In the present work the change in natural frequencies, damping and mode shapes of a prefabricated timber floor element have been investigated when it was integrated into a building structure. The timber floor element was first subjected to modal testing in laboratory with ungrounded and simply supported boundary conditions, and then in situ at different stages of building construction. The first five natural frequencies, damping ratios and mode shapes of the floor element and the entire floor were extracted and analysed. It may be concluded that the major change in natural frequencies occur as the floor element is coupled to the adjacent elements and when partitions are built in the studied room, the largest effect is on those modes of vibration that largely are constrained in their movement. The in situ conditions have a great influence on the damping, which depends on the damping characteristics of the supports, but also on the fact that the floor is integrated into the building and interacts with it. There is a slight increase of damping in the floor over the different construction stages and the damping values seem to decrease with ascending mode order.

Keywords: timber floor, vibration, damping, frequency, mode shape

1 Introduction

In Växjö, Sweden, four eight storey timber frame residential buildings have been finished in the spring of 2009. The building system consists of prefabricated timber wall and floor elements. During the erection of the first and second building in situ vibration measurements were carried out in order to investigate the vibration performance of the timber floors. The change in vibration properties was studied by means of testing a single floor element, first in laboratory and then in situ at different stages of erection. The vibration properties of a floor changes as it is integrated in the structural system adding parts like supplementary surface layers, possible partitions, fittings and fixtures. These parts influence both floor mass and stiffness and consequently also the natural frequencies and the corresponding modes of vibrations determining the vibration performance of the floor. The interaction with the surrounding parts also has an influence on the damping properties. The damping is highly dependent on the assembly of these parts and will therefore change as parts are added. The damping affects the time it takes a vibration to decay. In contrast to mass and stiffness it is difficult to calculate the degree of damping in advance in a structure. In the building code the influence of damping is taken into consideration and has in the design calculations of floor performance due to vibrations a fixed rate. In Eurocode 5 (EC5) [1] the damping value is one of the design parameters that is defined in the national application document of each country. In Sweden the value is set to 1 % [2], which might be considered low and will yield results on the "safe side" compared to the UK that uses a value of 2 % [3]. The floor structures considered in the building code are traditional types of floors with joists in the load bearing direction and some kind of a sheathing on top of the joists that may be considered contributing to the load bearing capacity if properly fastened to the joists. Other types of floor structures with no discrete joists, with the stiffness more evenly distributed along the width and with higher stiffness in the direction perpendicular to the load bearing direction are not embraced by the design code [1] and consequently the design guidelines should then be used with consideration.

2 Aim and scope

The aim of the current work has been to investigate the change in natural frequencies and damping of a prefabricated timber floor element when integrated into a building structure. The main interest has been to study the frequency range below 50 Hz, since a human step contains the force components up to this level.

3 Evaluated structure and measurements

3.1 Prefabricated floor element

The prefabricated floor elements in the Limnologen project are generally 2400 mm wide and consist of a three-layer cross-laminated timber (CLT) board and glulam beams with center distance 460 mm in the load carrying part of the floor. The CLT board at the top of the element is 73 mm thick and the beams underneath consist of C40 glulam webs and flanges, with dimensions 42×220 mm^2 and 56×180 mm^2 respectively, see Figure 1. The beams are both glued and screwed to the CLT. The space between the beams is filled with mineral wool. The ceiling is separated from the load carrying part and is self-supporting on the walls in the underlying room. Half of the secondary spaced boarding in the ceiling is pre-assembled at the factory and the rest is nailed up in situ.

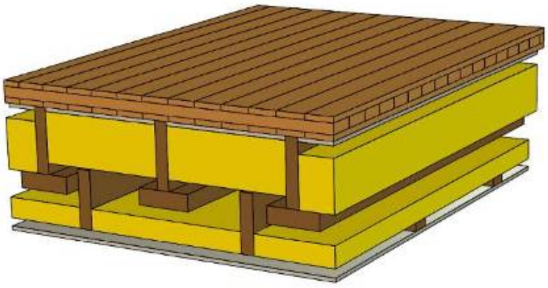


Figure 1 - Basic layout sketch of floor element and a photo of the end part of a floor element when installed. A Sylodyn® strip may be seen on top of the wall.

The ends of the floor elements are placed on the walls or beams below resting only on the CLT board, meaning that the glulam beams are cut off at the ends of an element and not laid up on the supports. The floor elements also rest on walls parallel with the load bearing direction only on the CLT board, which implies that the floors to some extent are load bearing in two directions. In cases where the floor has an intermediate support the glulam beams are continuous over the support. To reduce the flanking transmission strips of Sylodyn® are placed between the supporting walls and the CLT board at all supports as shown in Figure 1. The stiffness of the Sylodyn® strips is adjusted to the expected final loading.

3.2 Measurements

To investigate how the damping in a floor changes as it is integrated in the building a simply supported floor in a 3.1 m wide and 5.2 m long bedroom on storey three in one of the buildings was tested, see Figure 2. The same floor on the same storey was subjected to testing at different stages of building construction as follows:

1. *Uncoupled* test, when the floor had been laid up on the supporting walls and fastened, but still not coupled to the adjacent floor elements. The ceiling in beneath was lowered to its final position on the walls in the room below i.e. in no contact with the load bearing floor structure.
2. *Coupled* test, when the floor elements in the measurement room had been coupled to each other.
3. *3rd walls* test, after the erection of load bearing walls on the measurement storey 3.
4. *3rd floor* test, after installing floor elements on top of the walls in storey 3.
5. *4th storey* test, when erection of walls and floor elements of storey 4 was completed.
6. *6th and 7th* storey test, when erection of storey 5, 6 and walls on storey 7 was completed.
7. *7th and 8th storey* test, when the floor elements on top of the walls on storey 7 and the walls on of the top storey 8 had been installed, the partitions in the measurement room was built, plasterboard had been installed on walls and ceiling, and the stabilizing tie-rods had been pre-tensioned, but before the roof had been erected.

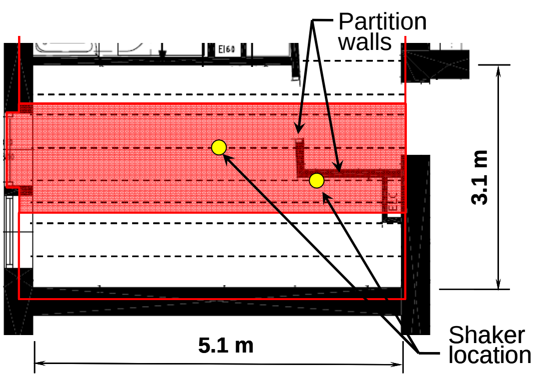


Figure 2 - Bedroom plan and suspension of shaker from tripod in situ. The location of the shaker on bedroom floor is marked with yellow dots. The red area marks the floor element that also was tested in laboratory. The dashed lines correspond to the beams beneath the floor.

In laboratory two tests were performed on a copy of the the floor element in the bedroom floor marked red in Figure 2. The test specimen was tested both with ungrounded and simply supported support conditions. Only the load carrying part of the floor element was tested i.e. it had no ceiling underneath and there was also no mineral wool installed between the load bearing glulam beams.

3.3 Test setup

The floor both in situ and in laboratory was excited with an electromagnetic shaker. In the laboratory the excitation was carried out with the shaker suspended from an overhead crane and in situ the shaker was suspended from a tripod standing on the tested floor, as shown in Figure 2. The floor response was measured at 9 points along each of the glulam beams of the floor. To excite both the first and second bending modes two different locations of the shaker were used; a symmetrical and an asymmetrical location as shown in Figure 2. The location of the excitation on the simply supported floor element in laboratory coincides with the excitation locations of the floor element in situ. The simply supported support condition was accomplished with a steel beam that was underpinned with concrete on the floor and a wooden beam placed on top of the steel beam to support the CLT board as shown in Figure 3. The ungrounded condition in the laboratory test was accomplished by placing the floor on spring mattresses as shown in Figure 3. The shaker was during this test located in two diagonal corners of the floor element (corner 1 and 4).

Figure 3 - Laboratory setup, ungrounded and simply supported support conditions

3.4 Checks of FRF data

3.4.1 Coherence

During testing a check of the coherence function of each channel was observed to ensure that the value was close to unity in the studied frequency range and that possible drops did not occur at resonances. If a measurement showed dropping coherence function it was interrupted and remade after check and adjustment of equipment and setup. The cause to dropping coherence could be for instance a loose accelerometer or disturbing vibrations from other parts of the building. The coherence function was very close to unity in the frequency range above approximately 10 Hz and the estimated FRF:s are of good quality in the frequency range of interest. Some problems were identified below approximately 10 Hz is due to the limited inertial mass of the shaker.

3.4.2 Reciprocity

The FRF:s was collected at 15 points simultaneously, but with a single excitation. As the excitation was performed at two different points at different occasions on the floor structure, two sets of FRF:s were obtained from both in situ and laboratory measurements. A check of the reciprocity between the two data sets i.e. the transfer mobility between the two different excitation points, the symmetrical and the asymmetrical one was made. A perfect reciprocity would result in two identical FRF:s. In the performed tests the reciprocity was almost identical in the laboratory tests, when the shaker was suspended from an overhead crane, but for the in situ tests, when the shaker was suspended from a tripod on the floor, there were some differences, especially in the frequency range above 60 Hz. These differences indicate that there might be a problem with the reciprocity of the data. This could be due to the loading of the floor with the weight of the tripod and shaker or that the shaker is not decoupled from the building structure and influences the excitation load.

4 Experimental modal analysis and FE modeling

The natural frequencies, damping ratios and the mode shapes were extracted by means of experimental modal analysis. The different methods of modal analysis and the steps during analysis are explained in more detail in references [4] and [6].
To analyze the laboratory test measurements the polyreference time domain (PTD) method was used and the extraction of modal parameters was not too difficult since the FRF data were quite clear with well separated resonances. To analyze the in situ test measurements proved to be laborious due to complex and coupled modes. First the PTD method was used, but the results proved not to be stable, the frequencies and damping values shifted and the mode shapes were very hard to distinguish. Further analysis was performed with a CMIF (Complex Mode Indicator Function) that gave stable results but sometimes clearly overestimated the damping values of resonances with low amplitude or those close to a high amplitude resonance. In the final curve-fitting the frequency and damping of each mode were fitted to the measured FRF:s. The damping values of the resonances that in the earlier CMIF analysis were too high were now adjusted to lower values that gave a more probable curve-fit. The percentage difference between synthesized and measured FRF:s were calculated over the frequency range covering the extracted frequencies. A total error smaller than 20 % over the frequency range was considered an acceptable curve-fit. As an example the average error between the FRF:s was 16 % for both symmetrical and asymmetrical excitation for the 4th storey test. The error of the simply supported floor test in laboratory was better over the whole frequency range compared to the ungrounded floor test in laboratory, with 18 % and 27 % averaged error respectively. The high error of the ungrounded test may be explained by the fact that the antiresonance parts of the FRF that are pronounced in this test, are very sensitive to differences and therefore the curve-fitting may be expected to be worse in these parts.

A finite element model of the floor structure was established in order to enable an eigenvalue analysis of it. The floor element was modeled with solid hexahedral structural elements (Abaqus C3D8R element) with reduced integration and size 10 mm. The support conditions from the laboratory setup, ungrounded and simply supported, were simulated. The material properties used for modeling the CLT board and the glulam are presented in **Error! Reference source not found.**.

Material	E_l (MPa)	E_t (MPa)	E_r (MPa)	ν_{lt} (-)	ν_{lr} (-)	ν_{rt} (-)	G_{lt} (MPa)	G_{lr} (MPa)	G_{rt} (MPa)	ρ (kg/m^3)
CLT	13700	400	400	0.5	0.5	0.7	750	750	75	420
Glulam C40	13700	400	400	0.5	0.5	0.7	750	750	75	420

Table 1 - Material properties used modeling the CLT board and glulam of the floor elements.

The CLT board is modeled with consideration to the orientation of the three layers of boards, the two outer layers in the load bearing direction of the floor element and the inner layer perpendicular to this. In the model full interaction between the layers are assumed.

5 Results and discussion

In Table 2 the first four natural frequencies, damping ratios and mode shapes from the laboratory tests of the ungrounded support conditions are shown. For comparison the calculated eigenfrequencies and mode shapes from the FE analysis are also presented. When comparing the test and FE results for the ungrounded support conditions the first natural frequency seems to be accurate considering both frequency and mode shape, while the second one corresponds regarding the shape but not the frequency that has a higher value from laboratory test. This suggests that the stiffness properties used in the FE analysis are taken to too low or the mass too high. The higher modes in turn differ both in frequency and shape suggesting that the mode shapes from the FE analysis have not been found in the experimental analysis. In Table 3 the first five natural frequencies, damping ratios and mode shapes from the laboratory tests with simply supported support conditions and eigenfrequencies and mode shapes from a FE analysis performed with the corresponding boundary conditions are presented. The results from in situ testing of the uncoupled floor element and the entire floor after the 4th storey had been erected are also presented in Table 3. The same phenomenon of missing mode shapes from the experimental modal analysis may be observed here. When taking a closer look at the mode shapes from the FE analysis it is seen that the major movement in the floor is located to the beams underneath and just minor vertical movement is found in the floor surface. As the response is measured just in the vertical direction of the floor surface it is not surprising that these movements are not captured by the measurements. Another reason to the appearant mismatch of mode shapes could be that the spacing of the measurement points in the tests is too coarse. The points are all placed above the beams and therefore not able to capture the movement of the floor surface between the beams.

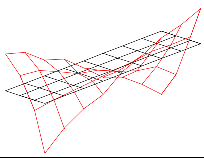
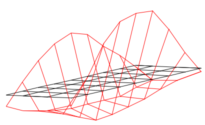
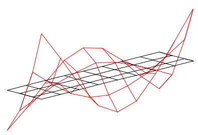
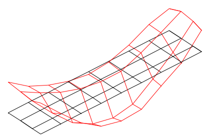
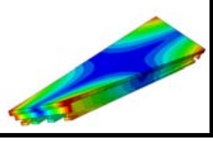
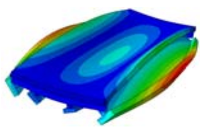
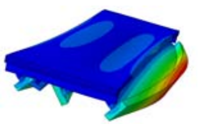
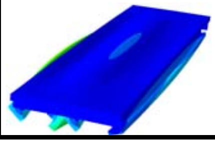
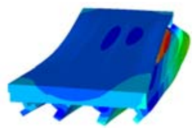
	Mode 1		**Mode 2**		**Mode 3**		**Mode 4**		**Mode 5**	
	Freq. (Hz)	**Damp.** (%)	**Freq.** (Hz)	**Damp.** (%)	**Freq.** (Hz)	**Damp.** (%)	**Freq.** (Hz)	**Damp.** (%)	**Freq.** (Hz)	**Damp.** (%)
Lab. ungrounded	8.8	1.4	23.1	1.7	53.1	1.2	54.2	1.7	-	-
									-	
FEM ungrounded	9.3	-	32.4	-	38.2	-	40.5	-	48.6	-
										

Table 2 - Frequency, damping ratio and mode shapes for ungrounded laboratory tests and corresponding frequencies and mode shapes from FE analysis.

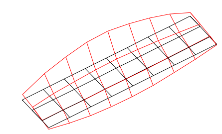
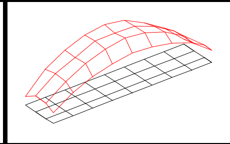
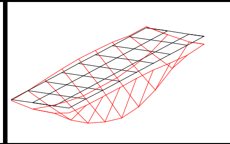
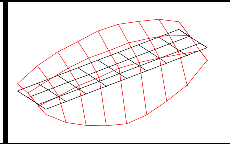
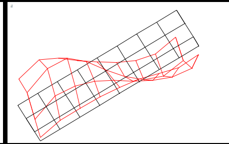
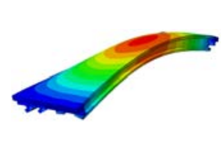
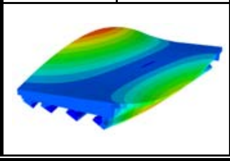
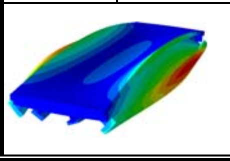
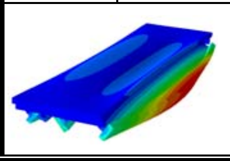
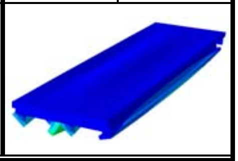
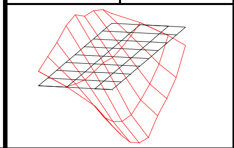
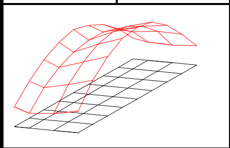
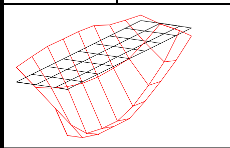
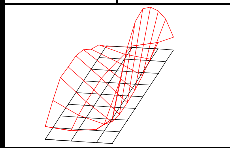
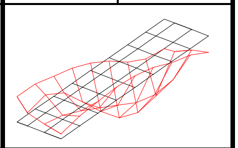
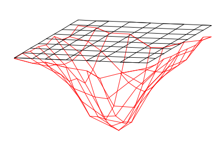
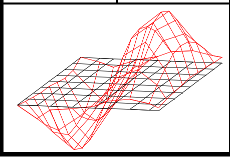
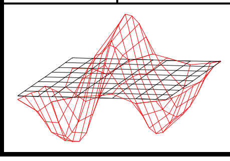
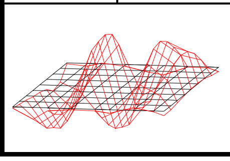
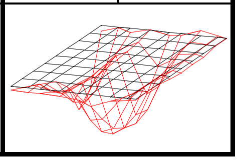
	Mode 1		Mode 2		Mode 3		Mode 4		Mode 5	
	Freq. (Hz)	Damp. (%)	Freq. (Hz)	Damp. (%)	Freq. (Hz)	Damp. (%)	Freq. (Hz)	Damp. (%)	Freq. (Hz)	Damp. (%)
Lab. simply supported	18.8	3.2	20.5	1.8	23.6	1.3	26.2	4.2	37.4	2.4
										
FEM simply supported	30.7	-	32.1	-	33.7	-	38.2	-	40.5	-
										
Uncoupled	19.0	4.0	22.8	8.0	25.9	2.8	28.0	5.0	33.4	8.0
										
4th storey	21.4	4.0	26.4	4.5	33.5	5.3	41.4	4.2	44.1	4.0
										

Table 3 - Frequency, damping ratio and mode shapes for simply supported floor test in laboratory, eigen frequencies and mode shapes from FE analysis for simply supported floor element, frequency, damping ratio and mode shapes for in situ tests for uncoupled floor element and entire floor after the 4th storey had been erected.

In Figure 4 the driving point mobility with symmetrical excitation of all the *in situ* tests and the simply supported laboratory test are plotted. It is clear that the in situ conditions have a large influence on the vibration performance. The resonances of the in situ floor element are flattened and not as obvious as in the laboratory test. This is not surprising since the floor is integrated into the building construction and interacts with it. The change may also depend on the support conditions as the floor in situ rests on the Sylodyn® strips that are put there to reduce the flanking transmission and will inevitably influence the vibration performance by reducing the vibration levels and introducing more damping to the structure.

In Table 4 and Figure 5 the first five natural frequencies and damping ratios of all the in situ tests and the simply supported laboratory test are presented. When comparing the results from measurements in laboratory and in situ the largest difference in damping occurs between the simply supported laboratory test and the uncoupled test in situ, which as mentioned before most likely is caused by the damping strips of Sylodyn® between the supporting walls and the floor but naturally also due to interaction with the surrounding building structure. It may also, if not so likely, be an effect from the insulation between the beams of the floor element or the ceiling beneath the floor, even if it should not be in contact with the upper load bearing part of the floor. When considering the change of damping values during construction it may, from the averaging of results, be concluded that there is a slight increase of damping over the different construction stages and that the value seems to decrease with ascending mode order.

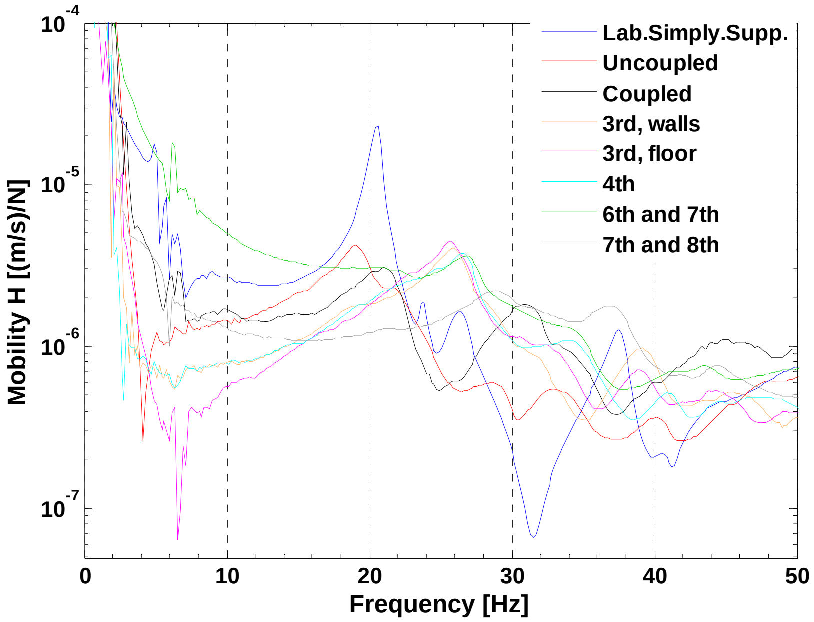


Figure 4 - Driving point mobility with symmetrical excitation of the in situ tests and the simply supported floor test in laboratory.

The average damping ratio of all the tests and modes is 4.8 %. This is a rather high value compared to the value of 1 % stipulated by the construction code. Maybe a higher value could be considered for this new type of structures with specially designed supports, but to assess that further investigations of damping values should be carried out.

	Frequency (Hz)					Damping (%)					
	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Ave-rage
Lab. Simply supported	18.8	20.5	23.6	26.2	37.4	3.2	1.8	1.3	4.2	2.4	2.6
Uncoupled	19.0	21.4	25.9	28.0	33.4	4.0	4.0	2.8	5.0	8.0	4.8
Coupled	21.4	23.4	31.1	34.9	39.6	5.7	5.5	4.3	4.6	3.5	4.7
3rd, walls	22.1	25.9	31.4	34.7	39.0	5.5	4.3	5.5	4.8	4.2	4.9
3rd, floor	23.2	25.7	32.3	38.0	44.1	5.8	4.8	3.9	4.2	4.0	4.5
4th	22.8	26.4	33.5	41.5	44.1	8.0	4.5	5.3	4.2	4.0	5.2
6th and 7th	20.7	22.1	27.0	33.8	39.3	7.0	5.0	5.0	5.6	5.6	5.6
7th and 8th	21.7	23.5	29.3	37.2	46.9	6.5	7.9	6.2	5.0	4.2	6.0
Average From Coupled to 7:th and 8:th test						5.7	4.7	4.3	4.7	4.5	Total average 4.8

Table 4 - The first five natural frequencies and damping ratios of all in situ tests and the simply supported floor test in laboratory

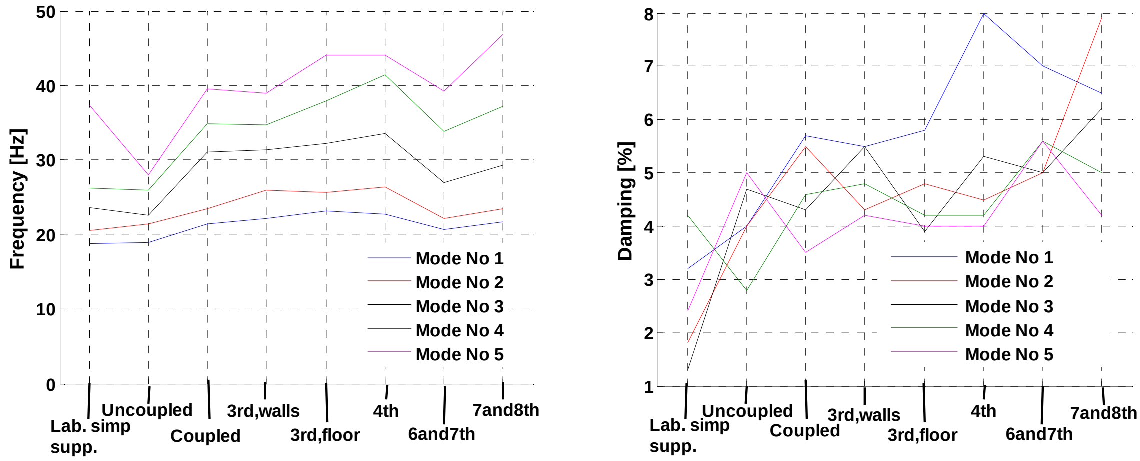


Figure 5 – The first five natural frequencies and damping ratios of all in situ tests and the simply supported floor test in laboratory.

If the frequencies of the uncoupled floor element in situ are compared with the ones for the simply supported test in laboratory the differences are small except for the fifth mode. One explanation of the larger difference here might be that when comparing the mode shapes in Table 3, they are not exactly equal and therefore not quite comparable when it comes to frequency value. When considering the frequency changes during construction it may be pointed out that the major increase seems to occur when the uncoupled floor element is fastened to the adjacent floor elements. This is not surprising since the floor stiffness is increased when the free long side edges have been coupled to the adjacent ones, i.e. it is integrated into the building structure and interacts with it. The second major change occurs between the erections of the 4th storey and the floor elements above the walls of storey 7. In this case the frequency values are reduced and the explanation could be that there was a large pallet with steel studs placed on the floor on storey 4. The frequencies increase again as the floor on the top storey has been installed, partitions in the measurement room built, plasterboards put on the walls and ceiling, and the stabilizing tie-rods had been pre-tensioned, and the pallet of steel studs had been moved away. The main increase in frequency in this case is probably caused by the added stiffness due to the installed partitions in the room. (The location of partitions are shown in Figure 3.) This is supported by the fact that the frequency increases the most in the higher modes that also are more affected by the added partitions.(Compare with the mode shapes of the entire floor in Table 3.) When considering the change in frequency of the entire floor during construction it can be concluded that the frequencies are rather stable during the different construction stages but changes by the addition of partitions for modes that are largely constrained in their movement.

6 Conclusions

The following conclusions may be drawn from the present investigation:

- The in situ conditions have a large influence on the floor damping and natural frequencies which naturally depends on the fact that the floor is integrated into the building and interacts with it, but also on the damping characteristics of the supports.
- When considering the change in frequency of the entire floor during construction the frequencies are rather stable during the different construction stages but changes by the addition of partitions for modes that are largely constrained in their movement.

- There is a slight increase of damping over the different construction stages and the damping values seem to decrease with ascending mode order.
- The average damping ratio in the order of 5 %, which is much higher than 1% that is used in the design guidelines. To assess that such a high damping value would be proper to assume in general fo this type of floor structures further investigations of damping values should be carried out.
- The overall vibration performance of the studied floor is good, it is high frequent (the first natural frequency is 21 Hz compared to the limit of 8 Hz for timber floors)

References

[1] BS EN 1995-1-1:2004. Eurocode 5: Design of timber structures. General-Common rules and rules for buildings, British Standards Institution.
[2] BFS 2009:6 (EKS 4), Boverkets föreskrifter om ändring i verkets föreskrifter och allmänna råd (2008:8) om tillämpning av europeiska konstruktionsstandarder.
[3] NA to BS EN 1995-1-1:2004. UK National annex to Eurocode 5: Design of timber structures. General-Common rules and rules for buildings, British Standards Institution.
[4] Ewins D.J., Modal Testing: Theory, Practice and Application. Second Edition, Research Studies Press Ltd., Baldock , Hertfordshire, England, 2000.
[5] Inman D.J., Engineering Vibrations, Third Edition, Pearson Education International, Inc., Upper Saddle River, New Jersey, 2009.
[6] Heylen W., Lamms S., Sas P.: Modal Analysis Theory and Testing, ISBN 90-73802-61-X, Katholieke Universiteit Leuven, Faculty of Engineering, Department of Mechanical Engineering, Heverlee, Belgium.