Design of Lightweight floor system for optimized vibration comfort

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Abstract

A major trend in the current building practice is to reduce the weight of structures. The main incentives for this trend are the scarcity of materials and the rising costs of labor and materials. This is one of the goals of IFD (Industrial, Flexible and Demountable) way of building which is the prevalent Dutch approach to sustainable building. One of the heaviest and most complex parts of a building is the floor. Therefore the focus of this research is to develop a lightweight floor system. However, these lightweight floor systems are sensitive to vibrations and are therefore, without taking measures, regarded less comfortable than heavier, more traditional floor systems.

This paper describes structural measures to increase vibration comfort. A quality measure, based on the velocity of the vibration, is used to compare the comfort value of a structure subjected to vibrations. This quality measure includes human sensitivity for vibration that is frequency dependent. The structural measures include intelligent coupling of structural elements and support conditions. A detailed study on the effects of these structural measures and a design principle with improved vibration comfort will be presented.

1 Introduction

Traditionally floor systems used in housing and office-buildings in the Netherlands were made of stone-like materials. These floor systems, which can be characterized as heavy, normally posed little problems concerning vibrations. In recent years, in light of sustainable building methods, the trend is to reduce the use of materials and thus build lighter. Lightweight structures are however often found to be more sensitive to vibrations. The vibrations are caused by dynamic actions such as walking persons or vibrating machines such as a washing machine.

There are a number of methods for describing the influence of a certain vibration on a human being. Often these methods use a criterion based on the acceleration (peak value or average value) or the velocity of a vibration, but are not specifically set up for the case described in the paper. Recently a quality measure has been established by TNO[1] as part of a European collaborative project and published (1;2). This method is specifically suited for the case of a lightweight floor structure subjected to an exciting force. The method provides both the characteristics of the exciting force and the influence this has on the human being. The key aspects of this method will be covered in section 3.

In section 2 and 4 the quality measure for vibration comfort is used to evaluate a large number of possible floor structures in order to maximize vibration comfort. All relevant parameters with regard to a light weight floor structure are taken into account. This evaluation is done using a finite element model.

[1]TNO: Organistion for applied scientific research

2 Setup of vibration comfort study

When designing a floor structure it is mostly designed from a failure criterion point of view. Seldom is a floor structure designed explicitly for vibrations. Especially in light weight structures this design criterion is very important. In this section the setup of the study of the effect on vibration comfort using only structural measures is discussed.

Traditional floor systems usually do not use all material optimally. This non-optimal used material will therefore add weight to the floor while not contributing to the overall performance. Light weight floor systems designs have to optimize material use to obtain comparable characteristics to the traditional heavier variants while adding little mass. Light weight floor systems that use this strategy can be described as being comprised of discrete optimized components. This is the strategy chosen for this research. The various design parameters will be evaluated on a discrete floor structure that is comprised of beams and discrete connections. The base structure will look like a series of 1 to 5 beams parallel to each other as shown in Figure 1.

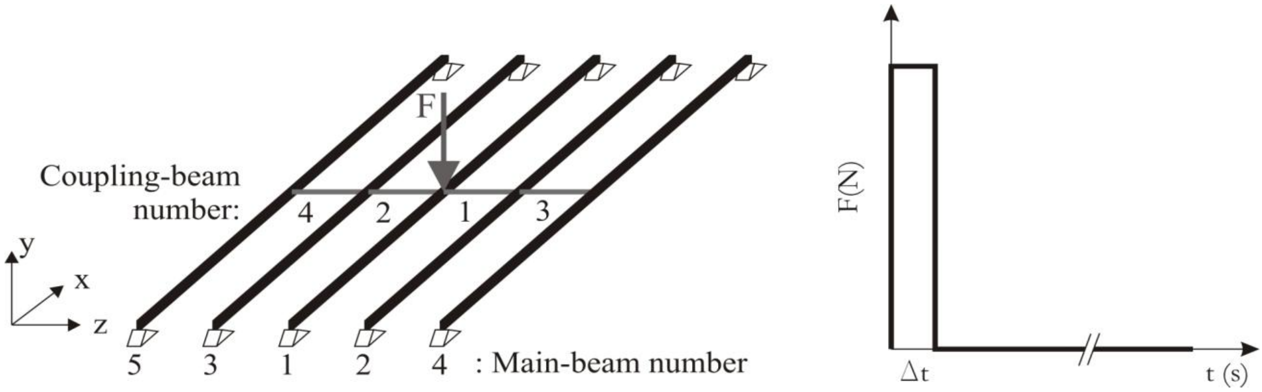


Figure 1, Setup comfort study and exiting force on center of beam number 1

In every variant, beam number 1 is in the middle position and will be excited at mid-span by a Dirac pulse. This will introduce a vibration in beam number 1 which in turn will excite the other beams through various couplings. If not defined otherwise the beams are coupled at mid-span using a beam with a stiffness ratio to the main beams of 10%.

The various parameters of influence on vibration comfort can be divided into two categories:

1. Main beam properties
2. Geometrical properties of coupling beams

The variants will be presented in more detail in section 4. For each variant a single parameter will be varied over a range of values. For each sub step in this parameter range the comfort value at the mid-span of the beams will be calculated. This will illustrate the influence of that particular parameter on vibration comfort.

The numerical model is modeled in the FEM program ANSYS and a transient analysis is performed. The model has the following characteristics.

- Nodes in main beam: 61
- Nodes in coupling beams: 21
- Mode superposition method for transient analysis
- Modes extracted: 20
- Output sample rate: 1024 samples / second
- Exiting force: 10 kN
- Coupling beams have a fixed connection to the main beams

3 Comfort criterion

The comfort criterion is ideally suited for evaluating the vibration comfort of floor systems due to walking people. This method was developed and published (1) by TNO and SBR[2] and used the results of a European research (3). The method is based on calculating the response of a floor system to a mathematical series of walking frequencies. Using a filter to accommodate for human sensitiveness to certain frequencies this method allows accurate predictions of the comfort level of a floor system. The input needed for the method is the transfer function of the floor system under investigation. This can be acquired by using an experimental or numerical approach. The resulting value, called the One Step RMS value or OS-RMS$_{90}$, is the measure for comfort for the floor system under investigation. As you can see the OS-RMS$_{90}$ value has the units mm/s which is a velocity, so a lower value will indicate better performance.

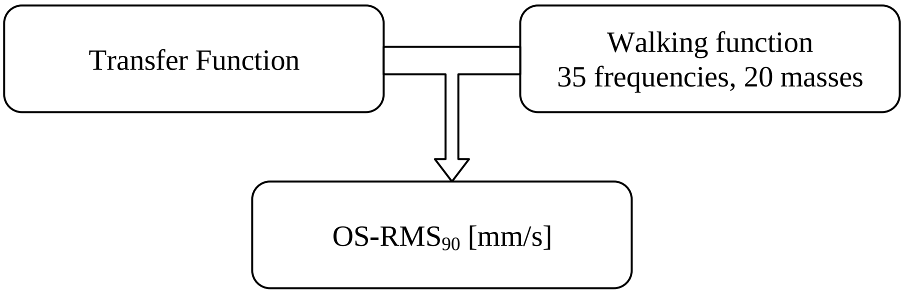


Figure 2, Principle of comfort value calculation using OS-RMS$_{90}$ method

The three parts of this method will be further discussed in the following paragraphs as they are applied to this paper.

3.1 Transfer function

In this paper the results presented are obtained using numerical simulations. As mentioned above the transfer function can be determined using numerical methods as well as experimental methods. Therefore the transfer function is determined numerically as well. To determine the transfer function numerically you need the Fourier transform of both the acting force and the response of the beams in the model. For this procedure the matlab routine ‘fft’ is used. The response, u_t, is obtained from the ANSYS output. The force transient, F_t, is created by constructing an array filled with zeros with just the first element corresponding to the exciting force used in the model, i.e. 10.000 N. By now calculating the ‘fft’ of both transients and dividing it using equation (1) the transfer function, H_f, can be calculated.

$$H_f = \frac{\mathrm{fft}(u_t)}{\mathrm{fft}(F_t)} \qquad (1)$$

This function has to be weighted to account for human sensitivity using:

$$\left|\mathrm{H}(f)\right| = \frac{1}{\mathrm{v}_0} \frac{1}{\sqrt{1+\left(\frac{f_0}{f}\right)^2}} \cdot \mathrm{H}_f \qquad f_0 = 5{,}6\,\mathrm{Hz} \qquad \mathrm{v}_0 = 1\ \mathrm{mm/s} \qquad (2)$$

[2] SBR: Stichting Bouw Research

3.2 Walking function

The walking function is a function that describes a single step of a person walking and was determined by using a large set of experimental data. This way it was possible to include the parameters of pace frequency, f_p, and mass, m_p, into the function. The function is an 8[th] order polynomial function given by:

$$F_{1\text{-step}}(f_p, m_p, t) = m_p g \sum_{n=1}^{8} K_n (f_p)_n t^n \qquad (3)$$

$$m_p = 30, 35.....125 \text{ kg} \quad f_p = 1.64, 1.68....3{,}00 \text{ Hz} \quad g = 9{,}81 \text{ m/s}^2$$

The factor K_n is defined for all orders, n, of the polynomial function. The function gives the force exercised during a single step onto the floor. This single step has to be combined in a series of steps as is shown in Figure 3.

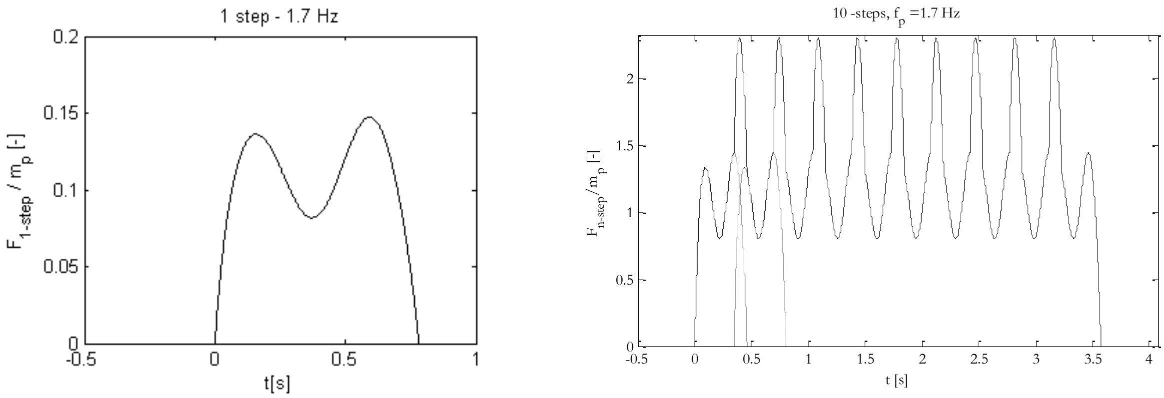


Figure 3, Generating walking function

3.3 Calculating OS-RMS$_{90}$ comfort value

After performing the first two steps you now have the transfer function and 700 different walking functions reflecting the combinations of the persons mass and pace frequency. Every combination has a certain level of probability of occurring, P_{mass,f_p} , and can be found by multiplying the individual probabilities, p_{mass} and p_{fp}, (2):

$$P_{mass,f_p} = p_{mass} * p_{f_p} \qquad (4)$$

By calculating the Fourier transform of all 700 walking functions and multiplying these with the transfer function from equation (2) you get the response of the structure under investigation. Every calculated response has a certain probability of occurring and by calculating the RMS value of the response and calculating the 90% confidence value you get the comfort value or OS-RMS$_{90}$. This value will be used in the analysis to rate the variants.

4 Comfort study

In section 2 the setup of the comfort study was presented. A large set of parameters are to be investigated. As reference a base configuration is used from which never more than one parameter will be changed in order to study the effect of this parameter on the comfort value. All parameters will have a range of values which will be investigated. The base structure has material properties for the main and coupling beams and in case of multiple main beams will have a single coupling beam at mid span. The various parameters with their corresponding base values and ranges of variation are listed in Table 1. Every range is subdivided into a suitable number of substeps, typically 30.

Table 1, Overview variants for main beam properties, 1 main beam model

Code	Parameter / varied by	Description	Range parameter	Base value
EIM1	EI_m / α	Stiffness main beam	0,5 .. 2,0 x base	1,04 x10^8 Nmm^2
MAM1	Mass	Mass main beam	50 .. 200 kg/m’	100 kg/m’
LEM1	Length	Length main beam	4 .. 12 m	7,50 m
RTS1	$C_{1,2}$	Rotation stiffness at support	0 .. 10^6 N/rad	0 N/rad

In addition to the base values for the reference structure the following base properties have been defined:

- EI_z , stiffness weak direction main beam: 7,6 x 10^6 Nmm^2
- I_t, torsion stiffness main beam: 3,13 x10^5 mm^4
- EI_c , $EI_{z;c}$ $It_{;c}$, stiffness values coupling beam: 10% of corresponding base value main beam
- M_c, Mass coupling beam: 0 kg/m’
- L_c, Length coupling beam = distance between main beams: 1,2 m

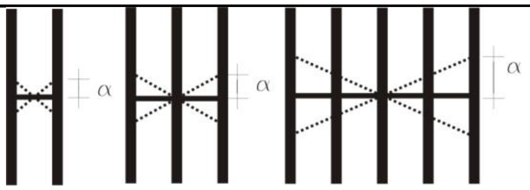
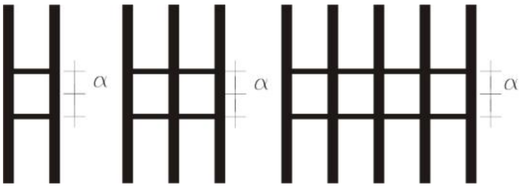
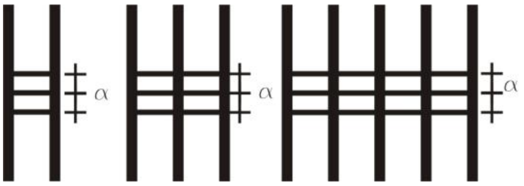
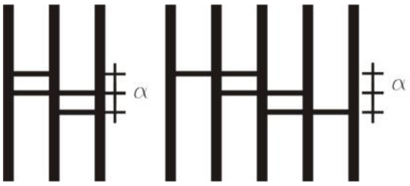
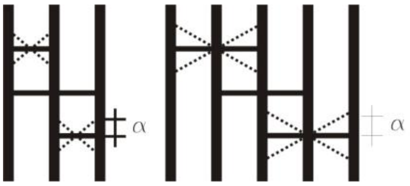
Table 2 lists all variants regarding main beam properties where the model contains multiple main beams. The aim for this series is to vary the distribution of the specific property while keeping the total value summed over all beams constant.

Table 2, Overview variants for main beam properties, multiple main beams model

Code	Parameter / varied by	Description	Distribution over beams (beam numbers)		Range parameter
EIM2	EI_m / α	Stiffness main beam	(1) 1+ α	(2) 1- α	-0,5 .. +0,5 x base
EIM3	EI_m / α	Stiffness main beam	(1) 1+ α	(2+3) 1- 0,5 α	-0,5 .. +0,5 x base
EIM5	EI_m / α	Stiffness main beam	(1+4+5) 1+ α	(2+3) 1- 1,5 α	-0,5 .. +0,5 x base
EIC2,3,5	EI_c	Stiffness coupling beam			10 .. 1x10^8 Nmm^2
MAM2	Mass / α	Mass main beam	(1) 1+ α	(2) 1- α	-0,5 .. +0,5 x base
MAM3	Mass / α	Mass main beam	(1) 1+ α	(2+3) 1- 0,5 α	-0,5 .. +0,5 x base
MAM5	Mass / α	Mass main beam	(1+4+5) 1+ α	(2+3) 1- 1,5 α	-0,5 .. +0,5 x base
MAC2,3,5	Mass	Mass coupling beam			0..200 kg/m’
LEC2,3,5	Length	Length coupling beam			0,6 .. 1,8 m
LEW3,5	Length / α	Length coupling beam constant total length	(1+3) 1,2+ α	(2+4) 1- α	0,0 .. 0,6 m
RTS2,3,5	$C_{1,2}$	Rotation stiffness ratio			0 .. 10^6 N/rad
RTM2,3,5	$C_{1,2}$	Rotation stiffness sup.	2 sides		0 .. 10^6 N/rad

Table 3 gives an overview of the variants in the configuration of the coupling beams in the multi main beam models.

Table 3, Overview variants in configuration of the coupling beams, multiple main beams

Code	Parameter	Description	Range
RBC2,3,5		Rotation 1 coupling beam fixed at center	0 .. 3,75 m or 0 .. 16 nodes
PDC2,3,5		Position double coupling beam	0 .. 3,75 m or 0 .. 16 nodes
PTC2,3,5		Position triple coupling beam	0 .. 3,75 m or 0 .. 16 nodes
PPC3,5		Position partial triple coupling beam	0 .. 3,75 m
PRC3,5		Rotation partial triple coupling beam	-1,88..1,88 m

4.1 Results comfort study

For all parameters listed in tables 1,2 and 3 the comfort value, or OS-RMS$_{90}$ value, was calculated at mid span of every main beam. The results for the variants are listed in Table 1. The x-axis of the graph has been scaled so that the range mentioned in the table is mapped on a zero to one scale. The graph shows the influence of the parameters on the comfort value. From the graph the general trend can be seen that a larger beam span will increase the comfort value or in other words worsen the performance. The general trends correspond to general expectations although the influence of mass has a somewhat remarkable influence. Over the entire range the comfort value remains more or less constant which is contradictory to general expectations.

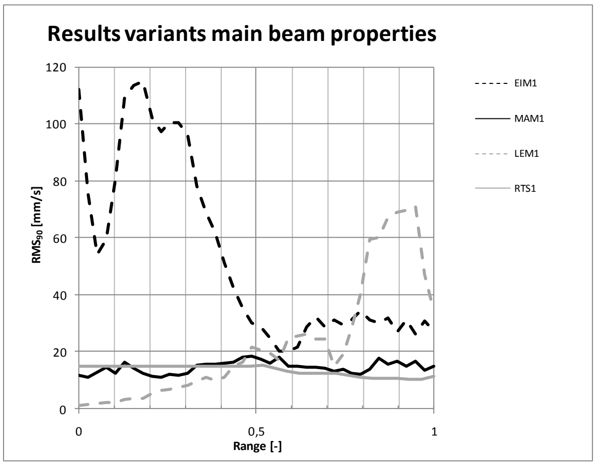


Figure 4, Results variants main beam properties – single beam (codes according to Table 1)

Some remarks can be made regarding the results presented in Figures 5 and 6. From the graph of the EIC-series it can be concluded that there is a range of values for the bending stiffness of the coupling beam that has a big effect on the comfort value but there is also a value for the stiffness where increasing the bending stiffness does not improve the comfort value anymore. Also in the variant concerning the mass of the main beams show only little effect on the comfort value. Regarding the distance between the main beams there seems to be no effect when these beams are closer together than 1 m and the effect is also most pronounced in the two beam configuration.

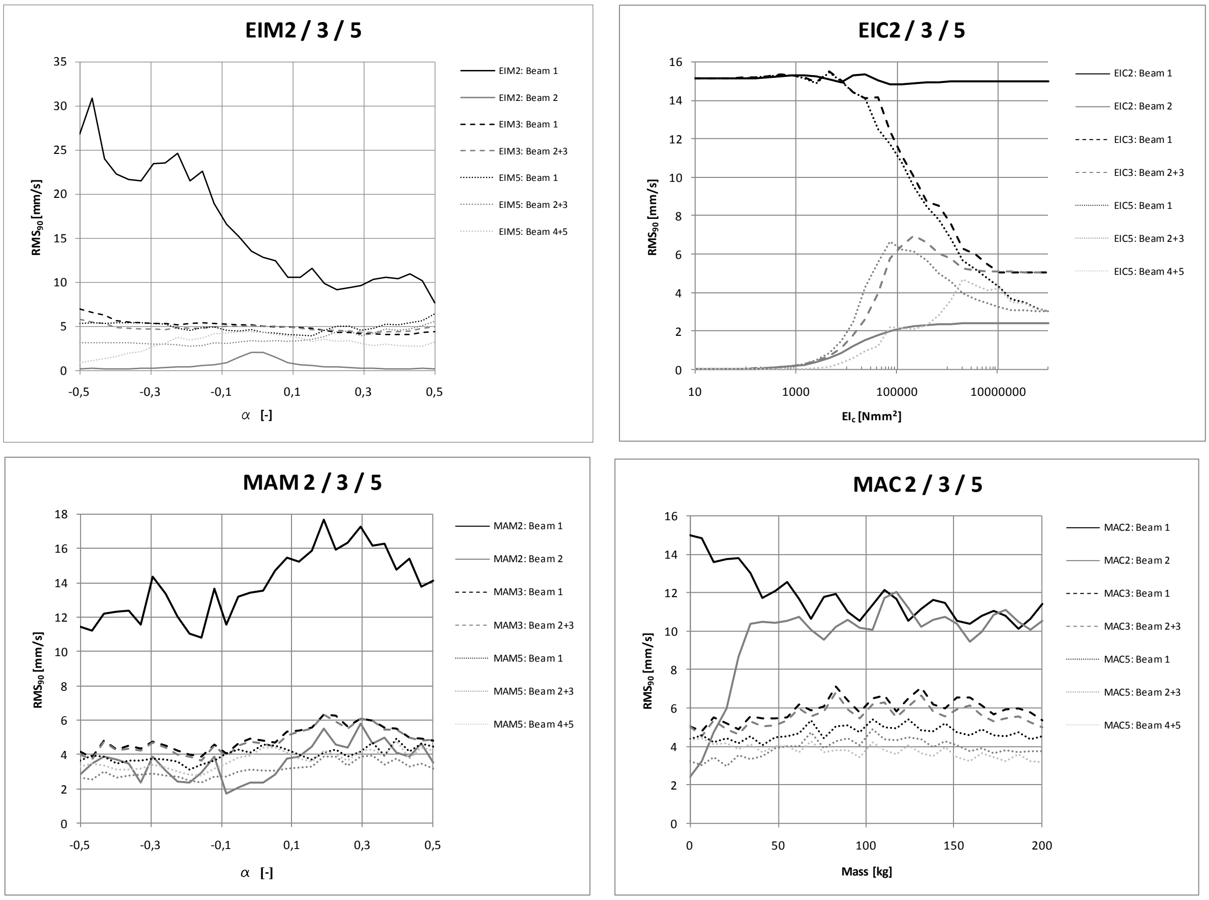


Figure 5, Results variants main beam properties – multiple beams – part 1 (codes according to Table 2)

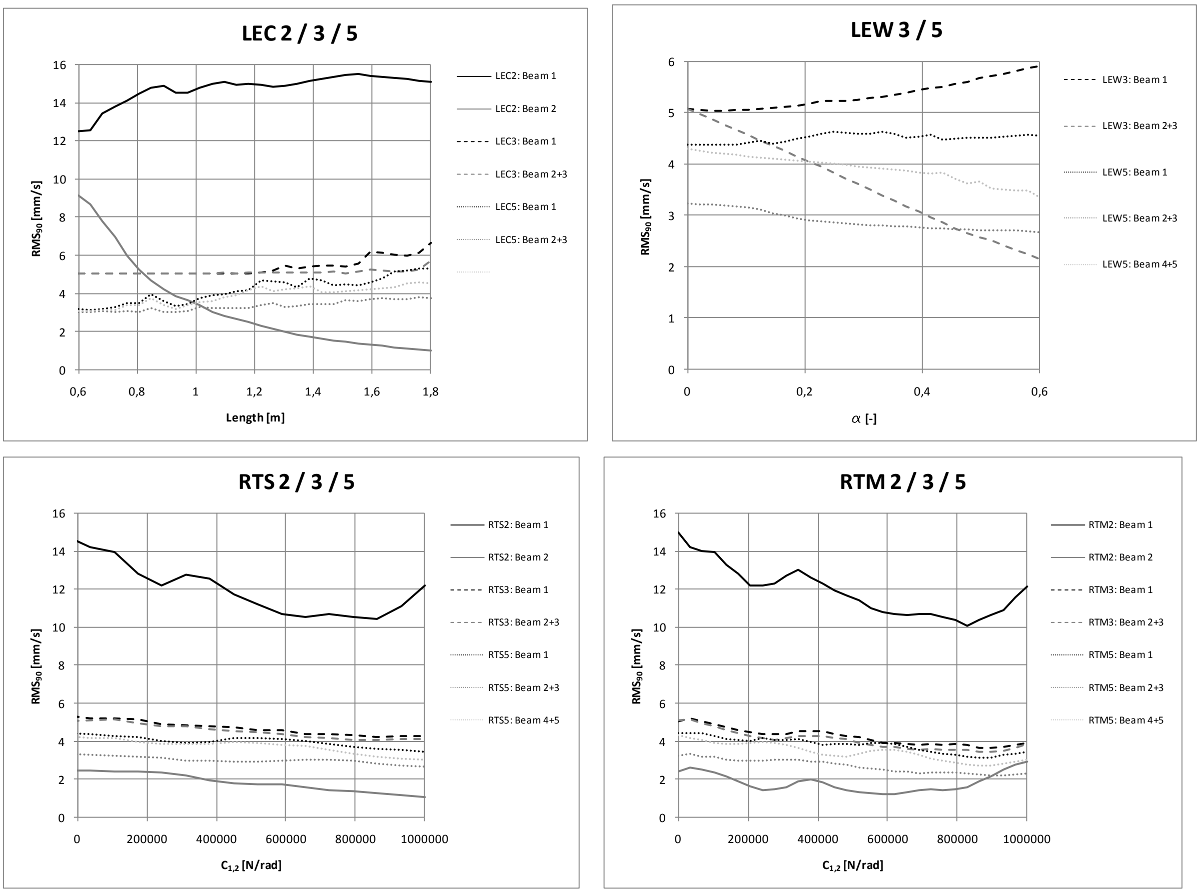


Figure 6, Results variants main beam properties – multiple beams – part 2

Some remarks can be made regarding the results presented in Figure 7 where the influence of the various coupling configurations is presented. It shows from the PDC and PTC series that there is not a big improvement of the comfort value when more than 1 coupling beam is used. There is another effect clearly visible for these graphs. When the coupling beams are connected to the main beams closer than about 25% of the length to the supports, the effect diminishes very quickly. Also the variant concerning partial coupling beams show that 1 coupling is equal to more coupling beams only if the coupling beam spans at least 2 bays.

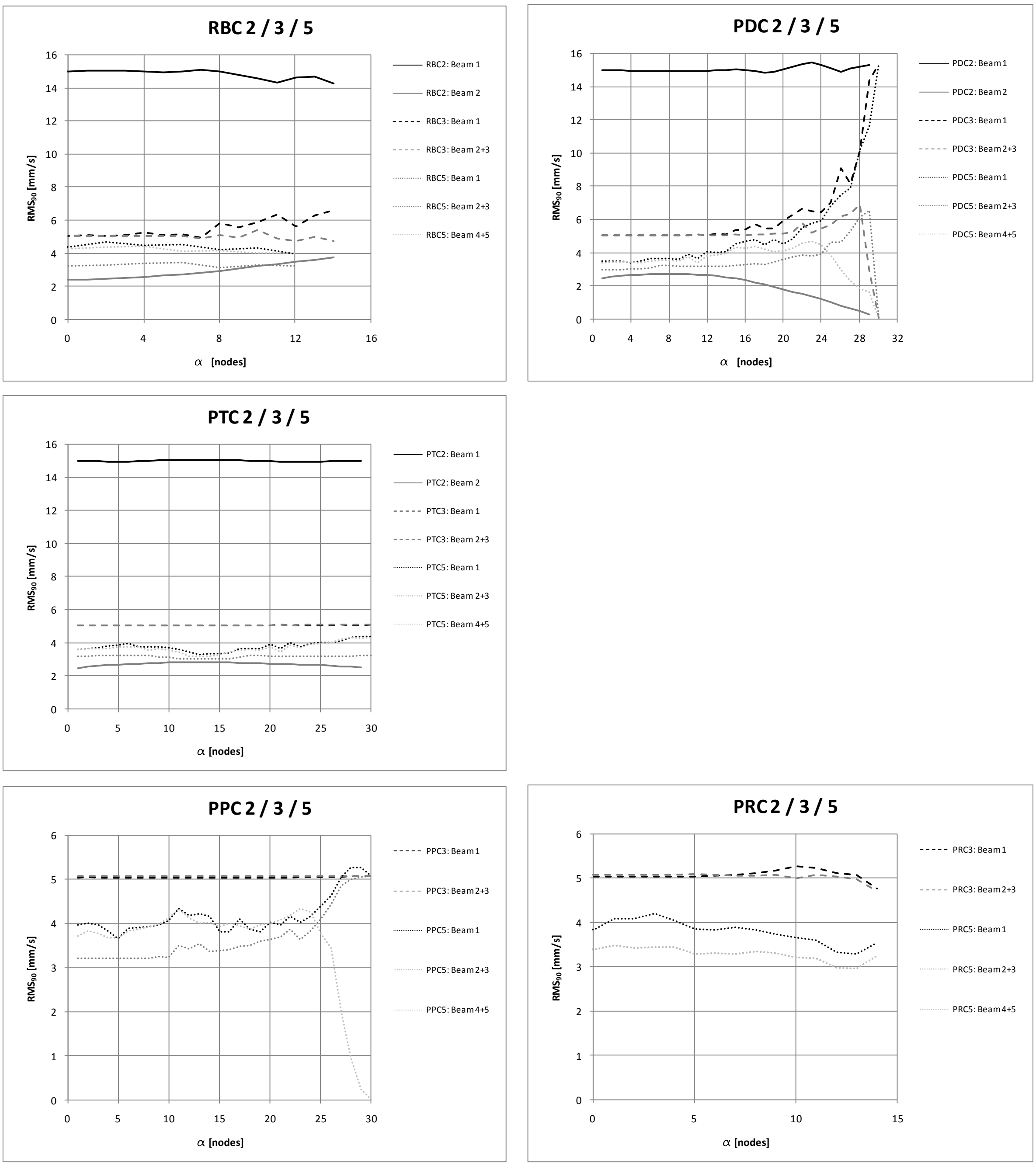


Figure 7, Results variants geometrical properties

5 Conclusions

A comprehensive set of parameters have been investigated regarding the influence of the parameter on the comfort value. The theory behind the vibration comfort value also has been presented. Not all parameters investigated have a big influence on the vibration comfort of a floor system. But some main conclusions can be stated.

- Coupling beams are very effective at spreading the vibration and thus improving the comfort of a floor system for vibration. This coupling beam has to span at least 2 bays to be effective

- Two or more coupling beams do not improve the vibration comfort significantly compared to only one coupling beam
- Mass does not influence vibration comfort of a floor system
- A center to center distance of the main beams smaller than 1 m do not improve the vibration comfort further
- The main parameters regarding vibration comfort of the main beams are stiffness of the main and coupling beams and the length of the coupling beams.
- The design of floor systems consisting of main beams connected with coupling beams has great potential for light weight floor systems with good vibration comfort.

References

[1] P.Waarts 2005. *Trillingen van vloeren door lopen*, SBR, Rotterdam.

[2] P.H.Waarts and F.van Duin 2006. *Assessment procedure for floor vibrations due to walking*. In L.J.Sluys, ed., pp. 251-264. Delft.

[3] ECSC 2006. *Generalisation of criteria for floor vibrations for industrial, office, residential and public building and gymnastic halls*. In RFCS publications, Brussels.