Comparative study of different modeling parameters for predicting vibrations on timber-frame floors

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Abstract
Existing buildings reforms should include quality parameters and in timber-frame building systems the vibration transmission should be well studied to comply with the acoustic requirements. The input parameters for the prediction of vibrational response of floors can influence the results in modelled building systems. In building structures, the analysis of radiation due to beam vibrations may be represented from the wave propagation relationships as a one-dimensional system, a two-dimensional system or a three-dimensional solid. Recent research indicates that for point connection, a beam is usually modelled as a one-directional element. However, for lightweight structures such modelling type does not show good correlation with experimental results. This study focuses on the differences that can be obtain in the vibrational response due to an impact source exerted on typical timber-frame floors. It also presents some examples for some modelling options for plate/beam systems with and without ceiling, considering different connection types.

Keywords: timber-frame floors, vibrational response, finite element analyses.

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1 Introduction

Vibration transmission estimations of buildings can provide relevant information for analyses of irradiation for different construction components of multi-storey buildings. Several aspects are studied for the acoustic behavior analyses of different types of floors in order to propose efficient design solutions. The type of building structures is one of the first aspects to be analyzed, since wave propagation is different for heavy and lightweight components.
The type of connection between components of lightweight floors should represent the way they were built, but estimates by computer models connections must represent the form of vibration transmission which occurs between attached components.
The plates (wood boards) and beams (ribs) in timber-frame constructions are attached with screws or nails and the connection type to be considered in the model is related to the spacing between the screws. There are basically two options: for small space between the screws, the coupling occurs as a line connection; for widely spaced between the screws, the connection type should be as a point [1].

Another point studied is the use of materials such as glue between wood boards/ribs interface. But research has shown that the effects of glue present negligible effects on the overall performance [2].
Timber-frame structures are often not well suited for simple structural acoustic prediction as the statistical energy analysis models because the modal density is not evenly distributed due to the spatial periodicity introduced by beams [3].
The orthotropic properties of timber are normally measured in three orthogonal directions, which are relative to timber rings and can be incorporated in models. In timber-frame sound waves along the beam's length and the axial Young's modulus is used [4]. However, in a plate/beam system transmission they can vary with connection type, and the waves can travel either along the beams length or across its depth. This complex variation of the material properties is difficult to model, a reason why simplifications are normally introduced in models [5].
The input parameters for the prediction of vibrational response of floors can influence the results in modelled building systems. The element type assigned to represent the ribs is the main issue in modelling plate/beam systems, more specifically the choice of the connections type, which can be basically a line or a point connection [5]. In building structures, the analysis of radiation due to beam vibrations may be represented from the wave propagation relationships as a one-dimensional system, a two-dimensional system or a three-dimensional solid.
Some existing buildings have combined systems which include heavy masonry walls and lightweight floors formed by timber-frame structures. Furthermore, ceiling can be used as a reinforcing component for slabs or other plate elements and can reduce irradiation transmission through vibration restricting of these component.
This study focuses on the differences that can be obtained in the vibrational response due to an impact source exerted on typical timber-frame floors. It also presents some examples for some modelling options for plate/beam systems with and without ceiling, considering different input connection types for 2D and 3D models.

2 Modeling parameters

The timber-frame floor model was 3.34 x 2.52 m, composed by nine ribs with 0.35 m spacing. The element type assigned to represent the timber-board was considered as a single plate and as a multi-plate (plate surface formed by individual boards), where the connection types between plates were bonded and not bonded interface. Dimensions of the elements are given in Table 1.

Table 1 – Dimensions of the elements

Element	Dimensions (m)		
	x	y	z
Single plate	2.80	3.34	0.02
Multi-plate (each)	0.40	3.34	0.02
Ribs (each)	2.80	0.06	0.12

This study focused on the radiation due the beam vibration of the in two-dimensional systems and a three-dimensional solid.
The boundary conditions used in the models consider the connection between a heavy wall and the ribs, typically used in some buildings, where the fixed support of the floor was placed in the rib ends. The ceiling was considered as a single plate not suspended, with line or face connections with the ribs.

The influence of timber-board model representation was also investigated. For 3D systems the timber-board was represented as a single plate, a multi-plate with bonded connections between plates and as a multi-plate with not bonded connections between plates.
The 2D system models were represented by the timber-board as a multi-plate with bonded connections between the plates and as a single plate. Not bonded connection between plates are unable due the admitted linear transmission of wave propagation relationships for two-dimensional systems.
Connections between timber-boards and ribs were admitted as face connections for all 2D and 3D models, because the load due to the real use of the building causes the effective contact surfaces.
The point force excitation was located in central area for all models.

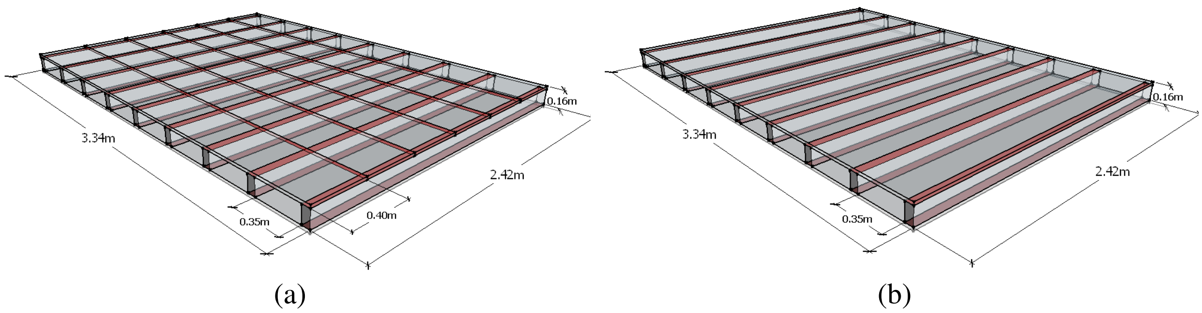


Figure 1 – Schematic geometry of the timber-frame with (a) multi-plate timber-board; (b) single plate timber-board

Table 2 – Variations of input parameters in multi-plate models and respective model name

Model	Connection between plates	Ceiling	Connection type	Model name
3D	Bonded	Without ceiling	Face connection	Multi 3D
		With ceiling	Face connection	Multi 3D B C FC
		With ceiling	Line connection	Multi 3D B C LC
	Not bonded	Without ceiling	Face connection	Multi 3D NB
		With ceiling	Face connection	Multi 3D NB C FC
		With ceiling	Line connection	Multi 3D NB C LC
2D	Bonded	Without ceiling	Face connection	Multi 2D
		With ceiling	Face connection	Multi 2D C FC
		With ceiling	Line connection	Multi 2D C LC

Table 3 – Variations of input parameters in single plate models

Model	Ceiling	Connection type	Model name
3D	Without ceiling	Face connection	Single 3D
	With ceiling	Face connection	Single 3D C FC
	With ceiling	Line connection	Single 3D C LC
2D	Without ceiling	Face connection	Single 2D
	With ceiling	Face connection	Single 2D C FC
	With ceiling	Line connection	Single 2D C LC

The orthotropic properties of timber are normally measured in three orthogonal directions which are relative to timber rings (axial, radial and tangential) and can be incorporated in models. For instance, in a timber frame sound waves travel along the beam's length and the axial Young's modulus is used [4]. Material properties are presented in Table 4.

Table 4 – Material properties assumed

E_x (MPa)	E_y (MPa)	E_z (MPa)	ν_{xy}	ν_{yz}	ν_{xz}
2.92	2.92	2,924	0.23	0.013	0.013

The analysis is carried out using software Ansys® Workbench 16.2. To verify that if the responses obtained in numerical models are acceptable, the natural frequencies were compared with results of an analytical model, using a simple plate of same size used in this study. The frequencies from 10 first modes obtained by finite element and analytical expression can be compared in Table 5 and Table 6 for 2D and 3D models, respectively.

Table 5 – Comparative of natural frequencies for 2D models

Modes	Frequency of Numerical Model (Hz)	Frequency of Analytical Model (Hz)	Difference (%)
1st	55.3	54.91	0.21
2nd	69.46	69.64	-0.13
3rd	122.99	123.45	-0.57
4th	156.83	157.21	-0.60
5th	205.75	205.96	-0.44
6th	210.99	211.16	-0.36
7th	287.42	287.46	-0.11
8th	290.89	290.71	0.52
9th	328.89	329.01	-0.36
10th	335.15	335.22	-0.23

Table 6 – Comparative of natural frequencies for 3D models

Modes	Frequency of Numerical Model (Hz)	Frequency of Analytical Model (Hz)	Difference (%)
1st	58.01	58.946	-0.56
2nd	94.00	93.782	0.20
3rd	141.00	140.73	0.38
4th	150.99	151.36	-0.56
5th	171.99	172.37	-0.66
6th	226.08	225.97	0.26
7th	230.00	229.98	0.05
8th	262.09	262.05	0.10
9th	291.94	291.95	-0.02
10th	300.14	300.02	0.36

3 Results

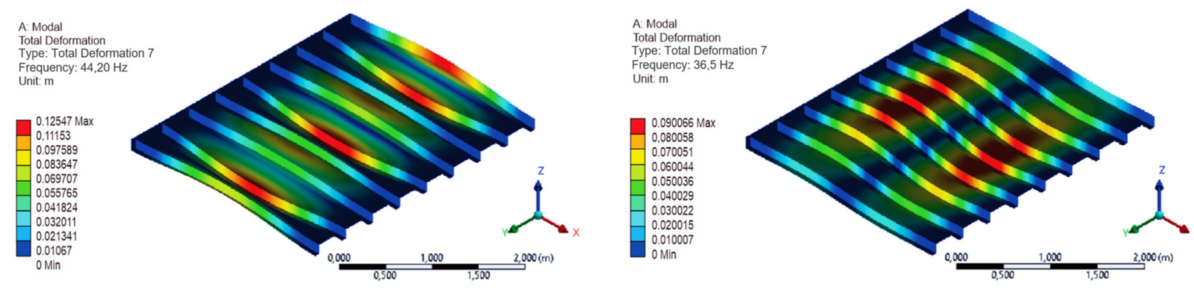
3.1 2D models

Models with line connection for single and multi-plates showed similar results to the single model without ceiling. For 2D systems ceiling addition showed differences results only for models with face connection (C FC) between ribs and ceiling plates.

Table 7 – Natural frequencies for 2D models

Modes	Frequencies (Hz)					
	2D SINGLE C FC	2D SINGLE	2D SINGLE C LC	2D MULTI	2D MULTI C FC	2D MULTI C LC
1	36.5	44.3	44.2	44.2	36.5	46.2
2	38.7	46.3	46.2	46.2	38.7	46.2
3	43.3	50.3	49.7	50.3	43.2	49.7
4	51.0	56.9	56.9	56.9	51.0	56.9
5	63.7	67.3	67.2	67.3	63.7	67.2
6	82.3	82.3	87.5	82.3	82.4	87.5
7	99.1	101.9	96.7	101.9	98.8	96.7
8	102.5	120.0	102.9	119.7	102.3	102.9
9	107.3	123.3	108.6	123.1	107.3	108.6
10	108.6	127.3	112.4	127.3	108.4	112.4

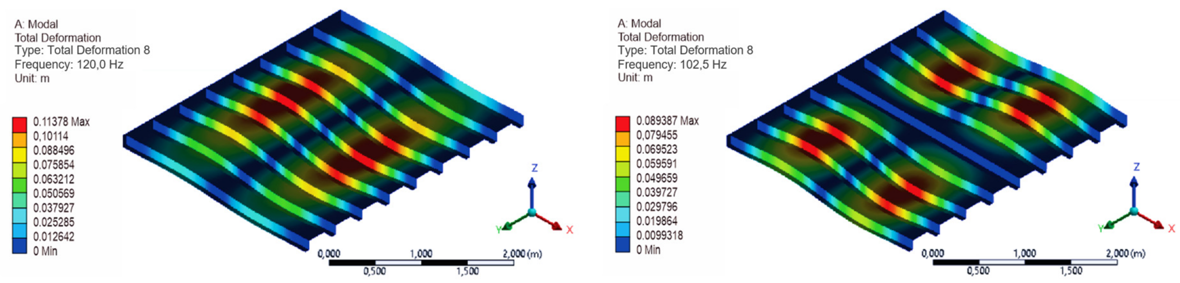
Mode shapes for 2D models can be divide into two groups. Models without ceiling and with ceiling connected by line connections from ceiling presents same modes shapes and models with ceiling connected by face connections were identified as a second group. The differences were from the 7^{th} mode, although it was known that ceiling installation increase the acoustic effect in this type of floor system for first vibration modes. For visualization of vibration response of beams the ceiling was hidden only for graphic representation and it was considered in prediction models.
Comparatively, 2D models with ceiling and face connection presents lower natural frequencies for the same vibration mode. Figures 2, 3 and 4 show mode shapes of 2D models that have difference of harmonic variations. At 7^{th} mode, simulations of 2D models show differences in the deformation configuration of the beams. In models with ceiling and face connections (Figure 2b) the bending waves are better represented, compared with the representation of other 2D models (Figure 2a).



(a) (b)

Figure 2 – 7^{th} mode shapes for 2D models (a) without ceiling and with ceiling and line connections, (b) with ceiling and face connections

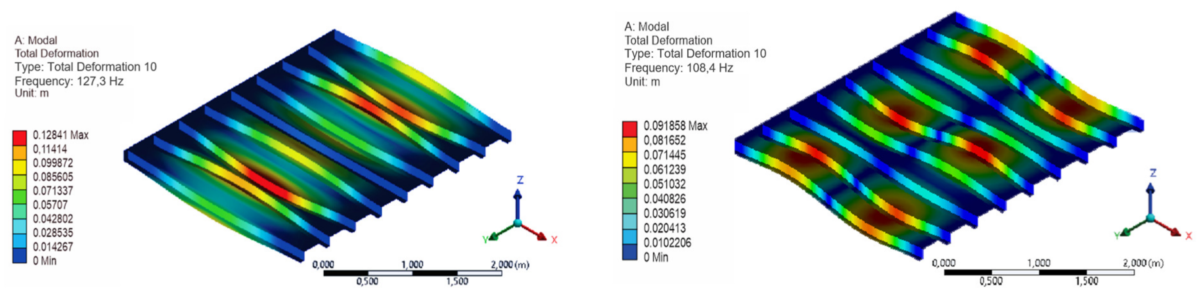
The 8th mode shape of 2D models can visualize in Figure 3. The estimated deformation of beams represents the effect of bending waves, which are restricted in the central beam for model with ceiling and face connections (Figure 3b).



(a) (b)

Figure 3 – 8th mode shapes for 2D models (a) without ceiling and with ceiling and line connections, (b) with ceiling and face connections

The same differences of 7th mode shape can also have displayed on 10th mode, with deformations due to different wave propagation accepted in 2D model.



(a) (b)

Figure 4 – 10th mode shapes for 2D models (a) without ceiling and with ceiling and line connections, (b) with ceiling and face connections

Amplitude results of 2D models showed distinct resonance peaks (Figure 5). Model with multi-plates (MULTI) and line connections (LC) between ribs and ceiling showed any difference with single model without ceiling component. However, face connection (FC) ribs/ceiling presented changes for acceleration response and natural frequencies, which is considered a more consistent result, because the ceiling reinforcement effect effectively influence the vibration irradiation control.

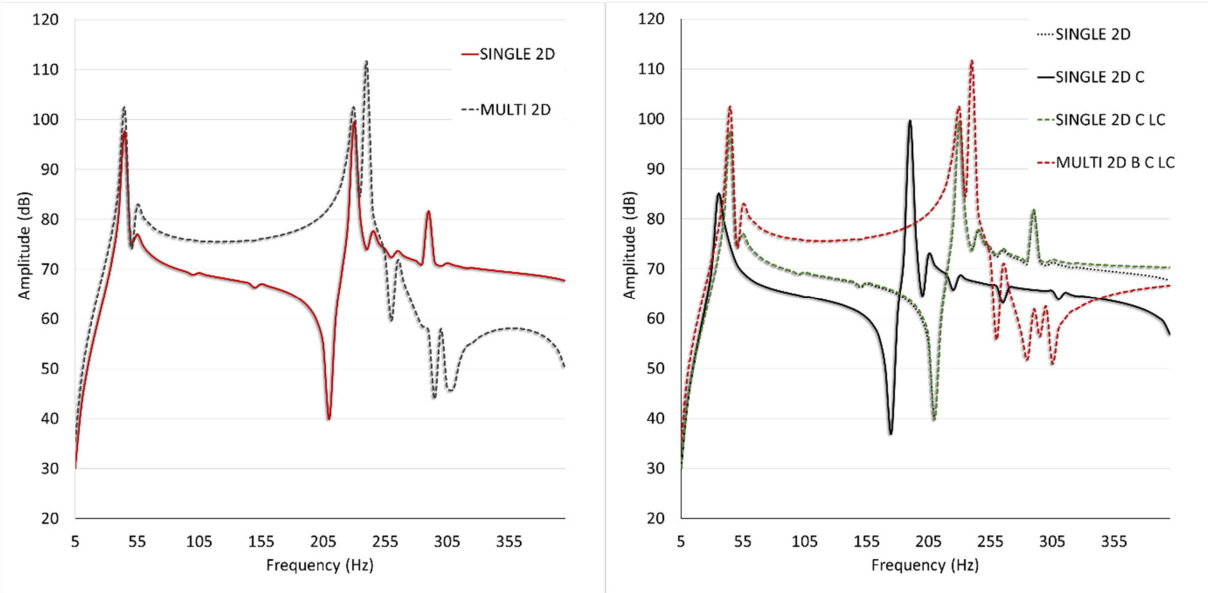


Figure 5 – Comparisons of amplitude responses of 2D models.

3.2 3D models

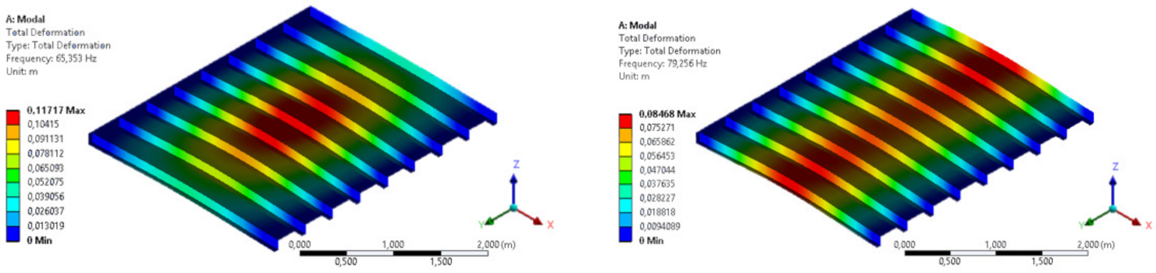
For timber frame models without ceiling the 1st natural frequencies are not significantly affected for connection type of timber-boards, of ~63-65 Hz (Table 7). Models 3D with single plate (SINGLE) and with multi-plates bonded (MULTI B) shoed same results and was identified in Table 7 only by 3D SINGLE. The same was occurred to models with ceiling and face connections for single (3D SINGLE C FC) and bonded multi-plates (3D MULTI B FC), that was showed in Table 7 only as 3D SINGLE C FC.

Table 8 – Natural frequencies for 3D models

Mode	Frequencies (Hz)						
	3D SINGLE	3D SINGLE C FC	3D SINGLE C LC	3D MULTI B C LC	3D MULTI NB	3D MULTI NB C FC	3D MULTI NB C LC
1	65.35	76.02	77.27	77.77	63.69	74.24	75.72
2	66.29	81.19	82.46	82.89	65.39	79.22	80.66
3	70.63	97.48	98.68	93.52	68.62	88.96	90.28
4	77.93	118.88	120.19	108.28	73.79	102.67	103.96
5	89.29	142.44	143.82	131.44	83.83	124.55	126.01
6	102.81	165.36	166.61	159.11	97.81	151.74	153.16
7	120.29	185.46	186.71	184.86	115.58	176.89	178.32
8	140.82	200.88	201.88	201.51	134.87	193.54	194.68
9	164.37	202.53	204.85	204.01	158.91	195.64	198.37
10	172.14	204.74	207.07	208.07	166.64	200.38	201.72

As in 2D models, mode shapes estimated for 3D models distinguish two groups: models with ceiling and face connections and the others. By comparing frequencies of these two groups, it is clear that for models with ceiling and face connection natural frequencies are higher for the same mode shape.
3D models showed difference already in 1st mode, which the ceiling addition results an distribution of transverse deformation joint formed by the different elements of the analyzed floor system (Figure 6b).

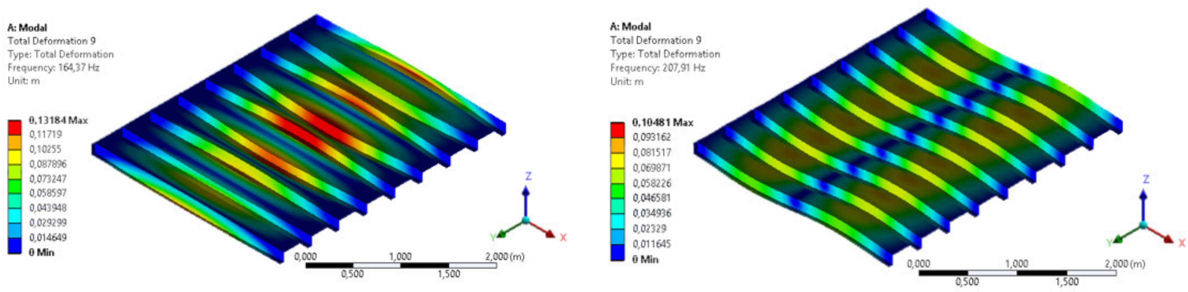
This effect is also observed in all the 10 modes shapes analyzed. For visualization of vibration response of beams the ceiling was hidden only for graphic representation and it was considered in prediction models.



(a) (b)

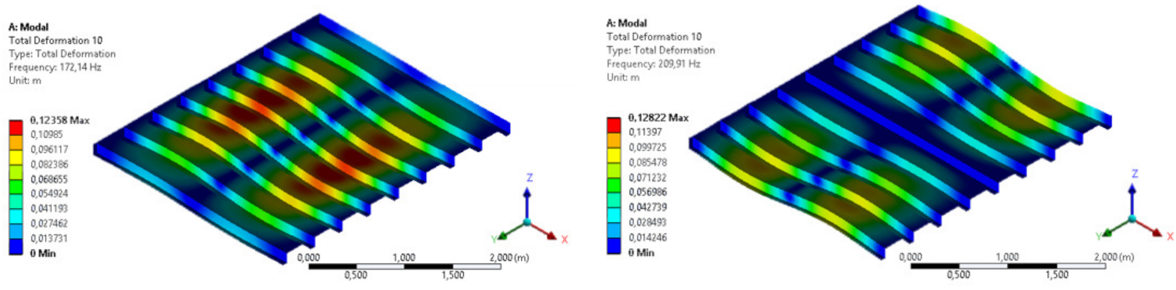
Figure 6 – 1st mode shape mode shapes for 3D models (a) without ceiling and with ceiling and line connections; (b) with ceiling and face connections

Some similarities can be indicated for simulations of mode shapes of 2D and 3D models. As in 2D models, the bending waves are better represented in 3D models with ceiling (Figure 7), especially for 9th mode shape (Figure 7). Likewise, as in 8th mode shape of 2D models, in 10th mode of 3D models the ceiling addition represents a constraint on the deformation of the central beam (Figure 8).



(a) (b)

Figure 7 – 9th mode shape mode shapes for 3D models (a) without ceiling and with ceiling and line connections, (b) with ceiling and face connections



(a) (b)

Figure 8 – 10th mode shape for 3D models (a) without ceiling and with ceiling and line connections, (b) with ceiling and face connections

Comparisons of amplitude response of 3D models without ceiling indicate that was an increase with the attachment between plates (Figure 9). The higher acceleration for single and multi-plate bonded models occurs on 1st natural frequency, but multi-plate with plates not bonded higher acceleration occurs at ~295 Hz.

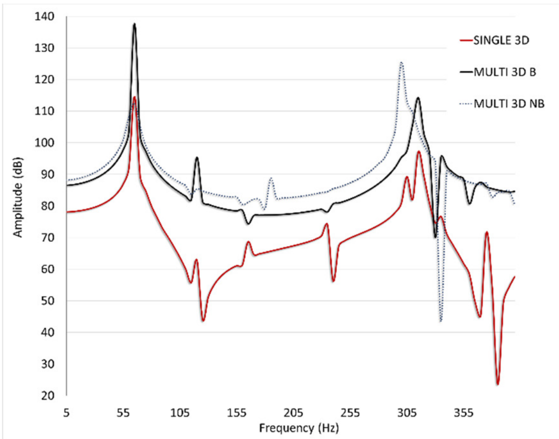


Figure 9 – Comparisons of amplitude responses for 3D models without ceiling.

For 3D models with ceiling the change of connection type of ribs/ceiling not affect significantly the natural frequencies for 3D models up to ~255 Hz (Figure 10).

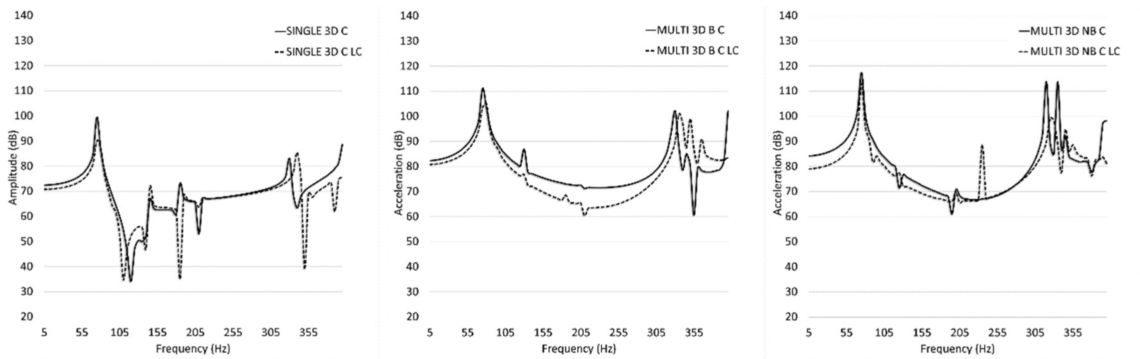


Figure 10 – Comparisons of amplitude responses of 3D models with face and line connections ribs/ceiling.

4 Conclusions

Estimation of vibration transmission in buildings should be compared with experimental results to obtain the response of a particular structural system. In this work, the aim was to present the differences that can be obtained from the adoption of different input parameters in models for comparative by finite element analysis.
Due to the geometry complexity and orthotropic characteristics of wood, estimates the vibrational response in timber-frame floors require methods to consider the different forms built. The major limitation in the analysis by finite elements of larger elements is the relationship between the expansion of the analyzed frequencies and limitations in discretization refining. Although this, comparative studies in larger elements may indicate the influence of considerations about types of connections that can be admitted in computer models and the relevance to real constructions.
Briefly, in this comparative study of timber-frame floor supported by heavy walls it can be pointed that:
- timber-boards can be represented as a single plate, because differences of beams irradiation are not significant;
- vibrational response of timber-floors with ceiling can be better represented by 3D models;
- face connections for prediction models can generate vibrational responses more similar to the expected behavior of beams, although real ceiling installation has been by screws or other type of point contact.

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