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Investigation of impact sound transmission through various mechanical connectors of lightweight structures

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Abstract The impact of mechanical connections between two plates on sound transmission is well-known. However, there is still a need for thorough scientific investigation into this phenomenon. Analyzing the influence of mounting elements on sound transmission can lead to effective reduction of sound propagation and improvement of partitions' sound insulation. The complexity of studying impact sound transmission through junctions arises from the various methods of connecting two parallel plates. Factors such as the number and arrangement of connecting elements, as well as the use of line or point connectors, can significantly affect sound transmission between a massive and lightweight plate. This study focuses on the influence of stud elements and the number of connecting points on the lightweight plate. An impact hammer was used to excite the massive plate, and frequency response functions were calculated for several points on both plates. The results were analyzed and compared to the theoretically derived transmission function for the investigated structure.

Keywords: mechanical connections, impact sound transmission, transfer functions.

1. Introduction

Impact sounds in building constructions are significant noise generators, and their effect on the frustration of occupants is supported by research in the literature [1]. Various articles describe impact sound insulation and sound transmission through massive [2–5] and lightweight building construction [6, 7], and many of them focus on flanking transmission in massive structures, mostly citing EN ISO 12354:2017 standards [8–11]. Nevertheless, while current standards provide comprehensive guidelines for measuring and analyzing heavyweight building junctions, they do not adequately address lightweight connectors. Therefore, scientists are continuously striving to enhance and rectify existing methods, as has been demonstrated in [3, 5, 12]. In addition, there is an additional path for impact sound transmission through mechanical connections in buildings that is often not reduced. In a study [12] conducted in 2009, Poblet-Puig et al. emphasized the significance of structural transmission in double-leaf structures and referred to studs as bridges between two connected elements. This same phenomenon may also occur between heavyweight construction elements and lightweight elements such as false ceilings, cladding panels which are commonly used for acoustic treatment, or ventilated façade systems. Despite its importance, this phenomenon has been overlooked in the literature, even though it has been shown that lightweight structures excited by structure-borne sounds transmitted through connections can significantly impact the sound pressure level in a room [13, 14]. Therefore, accurately predicting the amount of sound energy transmitted through mechanical connections can greatly improve the sound reduction value, as has been demonstrated for concrete elements [3, 15, 16].

This study introduces a measurement method designed to determine the influence of junction elements in double-leaf constructions. The objective is to describe transfer functions for commonly used elements in drywall constructions. The values obtained from experimental investigation are compared to numerically obtained results for the theoretical value of the transmission function that would be obtained if a perfectly rigid connector was used in the structure. Three different mounting elements were examined: a mechanical connector used for false ceiling construction, a common steel stud used in drywall constructions, and a steel stud with the highest stiffness, used to increase the stiffness of walls near doors. The detailed description of the space, methods, and measurement techniques can be found in Sec. 2. Results are presented in Sec. 3, while Sec. 4 contains conclusions and presents further work to be done.

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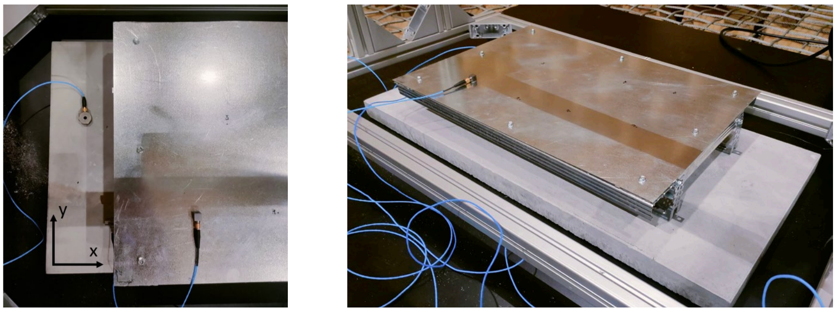
2. Experimental and numerical investigation

2.1. Test stand and experimental setup

Measurements were made using a test stand shown in Fig. 1a. The experimental setup included a concrete plate measuring 80 x 40 cm with a thickness of 3.8 cm, and a steel plate measuring 55.5 x 38 cm with a thickness of 0.1 cm, both connected using steel studs. The cross-section of the samples remained consistent throughout the study, and is presented in Fig. 1b. The study utilized three different mechanical connectors to establish connections between the elements, as depicted in Fig. 2.

a)



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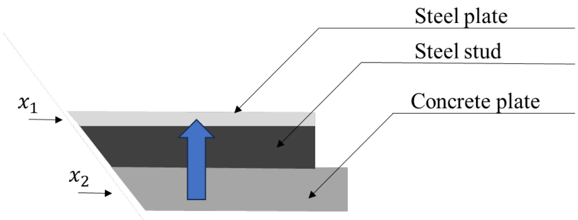


Figure 1. Test stand: a) left picture – view from above, right picture – side view, b) cross-section, schematic drawing; x_1 and x_2 are acceleration spectra on steel and concrete plate, respectively, according to Eq. (2), and the blue arrow indicates direction of impact sound transmission.

Various studs used for drywall constructions were tested. The first one, shown in Fig. 2a, is a CD-50 profile screwed to the steel plate and mounted on the concrete plate using an additional element– flat hanger ES 60 – to build a construction commonly used for false ceilings. Fig. 2b presents a CW-100 profile connected with an UW-100 profile in a way used in lightweight wall constructions, where connection between studs and plates is achieved by screws (further, connection is called CD-100 profile). Fig. 2c shows an UA-50 profile mounted in the same connection method as the CD-100 profile. Stiffness of the UA-50 element is the highest among the elements considered in the analysis. Thickness of the UA-50 is equal to 2 mm, while thickness of the CW-100/UW-100 and the CD-50 is equal to 0.6 mm and 0.5 mm, respectively.

a)  b)  c) 

Figure 2. Ways of elements' connections, a) the CD-50 profile, b) the CD-100, c) the UA-50 profile.

Four measurement points were identified on the steel plate (P1-P4), and three on the concrete plate (B1-B3). The distribution of the points can be seen in Fig. 3 and their coordinates are described in Tab 1. The coordinate values are based on the left-bottom corner of the concrete plate.

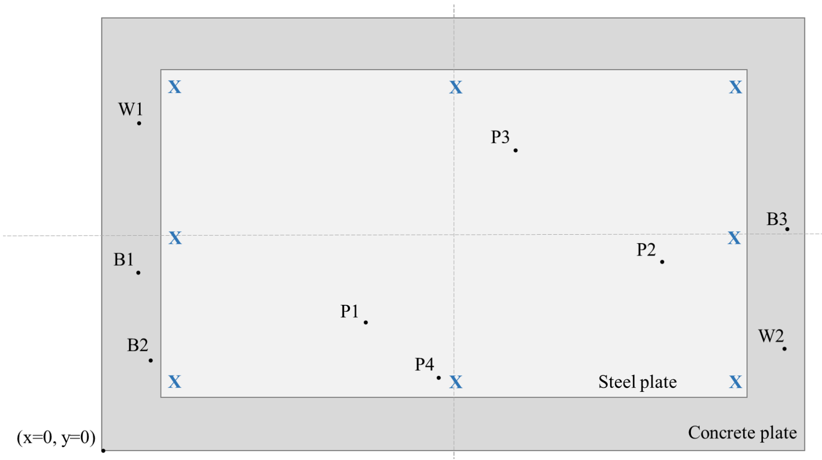


Figure 3. Approximate measurement points distribution; P1-P4 points on the steel plate, B1-B3 points on concrete plate, W1-W2 excitation points. Blue X indicate fixed points locations.

Table 1. Measurement points distribution, P_i – point on the steel plate, B_i – point on the concrete plate, W_i – excitation points on the concrete plate.

Point	X [cm]	Y [cm]	Point	X [cm]	Y [cm]	Point	X [cm]	Y [cm]
P1	36.5	10.0	**B1**	9.0	18.5	**W1**	7.0	28.5
P2	57.0	15.5	**B2**	10.0	11.0	**W2**	74.0	9.0
P3	47.0	27.0	**B3**	72.0	20.0			
P4	39.5	3.5						

Two different excitation methods were considered in the analysis. The first one considered a shaker as a source of vibrations, and the second one considered an impact hammer B&K type 8202. For eight fixed points on the steel plate (in the corners and the mid-lengths of the plate) and one excitation point W1, comparative analysis for the shaker and the impact hammer was conducted. Measurements were taken at points B1, B2 and B3. As the conclusions for every receiver point were the same, results for one selected receiver point are shown in Fig. 4. Despite many advantages of using shaker, like i.e. a possibility to excite selected frequency or specified frequency range, and repeatability of the excitation, only the impact hammer was used in the further analysis. The differences between two curves obtained in the analysis, and the lower value of acceleration observed for excitation by shaker, inform about insufficient energy and lack of possibility to excite the structure over a wide frequency range by shaker.

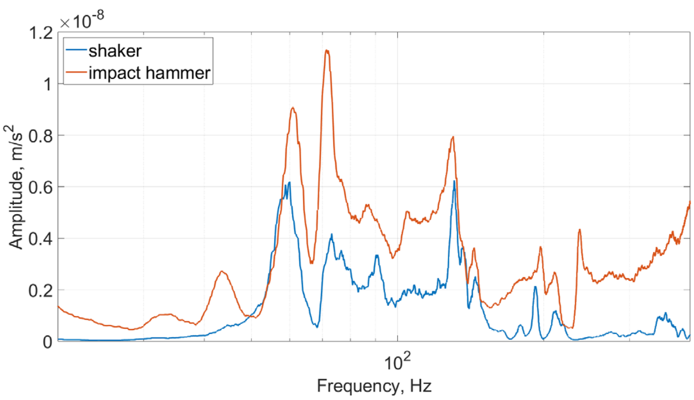


Figure 4. Impact hammer and shaker spectrum comparison for measurement point - B3, and excitation point - W1.

Two triaxial accelerometers were used in the analysis. Accelerometer ICP 356A45 was placed on the steel plate at measurement points P1-P4. ICP 354C03 was placed at points B1-B3. Specifications of the accelerometers are presented in Tab. 2.

Table 2. Accelerometers specification.

Accelerometer	Weight [g]	Axis	Sensitivity [mV/g]
ICP 356A45	4.2	X	96.8
		Y	95.4
		Z	98.1
ICP 354C03	15.5	X	102.4
		Y	99.9
		Z	102.6

Measurements were made simultaneously on the thin steel plate and on the concrete plate. Time signals were registered for each point configuration (P1-B1, P1-B2, P1-B3, etc.) by accelerometers described above. Frequency response functions, called in this work also transfer functions, were calculated according to:

$$\tau = 10 \log_{10} \eta, \tag{1}$$

where η is defined as:

$$\eta = \frac{x_1}{x_2}, \tag{2}$$

where x_1 and x_2 are acceleration spectrum measured for the thin and the massive plate, respectively. Calculations were made for the frequency range from 20 to 3000 Hz. The result value is an averaged value of twenty four transfer functions calculated from all receiver and excitement points configurations. Positive values of τ indicate a sound level increase relative to the initial value measured on the base concrete plate. Negative values of τ inform about the increase of impact sound insulation due to additional elements.

This work considers two different aspects. The first one is the influence of fixed points number on the steel plate, and the second is the influence of the junction element. Therefore, transfer functions were calculated for all of the following cases:

- eight fixed points on the steel plate, profile CD-50,
- four fixed points in the corners of the steel plate, profile CD-50,
- four fixed points in the mid-lengths of the steel plate, profile CD-50,
- eight fixed points on the steel plate, profile CD-100,
- eight fixed points on the steel plate, profile UA-50.

2.2. Numerical investigation

Two plates with size of the elements investigated in the experimental part, were preliminary modelled in COMSOL Multiphysics. The connection between elements was modeled as rigid elements with *rigid connector* boundary condition at the points of screws in experimental investigation, as it is shown in Fig. 5. Distance between plates in numerical simulation was equal to 5 cm, what corresponds to the height of CD-50 and UA-50 junction.

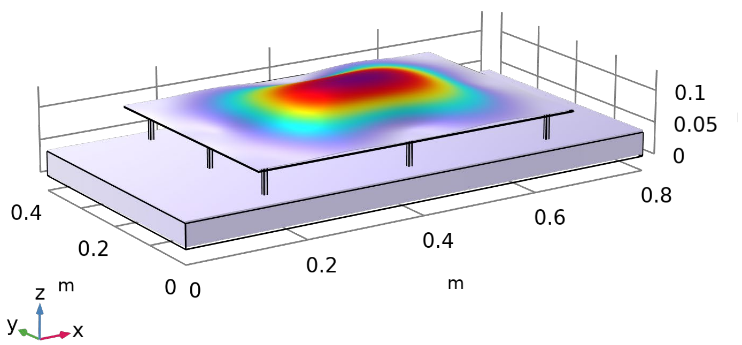


Figure 5. Numerical model of the specimen made in COMSOL Multiphysics.
Results for frequency = 50 Hz.

Locations of rigid boundary conditions corresponds to the points where screws were attached to the specimen during the experimental part of work. Borders of the elements – both concrete and steel plate – were considered free. At two points with coordinates corresponding to coordinates of points W1 and W2 force of 1N was applied. Four receiving points on the upper plate and three receiving points on the bottom plate were considered in the numerical analysis. Coordinates of all points in numerical analysis were corresponding to the points of the experimental analysis. Properties of the concrete and the steel plates used in numerical analysis are shown in Tab. 3. Transfer function was calculated as described in 2.1.

Table 3. Properties of concrete and steel used in numerical analysis.

Parameter	Steel	Concrete
Young modulus, GPa	205	45
Poisson ratio, -	0.28	0.3
Density, kg/m^3	7850	2400

3. Results

Results are shown in two different sections. The first one, Sec. 3.1, shows the impact of the steel plate's fixed point number on the sound transmission effect. The second section, Sec. 3.2, focuses on the influence of profiles used as a junction element on sound transmission. All analyses were made for *z*-axis in Cartesian coordinates.

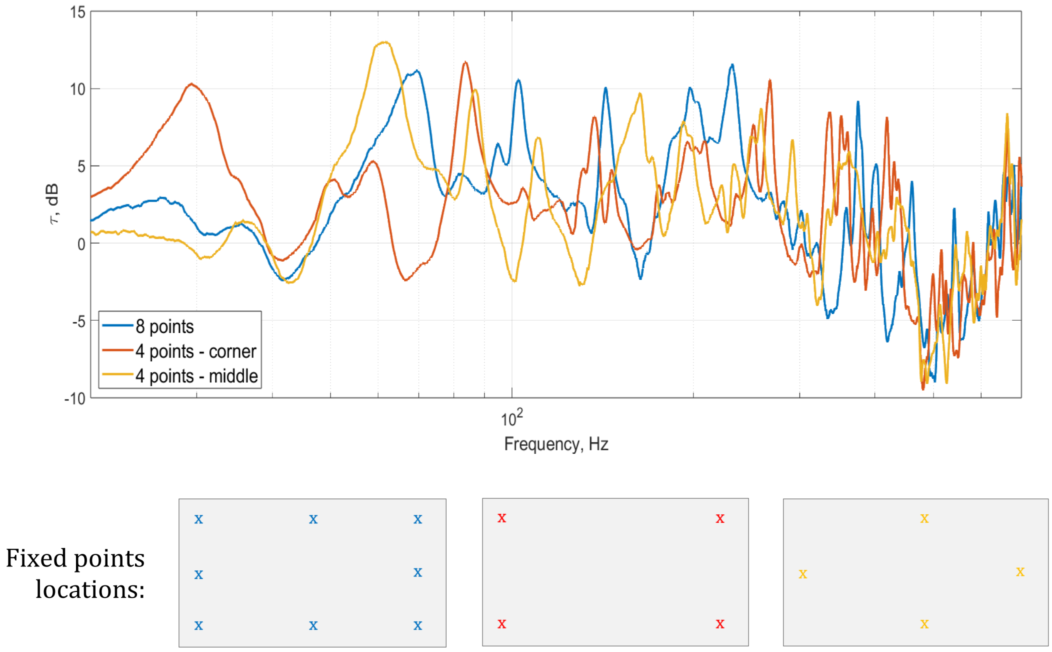


Figure 6. Transfer function obtained in CD-50 profile analysis: the impact of fixed point number. Fixed points distribution is presented in bottom part of the figure with colors respective to color of spectrum presented in upper figure.

3.1. Influence of a number of fixed points on impact sound transmission

Analysis of a different number of fixed points on the steel plate was made for the first junction, i.e. a construction used for false ceilings – CD-50 profile. Results are presented in Fig. 6. The analysis was performed between 20 and 700 Hz, as the most notable variations were observed in a low frequency range due to resonant frequencies of the fixed plates. Specifically, the increase in the transfer function around 30 Hz, seen in the case of the four-point-corner fixed plate, is a consequence of the first resonant frequency with the highest velocity occurring at the mid-lengths of the plate. This specific resonant frequency does not appear in the other cases we analyzed. A similar situation is evident around 170 Hz, where an increase in the transfer function is only observed in the case of the four-point-mid-length fixed plate, while the values for the other two cases remain close to 0 dB. Beyond 300 Hz, the transfer function values for all cases are similar, with no significant differences observed. The conclusion drawn from this analysis is that the transfer function is greatly influenced by the modal behavior of the structure being measured. To minimize the occurrence of resonant frequencies being emphasized in the transfer function values, it is recommended to either increase the number of measurement points or position them closer to the fixed points.

3.2. Influence of different kinds of studs on impact sound transmission

In order to thoroughly analyze the effect of stud elements on the transmission of impact sound between two parallel elements, the theoretical transfer function for a perfectly rigid junction was calculated using COMSOL Multiphysics. When dealing with a perfectly rigid junction, the transfer function is mainly affected by the resonant frequencies of the plate elements and the material's damping. This junction acts as the component responsible for transferring energy between the plates, without introducing any damping at the junction. Furthermore, comparisons of numerical and experimental values for each junction considered in this investigation are presented in Fig. 7. Fig. 7a presents τ values obtained for false ceiling junction. Noticeable difference between curves appears around 1800 Hz, where values for numerical investigation are consistent constant and values obtained for experimental investigation decreases reaching values lower than 5dB. The significance of this phenomena is mostly important for the estimation of the junction's resonant frequency, as above that value, the junction begins to exhibit damping behavior. Resonant frequency of two other junction – CD-100 and UA-50 – presented in Fig. 7b and Fig. 7c, respectively are not so obvious to estimate, as there is no visible decrease of the values referring to numerical spectrum. The effect of that might be not sufficient frequency range taken into consideration in the analysis, as the higher is stiffness of the element, the higher is resonant frequency. Furthermore, the biggest differences between numerical and experimental investigation are obtained for UA-50 junction. Mean value of τ, calculated as arithmetic average for frequencies from 20 to 2500 Hz, and presented in Tab. 4 is close to 5 dB, what informs about high impact of the junction on the sound transmission and vibration enhancement.

Table 4. Mean values of transfer functions obtained in the experimental and numerical analysis and RMSD value obtained for every junction analyzed referred to perfectly rigid junction obtained in MES analysis.

Junction type	μ, dB	*RMSD,* dB
CD-50	-1.7	7.6
CD-100	1.5	5.7
UA-50	4.9	7.6
Perfectly rigid - MES	0.5	-

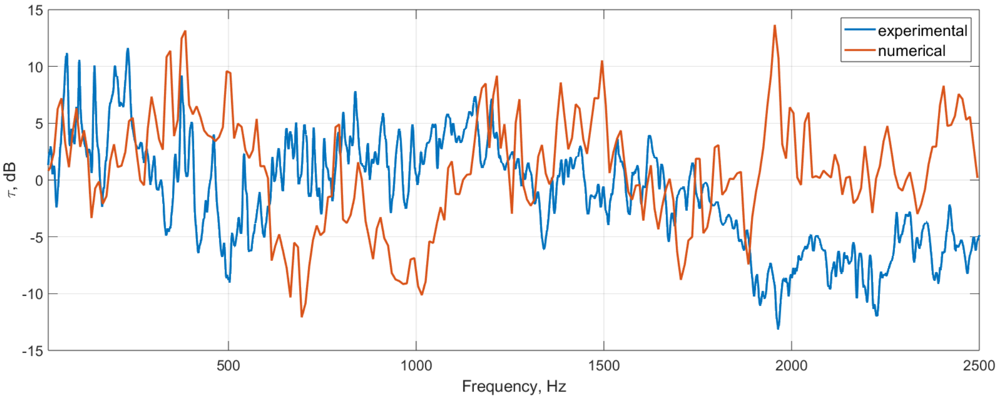
Although the experimental investigation shows lower values than the numerical simulation at around 2400 Hz for the CD-100 junction, which could be considered as a resonant frequency for the element, it is not possible to determine this for the UA-50 stud, which has the highest stiffness among all the cases analyzed. The best fit of numerical and experimental spectrum is obtained for CD-100 junction. However, the mean value calculated for the whole frequency range is 1dB higher referring to MES results, value of RMSD (Tab. 4) calculated according to:

$$RMSD = \sqrt{\frac{\sum(x_{MES} - x_o)^2}{n}} \tag{3}$$

is equal to 5.7 dB, where x_{MES} are values obtained in numerical analysis, x_o are values obtained in experimental investigation, and n is number of values.

The transfer functions show consistent trends, but variations between the numerical and experimental results may be attributed to the presence of additional mounting elements such as bolts and nuts and their resonant frequencies. This suggests that the behavior of the CD-100 junction closely resembles that of a perfectly rigid junction within the frequency range of 20 to 2500 Hz, based on the cases analyzed in this study. However, it is important to note that the numerical model used in this research was a preliminary model, and further, more comprehensive analysis is required for the numerical investigation.

a)



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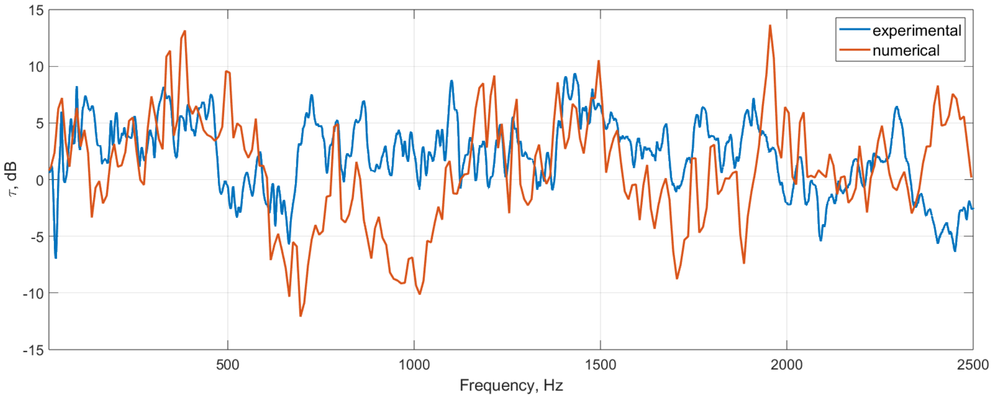

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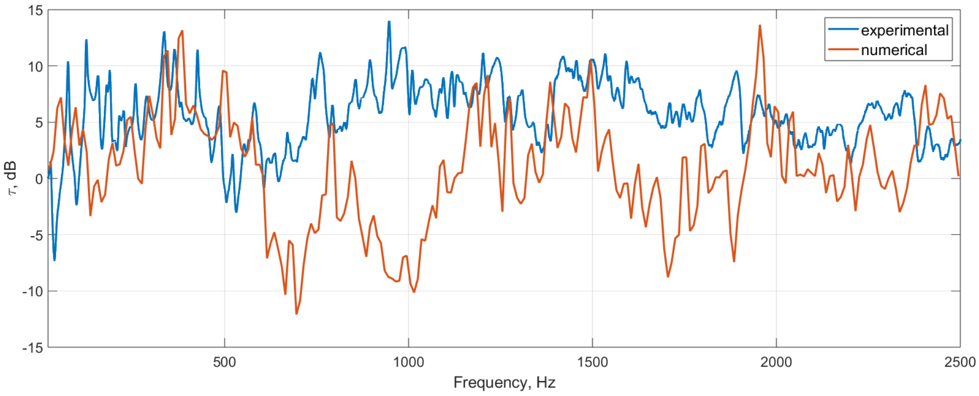

Figure 7. Comparison of transfer function obtained in numerical analysis and experimental investigation for a) CD-50, b) CD-100, c) UA-50.

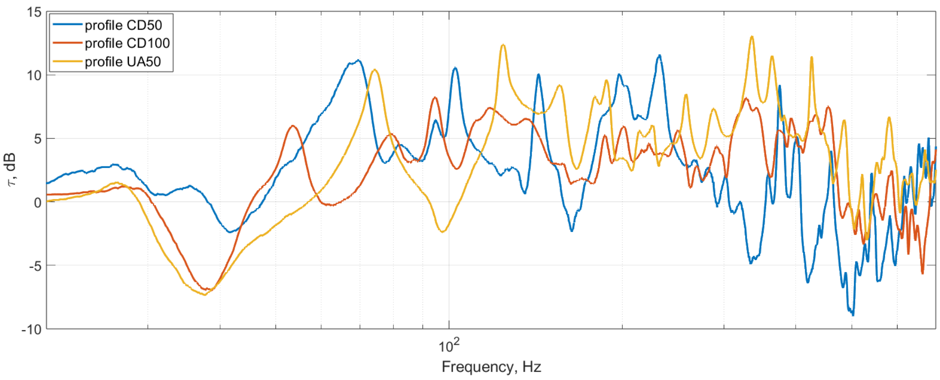

Figure 8. Transfer function, the influence of junction element – z-axis.

Figure 8 illustrates the transfer function values obtained from experimental investigations in the frequency range up to 700 Hz. The focus is on highlighting the differences between the various cases studied. The greatest discrepancies are observed in the low-frequency range. To ensure a fair comparison, the same mounting method and an equal number of fixed points were used in this segment of the analysis. This allows us to conclude that the variations observed in the curves are not due to the modal characteristics of the steel plate, but rather to the influence of the junction element.

4. Conclusions and further work

Transfer function analysis provides information about the transmission of impact sound from building construction to lightweight elements through lightweight junction elements. This parameter plays a crucial role in minimizing the transmission of impact sound through the construction. Understanding this phenomenon allows for the design of conscious solutions that can significantly reduce sound pressure levels.

This work presents the impact of various fixed point configurations at lightweight constructions and its influence on the transfer functions. The analysis was performed for three different numbers of fixed points, and shows mostly the influence of modal behavior of the steel plate. Insufficient number of receiver points located on both steel and concrete plate might be the reason of unexpected transfer function behavior in specific frequency ranges what was described in previous section. Unless these points were chosen to avoid critical locations as the mid-lengths or the plates' corners where the impact of resonant frequencies is the highest, the possibility of measuring at resonant frequencies locations is unavoidable. Furthermore, three different lightweight elements mounting methods on the concrete base element were presented and analyzed. The first one, used commonly for false ceilings aimed to be the most effective in impact sound reduction, as the resonant frequency of the junction element might be estimated to around 1800 Hz. Its effectiveness is probably caused by flat hanger usage. Two others profiles used in this work occurs similar impact sound reduction effect. Differences observed in the analysis are caused by various thickness and stiffness of the elements. In all analyzed cases, low frequency range (below 1000 Hz) are not reduced and impact sounds are transmitted freely in the transmission path. That phenomena and possibilities of damping low-frequency impact sounds are the interests of further work.

The following of this study will also take into account mapping the whole specimen with acceleration measurements on both steel and concrete plate to minimize the influence of modal behavior. Additionally, triaxial analysis is planned to be done to describe the impact of motion along *y*-axis and *x*-axis on the transfer function.

Additional information

The authors declare no competing financial interests that all material taken from other sources (including their own published works) is cited and that appropriate permits are obtained.

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