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Evaluation of Various Joints between Studs and Plates on Flanking Noise Transmission within Lightweight Periodic Structures

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Abstract

Noise propagation in lightweight building structures is an issue that needs attention in the current building trend. In this paper, a finite-element model is utilized for the analysis of flanking noise transmission in a lightweight panel structure consisting of two plates with internal ribs using various joints between the studs and the plates. Four different coupling configurations are considered: 1) all structural contact points are completely tied; 2) only nodes on the centre lines of the structure are tied; 3) a narrow strip of 5 mm, 10 mm or 20 mm tied elements connect the frame to the plates; 4) evenly spaces discrete elements are tied. The computations are carried out in the frequency domain with diffuse-field excitation of the source panel in the frequency range below 500 Hz.

Keywords: structural coupling, lightweight periodic structure, flanking noise transmission, diffuse-field excitation, finite element method.

1 Introduction

Evaluation methods for sound transmission in lightweight buildings are currently getting a lot of attention in the field of building acoustics. The use of lightweight structures with prefabricated building components offers many advantages—both economically and environmentally—but the vibro-acoustic performance for such constructions conflicts with the increasing demands and high standards for noise and vibration in buildings. This is due to the low mass of the structure along with the fact that lightweight structures with internal stiffeners are typically inhomogeneous and anisotropic regarding their material properties and the periodic nature of the design. This causes a non-uniform modal density and leads to the formation of stop-bands and pass-bands in the frequency response. The increase in sound transmission in lightweight structures compared to that of traditional heavy structures is mostly due to the higher flanking noise transmission.

For flanking noise transmission in general, research indicates that structural joints between elements allow most of the sound transmission [1, 2]. A general model of transmission of longitudinal and transverse waves at random incidence was studied by Whole and Kurtze [3] for junctions with an elastic connection between the plates. A detailed experimental approach was applied for analysis of the structure borne sound transmission at the corner junctions between elastically coupled rods. The influence of elastic layers at junctions between walls and floor elements on airborne and structure borne sound transmission in buildings was investigated by Osipov and Vermeir [4] and it was suggested that elastic layers at joints strongly affect the sound transmission in buildings, especially at long distance propagation involving multiple joints.

Observations on the effect of an interior panel within a double-leaf elastic plate on the structure borne sound radiation under point force excitation have been made by Motoki [5] who concluded that thick and heavy material as an interior panel reduces the sound transmission at high frequencies, whereas amplification of radiated power around mass–air–mass resonance frequencies cannot be avoided, neither by increasing the mass of interior panels nor by increasing the depth of the air cavity. A finite-element approach for modelling of flanking noise transmission in building acoustics has been taken by Dirk and Sabine [6] achieving computational results show good agreement with measured results within a large frequency range.

Direct sound transmission through various couplings in periodically connected lightweight panels and flanking noise transmission through varying periodic stiffeners in lightweight panels using the finite-element method have been predicted in previous work done by the authors [7, 8]. It was deduced that, loose couplings do not necessarily transmit less sound, which is due to a higher mode count in the investigated frequency range. Furthermore, the overall vibro-acoustic behaviour of a lightweight panel structure can be significantly changed by altering the positions of the internal stiffening ribs. It is well known that periodic stiffeners within lightweight panels have an important role in reduction of sound transmission due to the generation of stop bands [9, 10].

The current paper focuses on flanking noise transmission between three adjacent walls forming a Z-shape. The study is carried out as a parameter study where the coupling between plates and studs is varied in the finite-element model. The analyses concern the dynamic response to diffuse-field excitation with the load applied at the source wall and spatial RMS acceleration assessed and analysed on the receiving wall surface. Hence, a study is made of the flanking noise transmission at various frequencies within the frequency range below 500 Hz. The findings of the paper indicate that when using FEM to predict flanking noise in lightweight building structures, the couplings between studs and plates have significant effect on the predicted transmission of sound at various frequencies.

2 Problem Description

Lightweight building structures are often constructed using panels with plates on stud or joist frames. To obtain the desired structural properties, frames can be designed with either single or double studs or constructed with layers of foam or another viscoelastic material. In the present case, single-stud double-plate panels with periodic stud placement are considered. The structure consists of three identical panels connected through direct structural coupling (cf. Figure 1). The coupling between the plates and the frames are varied in the numerical model. The source wall is subject to diffuse-field excitation and vibration transferred to the receiving wall surface at other end of the structure is analysed. For the analysis, the spatial root-mean-square (RMS) of the acceleration in the normal direction is recorded on one surface of the receiving wall. The acoustic medium within the receiving room has not been included in the current analysis, and thus the acceleration serves as a stand-in measure of the sound radiated into the room, since this cannot be directly evaluated.

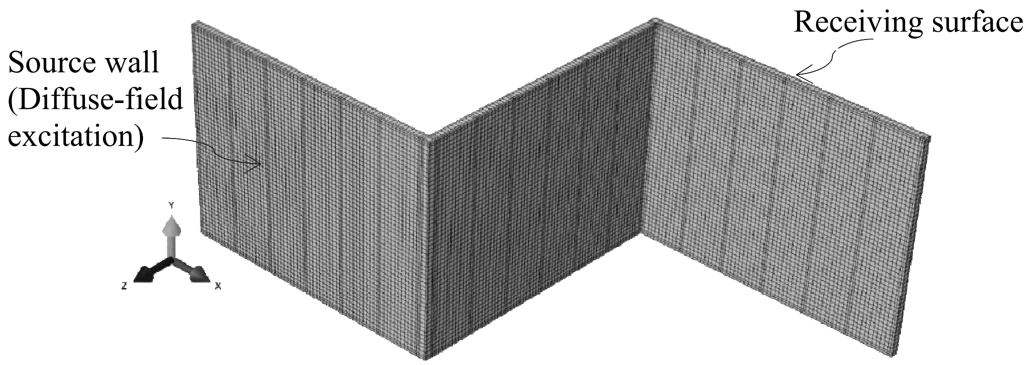


Figure 1: Geometry of panel structure with periodic rib stiffening under diffuse-field excitation.

2.1 Computational Model

The whole structure consist of three lightweight panels (source wall, centre wall, receiving wall) made of timber and placed into a Z-shape as illustrated in Figure 1. Each panel is constructed as a double plate attached to a timber frame with additional periodically placed studs as internal ribs. The plates have a thickness of 20 mm, whereas the frame has a thickness of 60 mm and each single stud is 50 mm wide. Columns with the cross-sectional dimensions 100 mm by 100 mm are put at the corners of the Z-shaped panel structure, thus connecting the source wall to the centre wall and the centre wall to the receiving wall. The total wall dimensions are 3350 mm (width) by 2600 mm (height) by 100 mm (thickness). The studs are placed with a distance of 550 mm (centre-to-centre). Homogeneous and isotropic materials are assumed. The material properties of timber (plates and frame) are: Young's modulus $E = 14$ GPa, Poisson's ratio $\nu = 0.35$, mass density $\rho = 550$ kg/m^3. Damping is set to 1% of the stiffness (frequency-independent structural damping).

A parameter study is carried out with various couplings between frame and plate structure. Hence, a total of six different coupling structures are taken into consideration to study flanking noise transmission from source wall to receiving wall as shown in Figure. The six cases can be described as follows (see Figure 2):

- All structural contact points are completely tied,
- only nodes on the centre lines of the structure are tied,
- a 5 mm wide strip of tied elements connect the frame to the plates,
- a 10 mm wide strip of tied elements connect the frame to the plates,
- a 20 mm wide strip of tied elements connect the frame to the plates,
- evenly spaced 1 cm^2 discrete elements are tied.

The panel is modelled in the commercial FEM package Abaqus using continuum finite elements. 20-node brick elements with quadratic spatial interpolation of the displacement are adopted. The minimum wavelength in the model is expected to be approximately 10 cm as this is the order of magnitude of the flexural wavelength in the plate at a frequency of 500 Hz:

$$\lambda_b = \sqrt[4]{\frac{E h_p^2}{12 \rho \omega^2 (1-\nu^2)}}, \tag{1}$$

where h_p is the thickness of the plate.

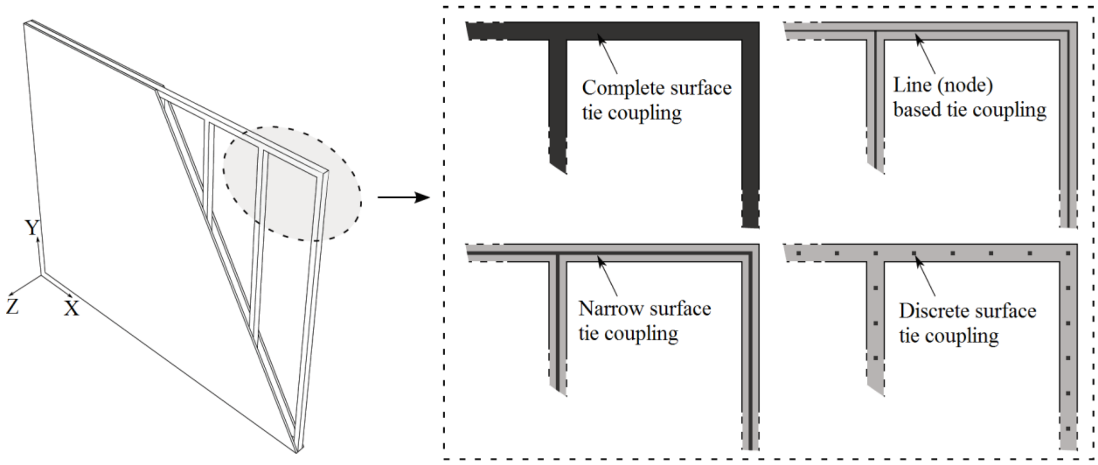


Figure 2: Six different coupling configurations for centre wall: (a) All structural contact points are completely tied; (b) only nodes on the centre lines of the structure are tied; (c) a narrow strip of 5 mm, 10 mm and 20 mm of tied elements connect the frame to the plates; (d) evenly spaced discrete elements are tied. In all cases the interaction between non-tied elements is neglected.

The mesh size is put to 50 mm to ensure a sufficiently high resolution of the model in the investigated frequency range. The mesh is designed such that the nodes constituting the plate mesh align with the nodes on the frame structure. All structural contact points are connected using tie constraints in x, y, and z directions. As three-dimensional solid continuum elements have no rotational degrees of freedom, only displacements are considered. The boundaries are clamped, i.e. all nodes on the top, bottom and side surfaces of the structure are constrained in all directions. Only direct structural transmission is considered.

In all cases the interaction between non-tied elements is neglected. Thus, effects such as friction or even hard contact between non-tied elements are not taken into account and the results can be considered to be extremes of a parametric study.

It should be noted that the air has not been included into the computational model, i.e. the acoustic medium inside and surrounding the walls has been disregarded. Introduction of the surrounding air has an anticipated effect of reducing some of the Eigen frequencies of the structure due to the added-mass effect, whereas other Eigen frequencies are increased due to an added stiffness where the air inside a panel acts like an air cushion. At the same time damping will occur due to radiation of sound.

2.2 Excitation

The diffused-field loading condition is generated by a built-in routine in Abaqus. Here it the diffuse field is approximated by a number of deterministic incident plane waves coming from angles distributed over a hemisphere encapsulating the loaded surface. The number of incident plane waves used for the approximation is given by N^2, where N is called the number of seeds. For the present analyses, $N = 30$ seeds have been employed, so the total numbers of incident plane waves are $N^2 = 900$.

2.3 Methods of Analysis

Two analyses are performed on the present lightweight structure: 1) Modal analysis; 2) analysis of the steady state response to diffuse-field excitation. In the modal analysis, the undamped Eigen frequencies and the corresponding Eigen modes are determined for the various panel configurations as described in Subsection 2.1. The Lanczos solver implemented in Abaqus is applied for the structural analysis and all modes occurring below 500 Hz are requested.

In case of the steady state response to diffuse-field excitation, direct steady state analysis is performed in the frequency domain. Thus, the response is calculated directly from the full stiffness and mass matrices of the global finite-element model rather than a model based on the modal analysis. The steady state response analysis is performed for six different specifications of the model under diffuse-field excitation:

- Transmission from source wall to receiving wall when all structural contact points are completely tied (see Figure 2) under diffuse-field excitation;
- transmission from source wall to receiving wall when only nodes on the centre lines of the structure are tied (see Figure 2) under diffuse-field excitation;

- transmission from source wall to receiving wall when a 5 mm wide strip of tied elements connects the frame to the plates (see Figure 2) under diffuse-field excitation;
- transmission from source wall to receiving wall when a 10 mm wide strip of tied elements connects the frame to the plates (see Figure 2) under diffuse-field excitation;
- transmission from source wall to receiving wall when a 20 mm wide strip of tied elements connects the frame to the plates (see Figure 2) under diffuse-field excitation;
- transmission from source wall to receiving wall when evenly spaced 1 cm^2 discrete elements are tied (see Figure 2) under diffuse-field excitation;

Diffuse-field excitation is considered in order to quantify the sound transmission from the source wall to the receiving surface via the centre wall, i.e. the flanking noise transmission is analysed.

3 Results and Discussion

The Eigen modes and the corresponding Eigen frequencies of the panel structures (that differ in the couplings between studs and plates) are extracted. Figure 3 and 4 show the accumulated number of modes appearing below a given frequency in the intervals from 50 to 250 Hz and from 250 Hz to 500 Hz respectively. With reference to Figure 3, the number of modes below 250 Hz in the different configurations listed are, in descending order: Line coupling, discrete 1 cm^2 coupling, 5 mm strip of tied elements, 10 mm strip of tied elements, 20 mm strip of tied elements, completely tied (surface coupling). Thus, the highest number of modes below 250 Hz is seen when studs and plates are connected through line couplings. This is due to the looser couplings which allow more bending along the length direction of the panels.

The first Eigen modes in the panels with line coupling, discrete coupling, 5 mm glued coupling, 10 mm glued coupling, 20 mm glued coupling and total surface coupling occur at 67 Hz, 68 Hz, 76 Hz, 81 Hz, 86 Hz and 89 Hz, respectively. Since the mass of all structures is identical, this demonstrates that the panel structure behaves significantly stiffer when a wider part of the contact area between the studs and the plates is tied.

A rapid increase in the number of modes is seen beyond 250 Hz in all the coupling configurations, except for the panels with 20 mm glued coupling and total surface coupling. For the panels with 20 mm glued coupling and total surface coupling, this rapid increase of modes is seen beyond 350 Hz and 400 Hz, respectively. This is due to the fact that these two configurations provide a stiffer panel structure and as a result of this the Eigen frequencies are generally increased compared to those of the more flexible panels.

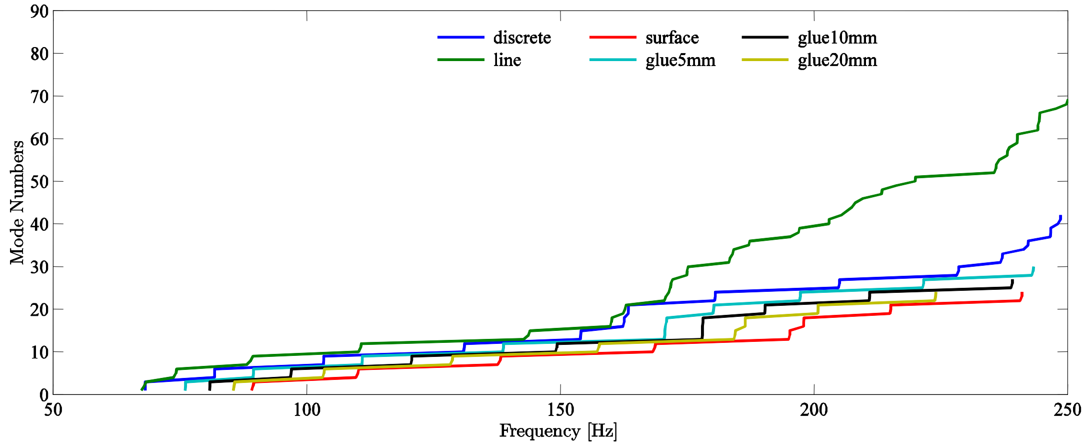


Figure 3: Eigen frequencies within whole panel structure from 50 to 250 Hz.

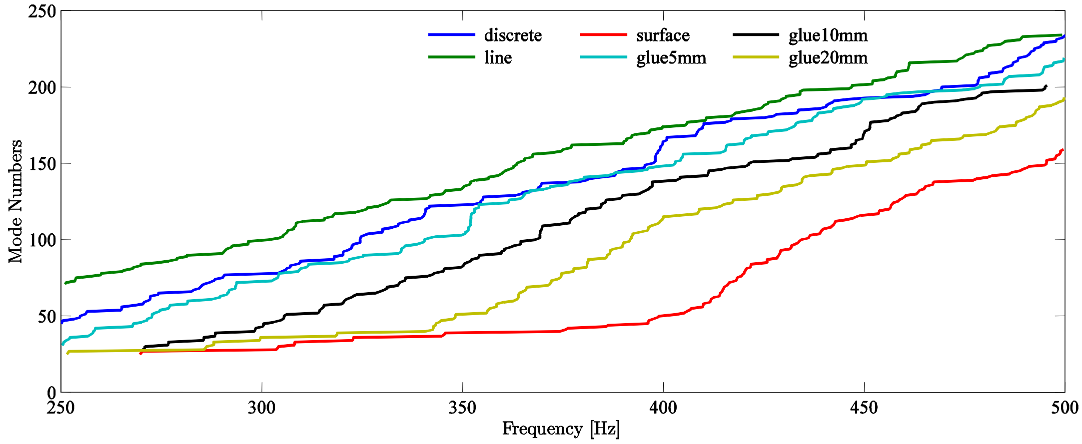


Figure 4: Eigen frequencies within whole panel structure from 250 to 500 Hz.

Figure 5 and Figure 6 show the frequency response of the receiving panel (spatial RMS acceleration level) when the source panel is loaded with diffuse-field excitation as previously described. Figure 5 shows the results from 50 Hz to 250 Hz, and Figure 6 contains the results from 250 Hz to 500 Hz. At lower frequencies (below 100 Hz), the vibration transmission is highest for the case of the panel structure with line coupling between studs and plates; the first high peak is seen at 67 Hz where the first mode was discovered in that case. Stop bands are visible in the frequency range from 60 to 200 Hz in all of the cases, which shows the effect of studs placed periodically within all of the panel structures.

Transmission of sound between 200 Hz and 300 Hz is significantly lower—especially in the panel structures with surface coupling, 20 mm glued coupling, 10 mm glued coupling (see Figure 5), which also relates to the lower number of modes seen in Figure 3. In the case of line coupling, the transmission of sound is higher due to an increased number of Eigen modes in the frequency range. In the 250 Hz to 500 Hz frequency range, the transmission of sound is increased above 300 Hz due to a higher number of Eigen modes, which leads to larger modal density.

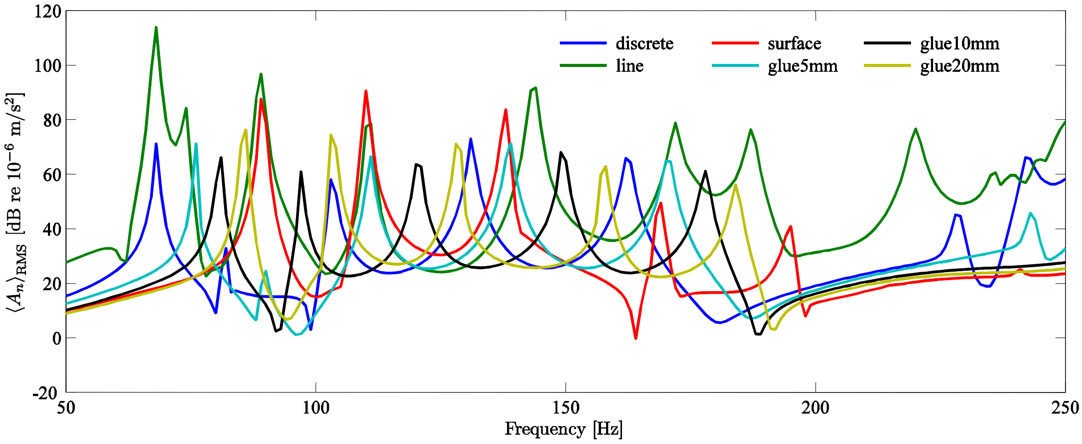


Figure 5: Acceleration levels (frequency range = 50 to 250 Hz) on the side surface of the receiving wall under diffuse-field excitation on the source wall surface.

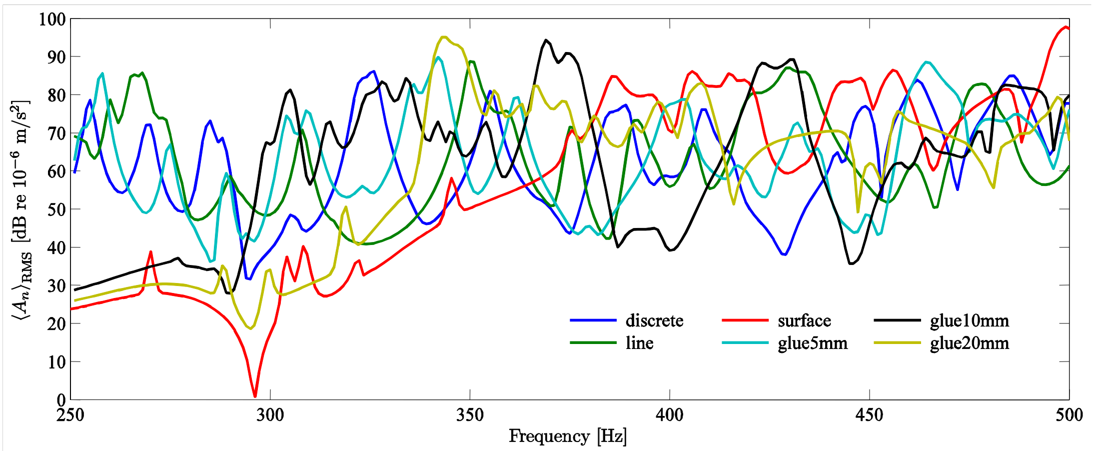
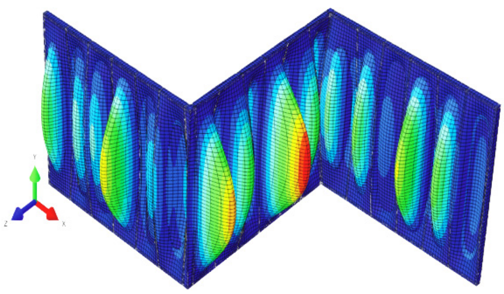
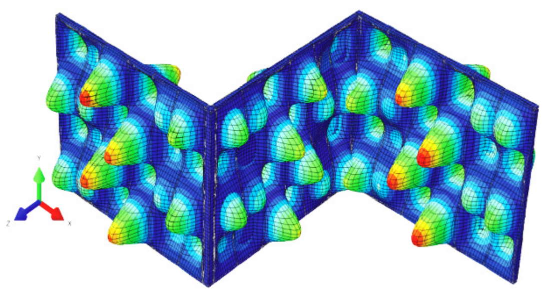


Figure 6: Acceleration levels (frequency range = 250 to 500 Hz) on the side surface of the receiving wall under diffuse-field excitation on the source wall surface.



(i) Mode shape at 368 Hz



(ii) Mode shape at 387 Hz

Figure 7: Mode shapes occurring at 368 Hz and 387 Hz within the panel structure where studs and plates are tied along a 10 mm wide glued strip of elements.

Band gaps are visible at higher frequencies as well due to the periodic nature of the structure (see Figure 6). In the case of coupling between the studs and the plates along a 10 mm wide strip of elements, an increased transmission of sound is seen at 368 Hz, which results from an Eigen mode occurring at that particular frequency. The corresponding Eigen mode is depicted in Figure 7(i). A sudden decay is seen in same structure between 380 Hz and 400 Hz, despite the occurrence of modes in that range. For example, Figure 7(ii) shows the mode at 387 Hz.

For the case of completely tied surface interaction between the studs and the plates, transmission of sound is rapidly increasing beyond 400 Hz due to an increase of the modal density. The performance of the various panel structures beyond 400 Hz is seen to be comparable in magnitude and modal density.

4 Summary

Flanking noise transmission from a source wall to a receiving surface of a Z-shaped lightweight panel structure has been investigated in terms of a parameter study of the influence of various coupling configurations between the plates and the stud-frames. The structural behaviour has been analysed for diffuse-field excitation on the surface of the source wall in the frequency range below 500 Hz. The first structural modes occur at 67 Hz, 68 Hz, 76 Hz, 81 Hz, 86 Hz and 89 Hz, respectively, for models in which the studs and plates are connected by line coupling, discrete coupling, 5 mm wide glued coupling, 10 mm wide glued coupling, 20 mm wide glued coupling and total surface coupling, respectively. It is illustrated that a panel structure behaves significantly stiffer when the studs and plates are coupled over a wider strip. An increase of the modal density in all the panel configurations is seen at the higher range of frequencies.

Under diffuse-field excitation, there are higher peaks at low frequencies which is the result of exciting the first structural modes in the respective panels. A similar behaviour is observed in all of the panels in the frequency range from 100 Hz to 200 Hz. A sudden increase of vibration transmission is seen above 300 Hz for all of the panels, which is due to a higher modal density. The panel structure with full surface coupling between the studs and the plates is transmitting a higher amount of vibration than other panel structures at higher frequencies. An interesting observation is made in the cases of the 10 mm wide glued coupling and full surface coupling: A sudden decay and rise in vibration transmission is seen despite of modes occurring in the frequency range from 350 Hz to 470 Hz. This is due to the fact that several of the structural modes do not allow transmission of vibration in the direction towards the receiving wall surface.

Future work involves a closer investigation of the influence of periodicity in the stiffening of lightweight structures by means of examining the occurrence of stop bands and energy dissipation at various junctions. The acoustic medium will be introduced in the adjacent rooms in order to predict flanking noise behaviour of the structure directly and compared with experimental results. The aim is to mitigate flanking noise transmission via joints as well as direct transmission between adjacent rooms by design of the periodic stiffening.

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References

[1] L. Cremer, M. Heckl & E.E. Ungar, “Structure borne sound”, Springer, Berlin, 1973

[2] D.B. Pedersen, “Estimation of vibration attenuation through junctions of building structures”, Technical report 2600 8050, Danish Technological Institute, 1992.

[3] W. Whole, H. Schreckenbach, “Coupling loss factor for statistical energy analysis of sound transmission at rectangular structural slab joints, Part 1”, Journal of Sound and Vibration, 323 -334, 77 (1981).

[4] A. Osipov, G. Vermeir, “Sound transmission in buildings with elastic layers at joints”, Applied Acoustics, Vol 49, No. 2, 141-162, 1996.

[5] Y. Motoki, S. Kimihiro, S. Eiji, M. Masayuki, M. Atsuo, A. Kei, “Sound radiation from a double-leaf elastic plate with a point force excitation: effect of an interior panel on the structure-borne sound radiation”, Applied Acoustics, 63, 737-757, 2002.

[6] C. Dirk, L. Sabine, “Finite element approach for flanking transmission in building acoustics”, Building Acoustics, Volume 14, No.1, 1-14, 2007.

[7] K.A. Dickow, P.G. Domadiya, L. Andersen, P.H. Kirkegaard, “A parameter study of coupling properties in finite elements models of single-stud double plate panels”, 4-7 September, Internoise 2011, Osaka, Japan, 2011.

[8] P.G. Domadiya, K.A. Dickow, L. Andersen, P.H. Kirkegaard, “ Influence of periodic stiffening on flanking noise transmission- Numerical analysis based on various frame designs of a lightweight panel structure”, 4-7 September, Internoise 2011, Osaka, Japan, 2011.

[9] T.R.T Nightingale, “On the distribution of transverse vibration in a periodic rib stiffened plate”, Forum Acusticum, 2005.

[10] L. Galbrun, “Vibration transmission through plate/beam structures typical of lightweight buildings: Applicability and limitations of fundamental theories”, Applied Acoustics, 71, 587-596, 2010.