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Acoustic Performance of Different Cold-Formed Studs in Double-Leaf Walls by Finite Element Analysis and Experiment

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Abstract

Cold-formed steel studs are often used in lightweight partition walls to provide structural stability but in the same time they change the acoustic performance of the whole system. The overall design of such lightweight structures for acoustic sound insulation becomes very complicated as the sound passing through stud needs to be quantified. One of the greatest challenges is to characterise the stud's geometric effects on the sound transmission of the partition walls. This paper presents a Finite Element modelling approach and results into the acoustic performance of cold-formed studs in double-leaf walls which are placed in between a source room and a receiving room. The acoustic medium was modelled using fluid elements and the structure was modelled with conventional stress elements. The interaction between the acoustic medium and the structure was modelled in a coupled structural-acoustic analysis. An FE modelling setup which includes appropriate model parameters to be used in the structural-acoustic analysis was presented. The FE sound transmission loss of double-leaf walls using two different stud profiles was then calculated. Experimental tests complying with BS EN Standards 717 and 140 were also carried out to evaluate the FE results. It has shown that the FE results have similar trends and are in fair agreement with the experimental results; and the stud's shape has significant effects on the sound transmission of the double-leaf walls. The FE analysis is a powerful tool and can be used as a complementary and alternative method to the laboratory tests for acoustic performance of double-leaf walls with steel studs.

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Introduction

Double-leaf walls are constructed using cold-formed steel studs and plasterboard, which can give rise to significant savings in structural design compared to masonry alternatives. Big benefits also include lightweight structures, the speed of installation and reduction of overall build costs. However, the overall design of such lightweight structures including acoustic performance of the studs is much more complex. In partition walls, acoustic sound travels through the air cavity between the two boards and also the studs which connect the two boards. The studs affect the dynamic and sound radiation properties of each board, and thus change the sound transmission loss of the partition walls as a whole. The change in the sound transmission of the partition walls highly depends on the stiffness and cross-section shape of the connecting studs. Recent building standards such as BS EN ISO 140-3:1995 (1995) and BS EN ISO 717-1:1997 (1997) have required the acoustic insulation properties to meet a minimum threshold and they must be evaluated through laboratory tests in special acoustic rooms, in which a partition wall is placed in between a source room and a receiving room.

The acoustic performance of double-leaf walls consisting of metal studs has been the subject of both experimental and analytical investigations. Some laboratory measurements of the effect of studs in the sound transmission were carried out in Hongisto at al. (2002), Bradley and Birta (2001), Poblet-Puig at al. (2006) and Quirt and Warnock (2010). However, the characterisation of the stud as the connecting element on the sound transmission of the partition walls, i.e. shape and material properties, has not been investigated widely. A review of experimental studies concerning the influence of different physical parameters on the sound transmission index of double-leaf walls has revealed that only five of seventeen prediction models included studs, and only two of them considered the effect of studs' stiffness (Hongisto et al. 2002).

Several analytical models dealing with sound transmission of double-leaf walls using steel studs were introduced in the literature. In the simplest model that has been studied, the studs were considered as infinitely rigid connections between the boards (Fahy 1989). These models can be suitable for rigid studs but not applicable for lightweight studs as they do not take into account the flexibility of the studs to reduce sound transmission. Some existing models for sound transmission consider the studs as elastic springs including both translational and rotational springs (Kropp and Rebilard 1999, Wang et al. 2005). A complete model of sound transmission in which both the air cavity and stud paths are considered, was introduced in Brunskog (2005). In these models, the spring stiffness is typically taken as the cross-section elastic stiffness of the stud but this leads to an underestimate of the sound transmission. The effects of adding resilient channels to a rigid double-leaf wall were presented in Bradley and Birta (2001) and Davy (2010). In these models, the surface layers mounted on resilient channels were treated as a vibration isolator with a fundamental resonance frequency determined by the combination of the stiffness of the resilient channels and the stiffness of the air cavity along with the masses of the surface layers.

The analytical models mentioned above predict the sound transmission of the double-leaf wall with studs but cannot model accurately the stud's shape and material properties, which define how fast and strongly different structural waves propagate through it. However, numerical methods such as Finite Element (FE) analysis are now available to accurately predict sound transmission in room acoustic analysis as it can consider the actual shape and material properties of the studs. Del Coz Diaz et al. (2010) employed FE analysis to find the most efficient numerical procedure to predict the transmission loss through a multilayer wall for frequencies ranging from 100 to 5000 Hz. The effects of the material properties and the shape of the stud including various dimensions and thicknesses were presented in Guigou-Carter et al. (2012); this, however, was done for isolated stud-board systems, not in room acoustic systems. The role of the stud stiffness in the sound transmission of double-leaf walls was investigated using FE analysis in Poblet-Puig et al. (2009). Recently, a 2-D finite element model has been developed (Arjunan et al. 2013) to predict the sound reduction index for a steel stud based double-leaf wall using ANSYS software. The effects of the mesh size, connection between board and stud, and position of the sound source on the sound reduction index were also considered in their study. However, the influence of the stud's shape has not been touched in these studies.

This paper aims to study the effect of the stud's shape on the sound transmission of double-leaf walls. FE models to predict airborne acoustic performance of two different cold-formed stud profiles having the same height and thickness but different shapes, in double-leaf walls were developed. A methodology of setting up FE models was developed in order to obtain appropriate results. Experimental tests were carried out for two different stud's profiles and the results were used to evaluate the FE results.

Experimental setup

The experimental tests were conducted at the Sound Research Laboratories (SRL) in accordance with BS EN Standards (1995, 1997). In the laboratory, airborne sound transmission is determined from the difference in sound pressure levels measured across a test sample installed between two reverberant rooms at one third octave band frequency ranging from 50 Hz to 10000 Hz. The test is done under conditions which restrict the transmission of sound by paths other than directly through the sample. The source sound field is randomly incident on the sample.

Two different shapes of cold-formed steel stud were tested within a plasterboard partition wall. All the studs have the same height and thickness but different shapes, mainly in the web; they are a standard stud, called “Stud A”, and a sigma stud, called “Stud B”. Their shapes and dimensions are illustrated in Figure 1.

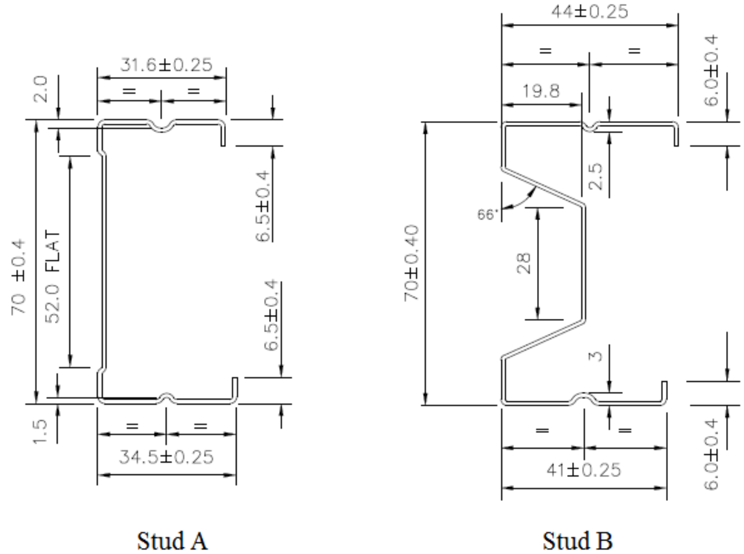

Figure 1 Two different stud shapes and their dimensions (mm)

The partition wall forms the aperture between the two rectangular reverberant rooms, both of which are constructed from 215 mm brick with reinforced concrete floors and roofs, and are 2900 mm in height. Figure 2 shows the plan view of the experiment setup which includes the position and dimensions of the acoustic rooms, plasterboard partition wall and studs.

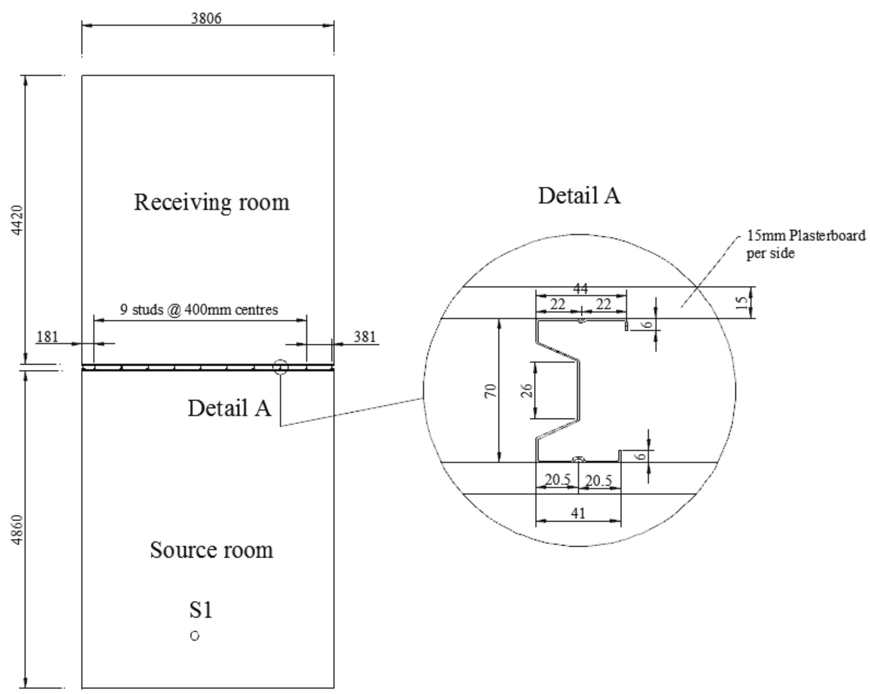

Figure 2 Plan view of the experiment setup in which S1 is the location of a loud speaker that produces acoustic sound pressure; Stud B is presented as an example

The cold-formed studs were tested within a plasterboard partition wall. There were 11 studs and they were positioned at 400 mm centres in the perimeter channel which spanned the top and bottom of the aperture. The partition wall was one layer of 15 mm dense acoustic plasterboard either side of the stud. Boards were screwed to the studs at 300 mm centres. Broad band noise is produced in the source room from an electronic generator, power amplifier and loudspeaker. The resulting sound pressure levels in both rooms are sampled, filtered into one third octave band widths, integrated and averaged by means of a Real Time Analyser using a microphone on an oscillating microphone boom. A single omnidirectional 12 mm microphone was mounted onto the end of a rotating boom, one in the source room and one in the receiving room. Boom has a 1 m radius and speed of rotation was 360^o per 30 s. The average of sound pressure levels for either source or receiving rooms at any particular frequency was measured.

The sound transmission loss is calculated as the difference between the average sound pressure levels obtained in the source and receiving rooms, respectively, according to the following equation (not taking into account the logarithmic correction indicated in the BS EN Standard 140 for laboratory tests):

$$TL = L_1 - L_2 \tag{1}$$

Where TL is the sound transmission loss; L1 is the equivalent sound pressure level in the source room (dB); L2 is the equivalent sound pressure level in the receiving room (dB). For rating the airborne sound insulation and for simplifying the formulation of acoustical requirements in building design, a single-number quantity value also known as weighted sound reduction index R_w ($C;C_{tr}$), in decibels, was used in accordance with the BS EN Standard 717. In which, the spectrum adaption terms are C (A-weighted pink noise) and C_{tr} (A-weighted urban traffic noise) were also calculated.

Finite Element analysis

Theoretical background

In this paper, Finite Element analysis was conducted using Marc (MSC Software, version 2012). The acoustic medium is called the fluid and is considered to be in-viscid and compressible. The specified boundary condition and radiated acoustic field are assumed to be time-harmonic. The wave equation can be expressed in terms of the pressure as:

$$\frac{1}{c^2}\frac{\partial^2 p}{\partial t^2} - \nabla^2 p = 0 \tag{2}$$

Where $c = \sqrt{K_f/\rho_f}$ is the speed of sound in the fluid medium; ρ_f is the fluid density; K_f is the bulk modulus; *p* is the sound pressure and *t* is the time.

Non-reflecting or reflecting boundary conditions are introduced using a spring-dashpot analogy on the fluid interface Γ_{fn} as $\frac{1}{\rho_f}\frac{\partial p}{\partial n} = \frac{\dot{p}}{c_I} + \frac{\ddot{p}}{k_I}$ (3) in which k_I is the spring parameter and c_I is the dashpot parameter. A reflecting boundary is described by $\frac{\partial p}{\partial n} = 0$ (4). Where n is an inward normal.

Combining equations for fluid and structure gives the desired coupled complex equation system for coupled acoustic-structural analysis as follows:

$$\begin{bmatrix} \omega^{-2} A_f & S_{fs} \\ S_{fs}^T & A_s \end{bmatrix} \begin{bmatrix} p \\ u \end{bmatrix} = \begin{bmatrix} \omega^{-2} F_f \\ F_s \end{bmatrix} \tag{5}$$

In which $A_f = K_f + i\omega C_f$ and $A_s = K_s + i\omega C_s$

With K_f, C_f and M_f are the stiffness, damping and mass matrices of the fluid; ω is the frequency of the sound pressure; S_{fs} is the surface area at the fluid-structure interface; F_f is the external load vector on the fluid; K_s, C_s and M_s are the stiffness, damping and mass matrices of the structure; F_s is the external load vector on the structure.

The procedure to perform a coupled acoustic fluid-structural is as follows. The acoustic medium and the structure are modelled separately: the acoustic structure using acoustic elements with acoustic material properties and the structure using conventional stress elements. The elements representing the acoustic medium are assigned to an acoustic contact body and the elements representing the solid to a deformable contact body. The interface between the acoustic medium and the structure is determined through elements which are in contact. The acoustic boundary admittance of the interface elements is used to define the respective absorbed surfaces.

The damping matrix of the structure [C_s] is assumed to be proportional to the mass and stiffness matrices [M_s] and [K_s] as follows

$$[C_s] = \alpha[M_s] + \beta[K_s] \tag{6}$$

Where α is the mass-proportional damping coefficient; β is the stiffness-proportional damping coefficient. They are calculated from the following system of equations:

$$\xi_n = \frac{1}{2\omega_n}\alpha + \frac{\omega_n}{2}\beta \tag{7}$$

With ξ_n is the critical damping ratio corresponding to the natural frequency ω_n at mode of vibration n.

Finite Element model setup

A detailed programme of the model setup that related to the model description, element type and meshing parameters, material properties, boundary conditions, calculations of sound transmission loss, connections between stud, board and air, and sound source model was described in Nguyen (2013). Only main features of the model setup were presented in this paper.

2-D models with plane strain hypothesis were adopted in this study for simplicity since the thicknesses of the structural elements are very small with regards to the other dimensions. In the FE model, the arrangements and dimensions of the studs, boards and source/receiving rooms together with their actual geometries were accurately modelled as in the real test (Figure 2). Each stud was modelled by 238 plane strain elements; they are 2-D four-node, arbitrary quadrilateral elements. The minimum element size was 0.2 mm; the maximum element size was 2.6 mm. The gypsum board was also modelled by 30,746 plane strain solid elements. The minimum element size was 1.4 mm on the side connected to the stud; the maximum element size was 2 mm on the side connected to the source/receiving rooms. The acoustic air was modelled by 693,667 plane strain acoustic fluid elements; they are 2-D four-node, arbitrary quadrilateral elements formulated especially for fluid. In particular, there are 67,239 elements for air cavity in between the boards, 327,888 elements for air in the source room and 298,540 elements for air in the receiving room. In the air cavity mesh, the minimum and maximum element sizes were similar to those of stud mesh as the two meshes are congruent (Figure 3). In the source/receiving meshes, the element size was 7.5 mm. This was chosen to ensure that the room acoustic behaviour was accurately analysed by FE models for high frequencies up to 7500 Hz.

The connection between the air and studs, and air and boards were modelled as glued contact along their boundaries. The interface between them was modelled in a coupled acoustic-structural analysis, defining on the "contact" option. To model the fixed screw connection between studs and boards, point connection was applied by using rigid links to connect nodes of studs and boards' elements; in this model there was flexible (touching) contact along the line between studs and boards as illustrated in Figure 3. The air was considered to be in-viscid and compressible. The viscous dissipation of the acoustic medium was ignored as the effect of friction on the structure was negligible. Material properties of acoustic medium (air) and structures are shown in Table 1. Reflecting boundary conditions were assumed in this study so the boundary admittance of the material (stud and board) in contact with air was zero.

Table 1 Material property of acoustic medium and structures

Material	Young's modulus E (N/mm^2)	Density ρ (tone/mm^3)	Poison's ratio ν	Phase velocity c (mm/s)	Damping ratio ξ
Stud	205000	7.89E-09	0.30	–	0.025
Board	2000	8.48E-10	0.28	–	0.01
Wall	20000	2.00E-09	0.17	–	0.02
	Bulk modulus B (N/mm^2)				
Air	0.101	1.25E-12	–	343000	0.00

Damping coefficients of the gypsum board and stud α and β were calculated from Eq. (11) based on the method for large degrees of freedom systems as presented in Chowdhury and Dasgupta (2003). Values of α were very small and thus negligible; β was almost constant for the whole range of frequencies so it was taken as the value obtained from the first six modes. Therefore β = 5.72498E-05 for the board, β = 1.18E-04 and β = 1.49E-04 for the stud and wall, respectively.

The FE mesh and materials considered (see Table 1) of the Stud A and Stud B, are shown in Figure 3.

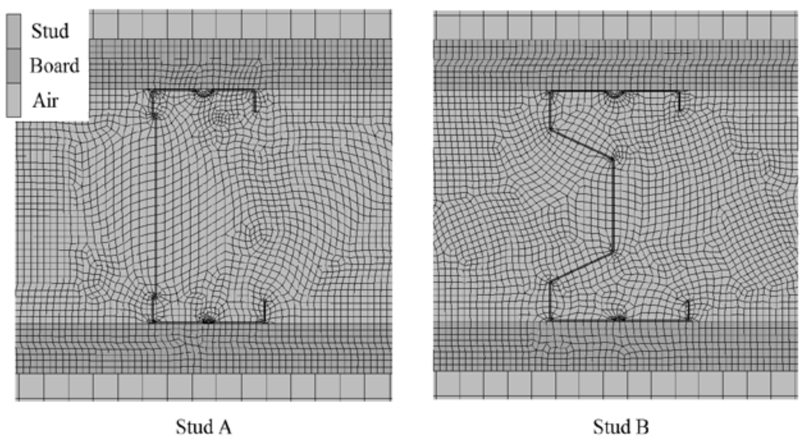

Figure 3 FE mesh and materials of the two studs: Stud A and Stud B. Darkest regions are for gypsum boards, light regions for acoustic air. For presentation, the stud is isolated from the whole system.

The FE sound transmission loss was then calculated by Eq. (1), and the FE sound reduction index was also obtained in the form $R_w(C;C_{tr})$ using the method presented in the Standard 717 (1997). FE results were obtained at one third octave band with 24 frequencies ranging from 50 to 3150 Hz as this frequency range is particularly of interest in building acoustics. Several excitation frequencies ranging from ±5% of each of the central frequencies of the one third octave band were considered. Therefore the FE sound transmission loss was estimated for a total of 3214 frequencies in the frequency range from 100 to 3150 Hz.

The sound source was represented by a harmonically frequency dependent pressure varying at one third octave band frequencies. The sound pressure level at each frequency was obtained as the average of the sound pressure magnitudes measured in the source room from the six experimental tests for that frequency. The sound source was modelled by applying sound pressure at a node located at the same position of the speaker S1 in the test (Figure 2).

Results and discussion

Figure 4 shows the comparison between the experimental and FE sound transmission loss for Stud A. Figure 5 illustrates the comparison between the experimental and FE sound transmission loss for Stud B.

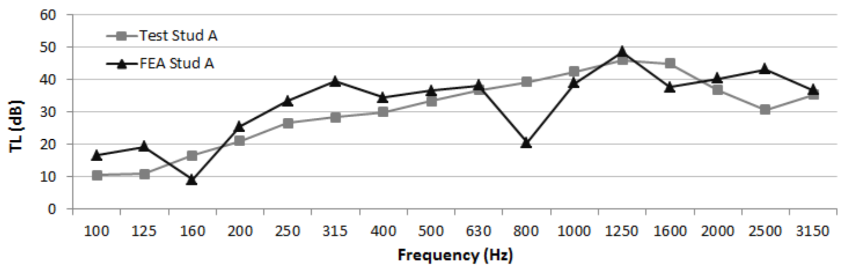

Figure 4 Experimental and FE results in the case of Stud A

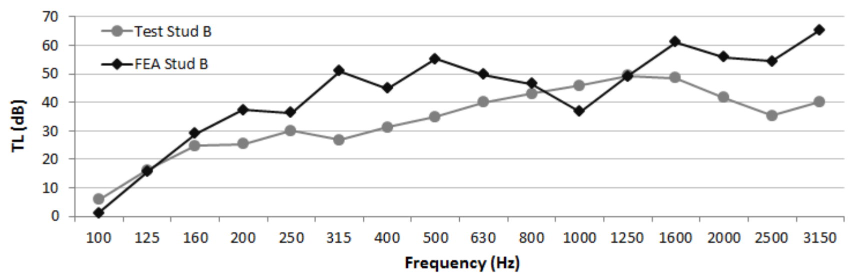

Figure 5 Experimental and FE results in the case of Stud B

The comparison of FE sound transmission loss for the two studs is shown in Figure 6.

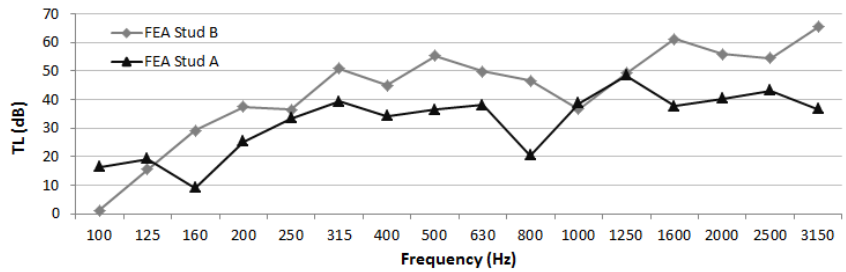

Figure 6 FE sound transmission loss of Stud A and Stud B

Several observations can be seen from Figures 4-6 as follows:

• Experimental results show that there is no significant difference between the two studs in low-frequency ranges but for high-frequency ranges, Stud B exhibits the greatest sound transmission for most of the frequencies.

• The FE models for Stud A and Stud B predicted similar trends of sound transmission in comparison with the experimental results. The coincidence dip (at the frequency of 2500 Hz) was reproduced in the FE results.

• In general, the FE results fairly correlate the experimental results, especially for Stud A. They overestimated the experimental results in the medium- and high-frequency ranges for Stud B. In particular, for the sound transmission loss of Stud A, maximum differences can be up to +11 dB at 315 Hz, and -19 dB at 800 Hz; for Stud B, maximum differences can be up to +11 dB at 315 Hz, and +15 dB at 3150 Hz. In the real test, the system could be considered orthotropic and the connections between boards and studs could be rather point connections at the screw locations than continuous connections. Since the current FE model is 2-D, these effects on the sound transmission were not included and that might cause the differences.

• Comparing the sound transmission loss level (TL) of the double-leaf wall using Stud A and Stud B, as shown in Figure 6, it was found that the stud's shape had an effect on the acoustic performance of the double-leaf wall partition.

The values $R_w(C;C_{tr})$, both FE and experimental tests, were calculated according to the BS EN Standard 717, and they are shown in Table 2, in which the uncertainty of tests at 95% confidence is also presented. It experimentally shows that when the stud geometry changed from Stud A to Stud B while maintaining the stud depth and thickness, the sound transmission improved significantly for Stud B; in particular, the weighted reduction index together with its spectrum adaption terms R_w $(C;C_{tr})$ increased from 40 (-3;-8) for Stud A to 42 (-3;-11) for Stud B. Stud B has greatest sound transmission loss, therefore is the best acoustic performance while Stud A is least effective. FE models predicted similar trends to the experimental results: Stud B have significantly better acoustic performance than Stud A. There is a good correlation between the experimental and FE results for Stud A, but an overestimated sound transmission loss for Stud B. The difference in R_w between the test and FE models for Stud A and Stud B is 0 dB and +2 dB, respectively. Also, the spectral adaption terms show that the results predicted by FE models for Stud A and Stud B are more fluctuated than the experimental results.

Table 2 Comparison between the FE and experimental results of the global sound insulation performance of Stud A and Stud B, as well as the test uncertainty

Stud	FEA	Test	
	R_w (C;C_{tr})	R_w (C;C_{tr})	Uncertainty, ±dB
Stud A	40 (-5;-9)	40 (-3;-8)	1.5
Stud B	44 (-8;-16)	42 (-3;-11)	1.5

It can be seen that the difference in sound transmission loss between Stud B and Stud A is more significant with FE results than with experimental results (+4 dB compared with +2 dB). It could be due to the assumptions of constant damping over frequencies or 2-D plane strain model which might have some effects on the FE sound transmission loss which are more for Stud B than for Stud A. However, it is not fully understood yet and will be studied with a 3-D system modelling in future work.

The fact that Stud B has greater sound transmission than Stud A could be largely due to their web's shape. This conclusion is based on an FEA parametric study which revealed that the stud's web shape had significant effects on sound transmission whilst the stud's thickness and flange width had little effects that can be ignored (Nguyen 2013). The reason could be due to the fact that Stud B's web has large diagonal parts which might reduce their structural stiffness; and therefore they become more effective in acoustic performance. This can be explained further by investigating the natural frequencies of modes of vibration of the double-leaf wall with respect to each stud's shape. For this purpose, natural frequencies versus vibration modes of the partition wall with different stud's shapes were obtained from modal dynamic analyses and they are shown in Figure 7; in which 200 vibration modes were considered. It can be observed that there is a substantial drop in the natural frequency of the system when stud's shape changed from Stud A to Stud B, especially for high vibration modes. The significant change in the natural frequency of the wall system was clearly attributed to the structural stiffness of the stud. A stiffer stud would exert a higher force resulting in increased acceleration towards the equilibrium state

(Newton's second law) and hence higher frequency. It deems that the natural frequencies of the stud-wall system increases with their structural stiffness. Therefore, a stud that is more resilient would generate lower natural frequencies and eventually improves the sound transmission of the double-leaf partition wall. This explains the case of Stud B as its web has large diagonal parts which made it more resilient and hence it provided better acoustic performance than Stud A.

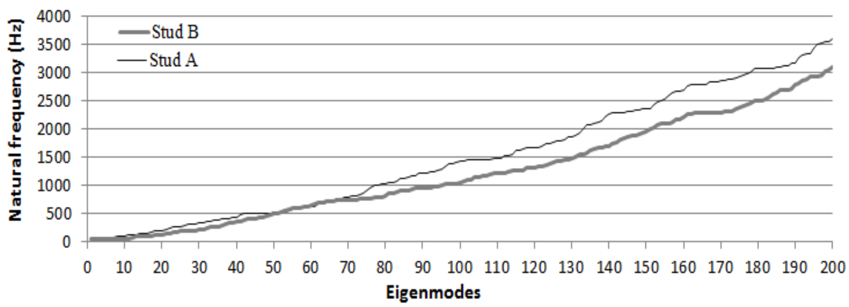

Figure 7 Natural frequencies versus vibration modes of Stud A and Stud B

Figure 8 shows an example of the acoustic pressure distribution in the source and receiving rooms for Stud A at frequencies of 125 Hz, 500 Hz, and 3150 Hz.

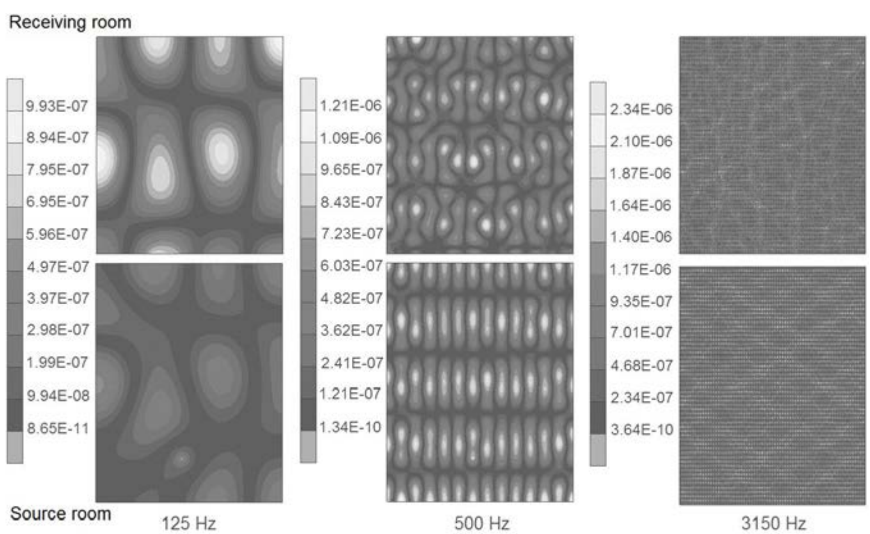

Figure 8 FE acoustic pressure distribution (N/mm^2); Stud A is presented.

Conclusion

In this paper, FE analysis has been used to simulate the acoustic performance of different cold-formed studs in double-leaf partition walls. The FE results were evaluated against experimental tests which were conducted in complying with BS EN Standards. Based on the validity of the FE models, the effects of the stud's shapes were evaluated.

The FE analysis predicted similar trends of acoustic performance for different stud's profiles and their results are generally in fair agreement with the experimental results. The FE study also revealed that the stud's web shape might have significantly positive effects on sound transmission. The improvement in acoustic performance of different stud's shapes could be related to their structural stiffness. Further studies may be required to establish a 3-D system modelling and relationship between the stud's shape and their structural stiffness.

It can be concluded that acoustic performance of different steel studs in double-leaf walls can be successfully simulated by using FE analysis. The FE analysis papered here provides a powerful tool to simulate the acoustic performance for double-leaf walls with different stud's profiles. It enables the consequences of the sound transmission generated by the steel studs to be quantified. The FE analysis can be used as an alternative and complementary method to the laboratory tests for acoustic performance of steel products.

References

BS EN ISO 140-3:1995. Acoustics - Measurement of sound insulation in buildings and building elements. Part 3: Laboratory measurements of airborne sound insulation of building elements. ISO; 1995.

BS EN ISO 717-1:1997. Acoustics – Rating of sound insulation in buildings and building elements. Part 1: Airborne sound insulation. ISO; 1997.

V. Hongisto, M. Lindgren, R. Helenius: Sound insulation of double walls - an experimental parametric study. Acta Acustica united with Acustica 88 (2002) 904-923.

J.S. Bradley, J.A. Birta: On the sound insulation of wood stud exterior walls. Journal of the Acoustical Society of America 110 (2001) 3086-3096.

J. Poblet-Puig, A. Rodrıguez-Ferran, C. Guigou-Carter, M. Villot: Experimental and numerical characterization of metallic studs. In Euronoise, Tampere, Finland, 2006.

J.J. del Coz Diaz, F.P. Alvarez Rabanal, P.J. Garcia Nieto, M.A. Serrano Lopez: Sound transmission loss analysis through a multilayer light weight concrete hollow brick wall by FEM and experimental validation. Building and Environment 45 (2010) 2373-2386.

J.D. Quirt, A.C.C. Warnock: Influence of sound-absorbing material, stud type and spacing, and screw spacing on sound transmission through double-panel wall specimen. Proc. Internoise 93, p.971-974, 1993.

J. Brunskog, P. Davidsson: Sound transmission of structures. A finite element approach with simplified room description. Acta Acustica united with Acustica 90 (2004) 847-857.

F. Fahy: Sound and structural vibration. Academic Press: London, 1989.

W. Kropp, E. Rebillard: On the air-borne sound insulation of double wall constructions. Acta Acustica united with Acustica 85 (1999) 707-720.

J. Wang, T.J. Lu, J. Woodhouse, R.S. Langley, J. Evans: Sound transmission through lightweight double-leaf partitions: theoretical modelling. Journal of Sound and Vibration 286 (2005) 817-847.

J. Brunskog: The influence of finite cavities on the sound insulation of double plate structures. Journal of the Acoustical Society of America 117 (2005) 3727-3729.

J.S. Bradley, J.A. Birta: A simple model of the sound insulation of gypsum board on resilient supports. Noise Control Engineering Journal 49 (2001) 216-223.

J. Davy: The improvement of a simple theoretical model for the prediction of the sound insulation of double leaf walls. Journal of the Acoustical Society of America 127 (2010) 841-849.

C. Guigou-Carter, R. Foret, A. Igeleke, S. Bailhache: Characterization of metallic studs used in gypsum board single frame walls. Proc. Acoustics 2012 Nantes Conference p. 3087-3092, 2012.

J. Poblet-Puig, A. Rodrıguez-Ferran, C. Guigou-Carter, M. Villot: The role of studs in the sound transmission of double walls. Acta Acustica united with Acustica 95 (2009) 555-567.

A. Arjunan, C.J. Wang, K. Yahiaoui, D.J. Mynors, T. Morgan, M. English: Finite element acoustic analysis of a steel stud based double-leaf wall. Building and Environment 67 (2013) 202-210.

I. Chowdhury, S.P. Dasgupta: Computation of Rayleigh damping coefficients for large systems. The Eleectronic Journal of Geotechnical Engineering 8 (2003) Bundle 8C.

V.B. Nguyen: Acoustic performance of different cold roll formed stud profiles in double-leaf walls by FE analysis and experimental validation. Report no. No. HGT.238.12. Hadley Industries plc, Smethwick, West Midlands, UK; 2013.