

Vibro-acoustic Performance of Different Steel Studs in Double-leaf Walls by Finite Element Analysis

Bac Nguyen^{1,2}, Tertia Morgan¹, Martin English¹ and Michael Castellucci¹

¹*Hadley Industries plc, Downing Street, Smethwick, West Midlands, UK
E-mail: bac.nguyen@hadleygroup.com*

²*Honorary Senior Research Fellow, University of Sussex, Brighton, UK
E-mail: vanb.nguyen@sussex.ac.uk*

(Received 30 March 2015 and accepted 6 August 2015)

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 characterize the stud's geometric effects on the sound transmission of the partition walls. This paper presents a 2-D Finite Element modelling approach and results into the vibro-acoustic performance of different studs in double-leaf walls which are placed in between a reverberant source room and a receiving room. The acoustic medium inside rooms was modelled using fluid elements and the structure was modelled with plane strain 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 reduction of double-leaf walls using two different stud profiles was then calculated. Experimental tests complying with standards ISO 717-1:1997 and 140-3:1995 were also carried out to evaluate the FE results. It has shown that the stud's shape have significant effects on the sound reduction of the double-leaf walls, and the FE results have similar trends are in fair agreement with the experimental results. A parametric study was conducted and the effects of the stud's shapes on the sound reduction were presented and discussed.

1. 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 to overall build costs. However, the overall design of such lightweight structures including acoustic performance of the studs is much more complex. Building standards such as ISO 140-3:1995 [1] and ISO 717-1:1997 [2] have required the

acoustic insulation properties to be adequate and they must be evaluated through laboratory tests in special acoustic rooms, in which a partition wall is placed in between a reverberant 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 reduction were carried out [3,4]. The effect of stud size and the spacing between wood studs in the sound insulation of exterior walls was studied in Bradley and Birta [5]. The influence of stud type, stud spacing and screw spacing on the sound reduction index in gypsum board double walls was demonstrated successfully by Quirt and Warnock [6]. The influence of the properties of the source room, wall, and receiving room system on the sound transmission in double walls at low frequencies based on a detailed geometric model has been investigated [7-9]. However, the characterization of the stud as the connecting element on the sound transmission loss 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 reduction 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 [4].

Several analytical models dealing with sound reduction of double-leaf walls using steel studs were introduced in the literature. The simplest model that has been studied is a double-leaf wall in which studs were considered as infinitely rigid connections between the boards [10]. 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 reduction consider the studs as elastic springs including both translational and rotational springs [11,12]. A complete model of sound transmission in which both the air cavity and stud paths are considered, was introduced in Brunskog [13]. The acoustic pressure inside the finite cavities is solved by means of cosine series and the cross section stiffness of the stud is modelled by means of a spring. The effects of adding resilient channels to a rigid double-leaf wall were presented in Bradley and Birta [14] and the effects of gypsum plasterboard cavity walls with and without sound absorbing material in their cavities were investigated in Davy [15]. In these models, the spring stiffness is typically taken as the cross-section elastic stiffness of the stud but this could lead to an underestimation of the sound transmission.

The analytical models mentioned above predict the sound reduction 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 is now available to accurately predict sound reduction in room acoustic analysis as it can consider the actual shape and material properties of the studs. del Coz Diaz et al. [16] 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. [17]; this, however, was done for isolated stud-board

systems, not in room acoustic systems. FE analysis was used to solve the vibro-acoustic problem to study the role of the stud stiffness in the sound transmission of double-leaf walls [18]. An FE model has been developed [19] to predict the sound reduction index for a steel stud based double-leaf wall. Systems of optimisation by means of FE analysis was used to study the relationship between the acoustic modes and the room geometry [20, 21]. In these studies, several variable local geometric modifications of the room walls are introduced and an optimisation procedure is developed to determine the optimal design of the test chambers. 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 reduction of double-leaf walls. 2-D FE models to predict airborne acoustic performance of two different cold formed stud profiles in double-leaf walls were developed. Experimental tests were carried out for two different stud's profiles and the results were used to evaluate the FE results. Based on the validity of the FE models, a parametric study was performed and the effects of the stud's shapes were presented and discussed.

2. EXPERIMENT SETUP

The experimental tests were conducted at the Sound Research Laboratories (SRL) in accordance with ISO Standards [1,2]. 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 rooms were constructed from reinforced concrete floors, roofs and rigid brick walls).

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.

The partition wall forms the aperture between the two rectangular reverberant rooms, both of which are constructed from rigid brick walls 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.

The steel studs were tested within a plasterboard partition wall. There were 11 studs and they were positioned at 400 mm centers in the perimeter channel which spanned the top and bottom of the aperture; the perimeter channel is fully fixed to the surrounding concrete floors and roofs. 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 centers and the joints were taped and jointed. The perimeter of the partition was sealed with mastic on both sides. The partition wall measured 3800 mm wide and 2900 mm high. 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 Analyzer using a microphone on an oscillating microphone boom.

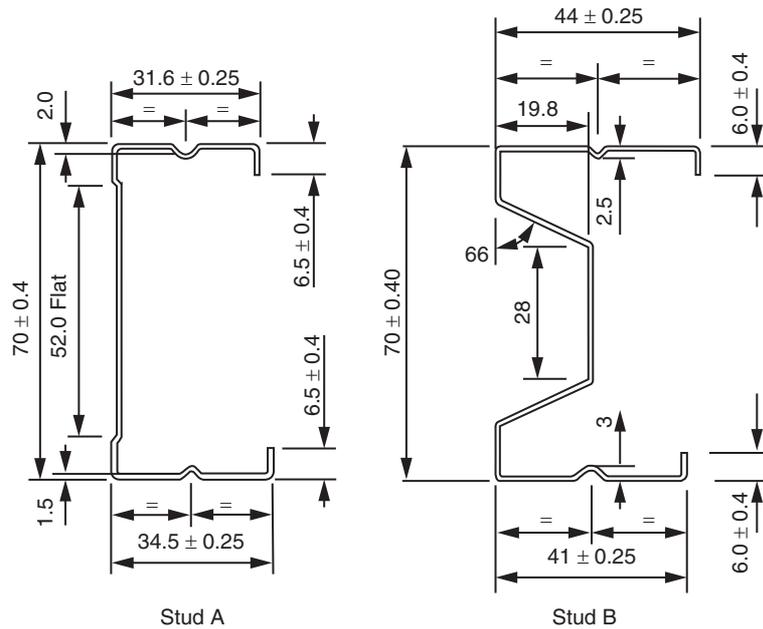


Figure 1. Two different stud shapes and their dimensions (in mm).

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° per 30 s. At each combination position of speaker and microphone, the average sound pressure level for either source or receiving rooms at any particular frequency was measured.

In this study the sound reduction is calculated as the difference between the sound pressure levels obtained in the central circles M1 and M2 (these two circles indicated where the rotating microphone registers pressure in the test as illustrated in Figure 2) in the source and receiving rooms, according to the following equation:

$$TL = L_1 - L_2 \quad (1)$$

Where TL is the level difference of sound pressure levels obtained in the source and receiving rooms which is defined as the sound transmission loss in this study; L_1 is the equivalent sound pressure level in the source room (dB); L_2 is the equivalent sound pressure level in the receiving room (dB). Although this sound reduction is a measure of the wall partition alone, invariant of the absorption in the receiving room, it is sufficient to study the effects of different stud's shapes on vibro-acoustic performance of the double-leaf wall. To take into account the variation in testing conditions, one duplicated test was carried out for each stud type. There were four tests in total.

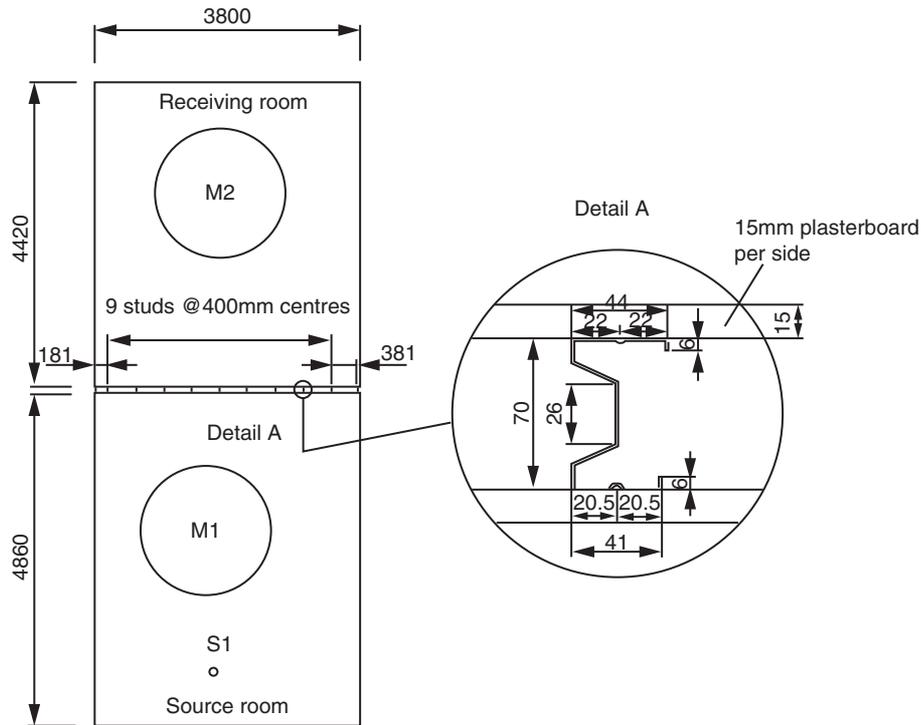


Figure 2. Plan view of the experiment setup in which S1 is the location of a loud speaker that produces acoustic sound pressure; Stud B is presented as an example.

3. FINITE ELEMENT ANALYSIS

3.1. Theoretical background

In this paper, Finite Element analysis was conducted using Marc (MSC Software, version 2014). 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:

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

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 $\frac{1}{\rho_f} \frac{\partial p}{\partial n} = \frac{\dot{p}}{c_f} + \frac{\ddot{p}}{k_f}$ (3) in which k_f is the

spring parameter and c_1 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:

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

In which $A_f = K_f + i\omega C_f - \omega^2 M_f$ and $A_s = K_s + i\omega C_s - \omega^2 M_s$. 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 (which is based on pressure/hydrostatic formulation) and the structure using conventional plane strain elements (which is based on conventional displacement formulation). 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 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

$$[C_s] = \alpha[M_s] + \beta[K_s] \quad (6)$$

Where α is the mass-proportional damping coefficient; β is the stiffness-proportional damping coefficient. They are calculated from the following system of equations (Clough and Penzien [23]):

$$\xi_n = \frac{1}{2\omega_n} \alpha + \frac{\omega_n}{2} \beta \quad (7)$$

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

3.2. Finite Element model setup

2-D models with plane strain hypothesis were adopted in this study to model the studs, boards and source/receiving room air medium for simplicity since the thickness of the structural elements is very small with regards to the other dimensions. It was not within the scope of this study to include a 3-D model since the 2-D assumption was deemed appropriate for the purpose of comparing the vibro-acoustic behavior between different stud profiles.

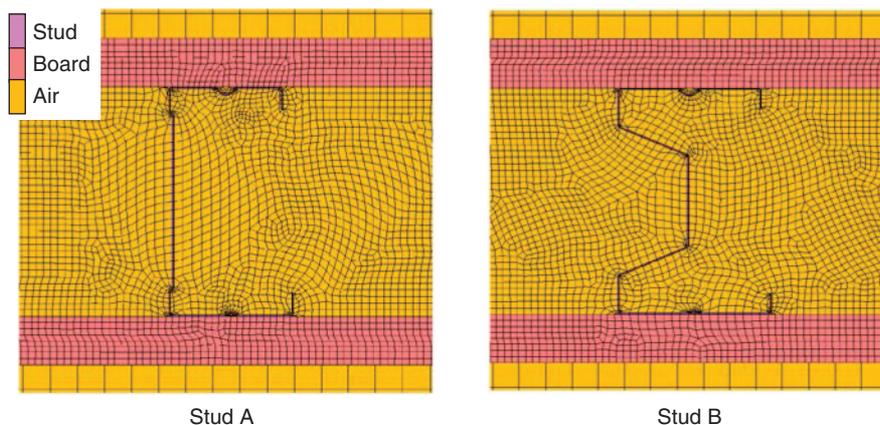


Figure 3. FE mesh and material properties of the two studs: Stud A and Stud B. For presentation, the stud is isolated from the whole system.

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 behavior was accurately analyzed by FE models for high frequencies up to 7500 Hz. A good rule of thumb is to use at least six elements to model a structural wavelength so the maximum mesh size or distance between adjacent nodes of an element could be calculated as $l = c / (6 \times f) = 343000 / (6 \times 7500) = 7.6$ mm, in which f is the maximum frequency. The FE mesh and materials considered (see Table 1) of the Stud A and Stud B, are shown in Figure 3. The mesh-independence of the solution taking into account different meshes of the source room and the receiving room was checked. In this way, a finer FE mesh was also used to examine the effect of mesh density on the results for both systems with Stud A and Stud B. The finer mesh had a much smaller mesh with elements in acoustic rooms are twice smaller than those in the proposed mesh (the element size in the finer mesh is 3.75 mm). The results of the sound reduction of the two FE meshes were obtained at one third octave band with 16

Table 1. Material properties of acoustic medium and structures where E is Young modulus, ρ is density, ν is Poisson's ratio, c is sound velocity, ξ is damping ratio.

Material	E (N/mm ²)	ρ (tone/mm ³)	ν	c (mm/s)	ξ
Stud	205000	7.89e-09	0.3	-	0.025
Board	2000	8.48e-10	0.2	-	0.01
Air	0.101*	1.25e-12	0.17	-	-

* Bulk modulus

frequencies ranging from 100 to 3150 Hz. It was found that there is no difference in the sound reduction between the two meshes for both Stud A and Stud B for frequencies from 100 to 630 Hz. At frequencies of 800, 1000, 1250, 1600, 2000, 2500 and 3150 Hz, the differences in percentage are +9%, -5%, -10%, +9%, -7%, +10% and +8% respectively, for Stud A; and the differences are -10%, -8%, -5%, +10%, -4%, +8% and +11% respectively, for Stud B (positive sign + indicates that the sound reduction of the proposed mesh is greater than the sound reduction of the finer mesh, and vice versa). Although it shows that the difference is more noticeable in medium and high frequencies but the maximum difference in the sound reduction between the two meshes is within 11%. Regarding to analysis time, the finer mesh was taken 3 times longer the proposed mesh. Therefore the proposed FE mesh was adopted in this study in order to reduce the computational effort while producing converged results in the selected frequencies.

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. The air was considered to be in-viscid and compressible. The internal loss of the acoustic medium was ignored as they are of no significant value. Material properties of acoustic medium (air) and structures are shown in Table 1. Reflecting boundary conditions were assumed in this study as in the test the rooms are constructed from reinforced concrete floors and roofs, and hard brick walls; they were assumed to be rigid at its boundary. Nevertheless, two models of acoustic boundary conditions for walls in receiving room including non-reflecting (impedance) and reflecting boundary conditions were investigated in Nguyen [22]. It was found that the difference of sound reduction between the two models is very small that can be neglected. Therefore, the FE model with reflecting boundary conditions was used to reduce computational costs.

Damping coefficients of the gypsum board and stud α and β were calculated from eqn (7) in which the natural frequencies ω_n at modes of vibration n were determined from a dynamic modal analysis for the first two modes (Clough and Penzien [23]). Values of α was very small and thus negligible. Therefore it was calculated as $\beta = 5.72498E-05$ for the board, and $\beta = 1.18E-04$ for the stud, respectively.

The FE sound reduction was then calculated by eqn (1). The sound pressure level in the source/receiving room L_i was computed by the following equation $L_i = 20\log_{10}(P_i/P_{ref})$. Where P_{ref} is the reference sound pressure (defaults to 20×10^{-6} Pa);

P_1 is the sound pressure level in the source/receiving room which was calculated as the average of sound pressure of all elements in the domains M1 and M2 in the source and receiving rooms, respectively, similar to the test.

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 two 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).

In the study of the two stud profiles, Stud A and Stud B, validated against tests, the FE results were obtained at one third octave band with 16 frequencies ranging from 100 to 3150 Hz as this frequency range is particularly of interest in building acoustics. The sound pressure level at a frequency of the one third octave band was calculated at the average of sound pressure levels of several excitation frequencies ranging from $\pm 5\%$ of that frequency. Therefore the FE sound reduction was estimated for a total of 3214 frequencies in the frequency range from 100 to 3150 Hz. Including all the 3214 frequencies within 1 Hz frequency resolution for the range from 100 Hz to 3150 Hz took approximately 60 hours for running and 48 hours for extracting the particular sound pressure results on a single computer Intel(R) Xeon(R) CPU E31280 at 3.50 GHz3 using 4 Logical Processors. This is very time consuming and is the main obstacle of using FE analysis to accurately predict the sound insulation.

A parametric study was carried out in order to understand the effect of the stud's shapes to the vibro-acoustic performance. In this study, the standard stud, Stud A, was used as the reference stud which is called Shape I whilst Stud B's shape is similar to Shape II. The influence of a variation in the stud's shape was investigated by modification of the reference stud's web to different shapes as shown in Figure 4. The height of the stud was kept unchanged as it was restricted by the double-leaf walls. In the parametric study of different stud's shapes, the FE results were obtained at one third octave band with 24 frequencies ranging from 50 to 10000 Hz and a limited frequency resolution was used to reduce the computational time as mentioned earlier. However, if a general consistency of the results could be obtained for comparing the sound reduction of different stud's shapes, it could seem to justify such simplification.

4. RESULTS

Figure 5 shows the comparison between the experimental and FE sound reduction for Stud A. Figure 6 illustrates the comparison between the experimental and FE sound reduction for Stud B.

Several observations can be seen from Figures 5 and 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 reduction for most of the frequencies.
- The FE models for Stud A and Stud B predicted similar trends of sound reduction in comparison with the experimental results. The coincidence dip (at the frequency of 2500-3150 Hz) was reproduced in the FE results.

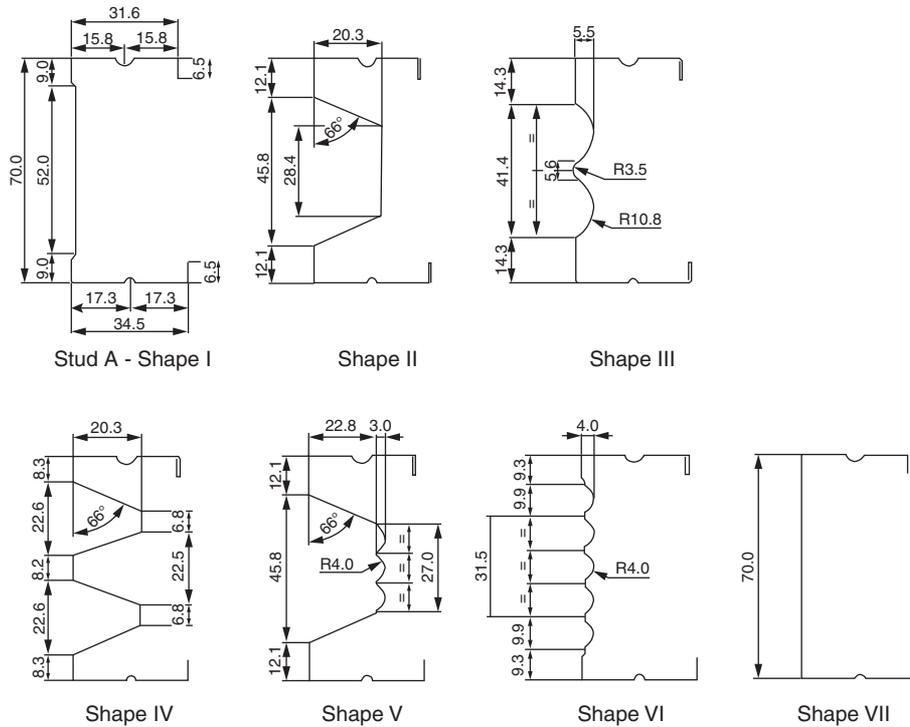


Figure 4. Different stud's web shapes considered for the parametric study.

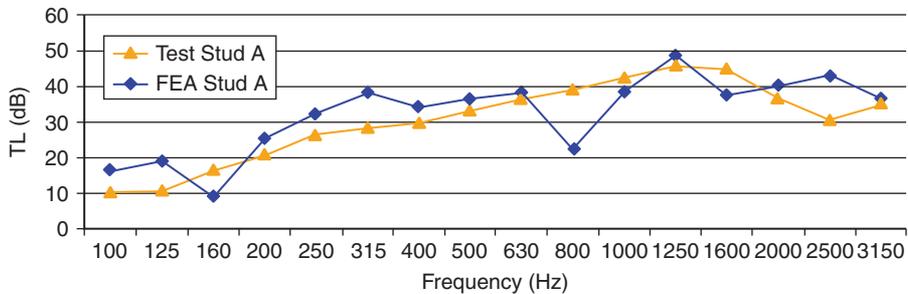


Figure 5. Experimental and FE results of Stud A.

- In general, the FE results fairly correlate the experimental results which show the system with Stud B has greater sound reduction than that of Stud A in most of frequencies. They overestimated the experimental results in the medium and high frequency ranges for Stud B. In particular, for the sound reduction of Stud A, maximum differences can be up to +10 dB at 315 Hz, and -17 dB at 800 Hz; for Stud B, maximum differences can be up to +11 dB at 200 Hz, and +12 dB at 3150 Hz. As the sound reduction was assumed to

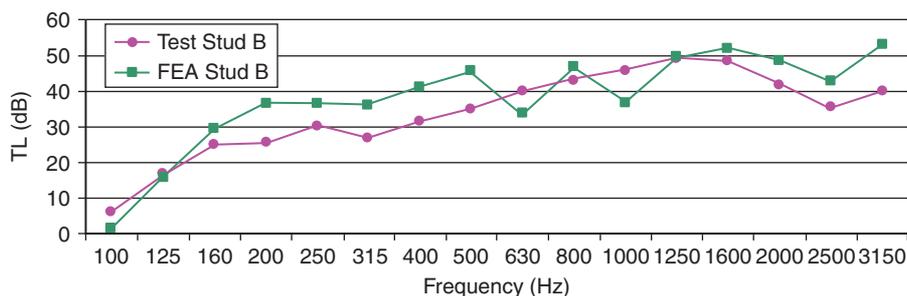


Figure 6. Experimental and FE results of Stud B.

be a measure of the coupling structures alone, there was no loss introduced to the acoustic fields and to the sound absorption in the receiving room. This might lead to some strong resonances in the room and might be a reason for the strong fluctuations in the sound reduction calculations, specifically at frequency of 800 Hz in Stud A system, and at 630 Hz and 1000 Hz in Stud B system. The FE results do not show excellent fit with test results that where natural frequencies of the wall partition in 2-D geometry could be different to those of real wall partition in 3-D case that can affect the result. The effect of connection between stud and board through screws to the acoustic performance was not included in this 2-D simulation while it might be noticeable in a 3-D model: in the medium and high frequency range the connections between plasterboards and studs could be rather punctual at the screw locations and the transition between touching connections to point connections could appear when the flexural wavelength of the boards is equal the distance between screws. In addition, the system in the real test could also be considered orthotropic which the 2-D model was not able to represent.

When comparing the sound reduction of the double-leaf wall using Stud A and Stud B for both test and FE results, as shown in Figures 5 and 6, it was found that the stud's shape had an effect on the acoustic performance of the double-leaf wall partition.

Figure 7 shows an example of the sound pressure distribution in the receiving rooms for Stud A and Stud B, respectively at frequencies of 125 Hz, 500 Hz, and 3150 Hz. Figure 8 illustrates the sound pressure distribution in the air cavity for Stud A and Stud B, respectively, at the frequency of 3150 Hz. The smaller sound pressure level for the partition wall using Stud B indicates that it has greater sound reduction than the case of Stud A.

The fact that Stud B has greater sound reduction than Stud A could largely due to their web's shape. This conclusion is based on an FE parametric study [22] which revealed that the stud's web shape had significant effects on sound reduction (presented in the following section) whilst the stud's thickness and flange width had little effects that can be ignored. The reason could be due to Stud B's web has large diagonal parts which might reduce their structural stiffness; and therefore they become more effective

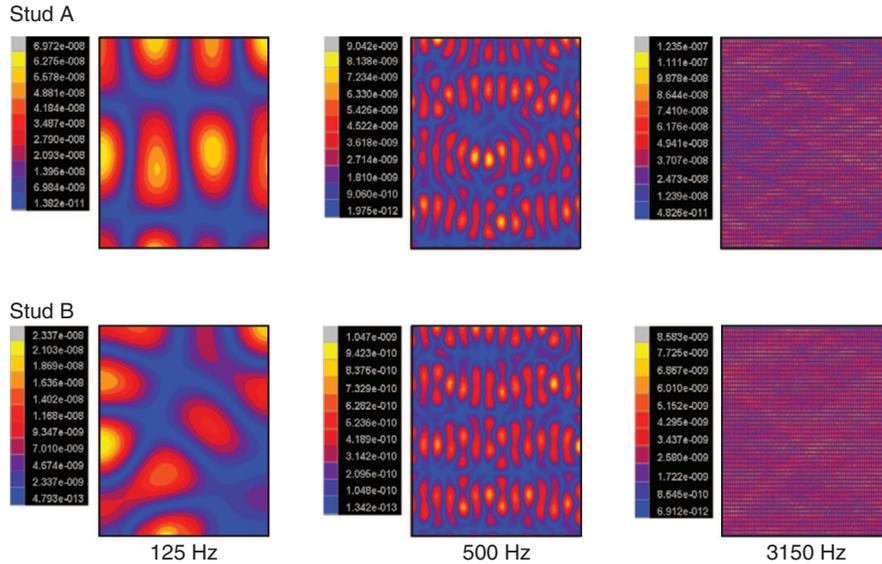


Figure 7. FE acoustic pressure's distribution in receiving room at 125 Hz, 500 Hz and 3150 Hz, for both Stud A and Stud B. Sound pressure magnitude in N/mm^2 is displayed.

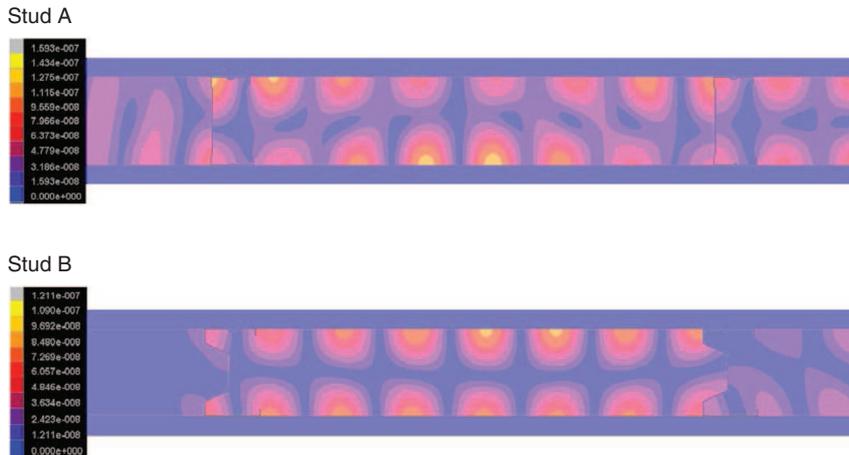


Figure 8. FE acoustic pressure's distribution in the air cavity at 3150 Hz, for both Stud A and Stud B. Sound pressure magnitude in N/mm^2 is displayed.

in acoustic performance. This can be explained later by investigating the natural frequencies of modes of vibration of the double-leaf wall with respect to each stud's shape in the parametric study.

In the parametric study, the sound reductions of the reference stud with the web's shapes as Shape I-VII are presented in Figure 9.

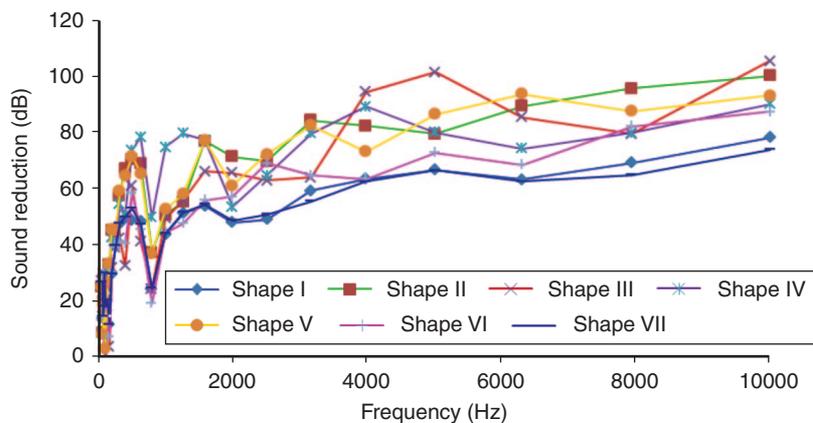


Figure 9. The sound reduction of different stud's shapes.

Overall, the sound reduction associated to studs with different web's shapes in this stud is greater than the reference stud especially for medium- and high-frequency ranges, as shown in Figure 9. It is greatly improved when using the web's shapes of Shape II, IV and V, followed by studs Shape II and VI. Studs Shape II, IV and V have greater sound reduction than the reference stud in all frequency ranges where Shape IV has greatest sound reduction in low- and medium-frequency ranges. Studs Shape III and VI show some improvement in medium and high frequencies, but not so in low frequencies. The comparison also shows that a small modification in the web shape from the reference stud to the stud Shape VII does not change much in the sound reduction. It is clear that different stud's shapes exhibit different levels of improvement in sound reduction. In this study, the stud Shape IV seems to exhibit the greatest sound reduction, followed by the stud Shape V, II, III and VI, in that order. The reason could be due to the fact that their webs have 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 10; in which 200 vibration modes were considered. It can be observed that there is a substantial change in the natural frequency of the system when different stud's shape is used.

Figure 10 shows that the variations of natural frequencies of different stud's shapes are minimal at low frequencies and increased when frequencies increase. Considerable drop in the natural frequency can be seen for the studs Shape IV, Shape V and Shape II, followed by Shape III and VI. Shape I and VII have similar natural frequencies which demonstrates that a small change in the web shape from the reference stud Shape I to the stud Shape VII had a little effect on their natural frequencies. The substantial change in the natural frequency of the wall system for different stud's shapes was clearly attributed to the structural stiffness of the stud. A stiffer stud would exert a higher force

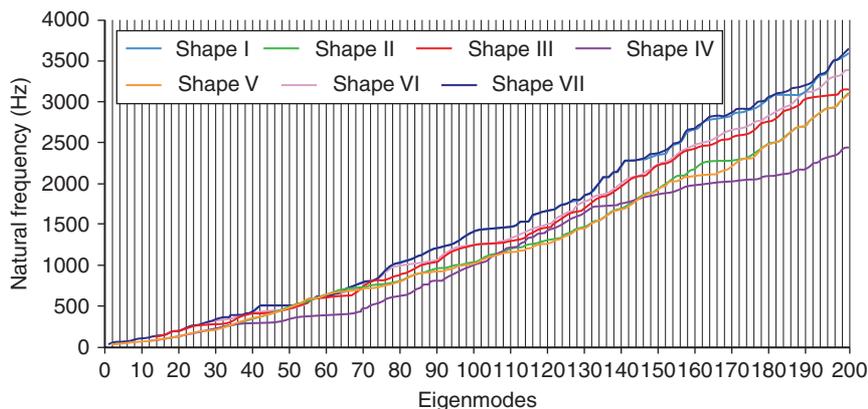


Figure 10. Natural frequencies versus vibration modes of different stud's shapes.

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 reduction of the double-leaf partition wall. This explains the cases of the stud Shape II, IV and V and that their webs have large diagonal parts which made them more resilient in room acoustic performance.

In particular, there is a substantial drop in the natural frequency of the system when stud's shape changed from Stud A (Shape I) to Stud B (Shape II), especially for high vibration modes. This explains the case of Stud B as its web has large diagonal parts which made it more resilient and hence better acoustic performance than Stud A.

5. CONCLUSIONS

In this paper, FE analysis has been used to simulate the sound reduction 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 sound reduction 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 loss. The improvement in sound transmission loss 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 sound transmission loss 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.

ACKNOWLEDGEMENTS

The authors should like to thank Hadley Industries plc for supporting the research reported in this paper. The authors are grateful to MSC Software for their technical supports on Marc software. Finally, the authors would like to thank the anonymous reviewers' valuable comments which help to improve the paper.

REFERENCES

- [1] Acoustics - Measurement of sound insulation in buildings and building elements - Part 3: Laboratory measurements of airborne sound insulation of building elements, *BS EN ISO 140-3:1995*, International Organization for Standardization, 1995.
- [2] Acoustics - Rating of sound insulation in buildings and building elements - Part 1: Airborne sound insulation, *BS EN ISO 717-1:1997*, International Organization for Standardization, 1997.
- [3] Green, D.W. and Sherry, C.W., Sound transmission loss of gypsum wallboard partitions. Report 1. Untilted steel stud partitions, *Journal of the Acoustical Society of America*, 1982, 71, 90–96.
- [4] Hongisto, V., Sound insulation of double panels - comparison of existing prediction models, *Acta Acustica united with Acustica*, 2006, 92(1), 61–78.
- [5] Bradley, J.S. and Birta, J.A., On the sound insulation of wood stud exterior walls, *Journal of the Acoustical Society of America*, 2001, 110, 3086–3096.
- [6] Quirt, J.D. and Warnock, A.C.C., Influence of sound-absorbing material, stud type and spacing, and screw spacing on sound transmission through double-panel wall specimen, *Inter-noise93*, 1993, 971–974.
- [7] Davidsson, P., Brunskog, J., Wernberg, P.A., Sandberg, G. and Hammer, P., Analysis of sound transmission loss of double-leaf walls in the low-frequency range using the finite element method, *Building Acoustics*, 2004, 11, 239–257.
- [8] Kropp, W., Pietrzyk, A. and Kihlman, T., On the meaning of sound reduction index at low frequencies, *Acta Acustica*, 1994, 2, 379–392.
- [9] Brunskog, J. and Davidsson, P., Sound transmission of structures. A finite element approach with simplified room description, *Acta Acustica united with Acustica*, 2004, 90, 847–857.
- [10] Frank Fahy, *Sound and structural vibration*, Academic Press, London, 1989.
- [11] Kropp, W. and Rebillard, E., On the air-borne sound insulation of double wall constructions, *Acta Acustica united with Acustica*, 1999, 85, 707–720.
- [12] Wang, J., Lu, T.J., Woodhouse, J., Langley, R.S. and Evans, J., Sound transmission through lightweight double-leaf partitions: theoretical modelling, *Journal of Sound and Vibration*, 2005, 286, 817–847.

- [13] Brunskog, J., The influence of finite cavities on the sound insulation of double plate structures, *Journal of the Acoustical Society of America*, 2005, 117, 3727–3729.
- [14] Bradley, J.S. and Birta, J.A., A simple model of the sound insulation of gypsum board on resilient supports, *Noise Control Engineering Journal*, 2001, 49, 216–223.
- [15] Davy, J., 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*, 2010, 127, 841–849.
- [16] del Coz Diaz, J.J., Alvarez Rabanal, F.P., Garcia Nieto, P.J. and Serrano Lopez, M.A., Sound transmission loss analysis through a multilayer light weight concrete hollow brick wall by FEM and experimental validation, *Building and Environment*, 2010, 45, 2373–2386.
- [17] Guigou-Carter, C., Foret, R., Igeleke, A. and Bailhache, S., Characterization of metallic studs used in gypsum board single frame walls, *Proceedings of the Acoustics 2012 Nantes Conference*, 2002, 3087–3092.
- [18] Poblet-Puig, J., Rodriguez-Ferran, A., Guigou-Carter, C. and Villot, M., The role of studs in the sound transmission of double walls, *Acta Acustica united with Acustica*, 2009, 95, 555–567.
- [19] Arjunan, A., Wang, C.J., Yahiaoui, K., Mynors, D.J., Morgan, T. and English, M., Finite element acoustic analysis of a steel stud based double-leaf wall, *Building and Environment*, 2013, 67, 202–210.
- [20] Papadopoulos, C.I., Redistribution of the low frequency acoustic modes of a room: a finite element-based optimisation method, *Applied Acoustics*, 2001, 62, 1267–1285.
- [21] Del Coz Diaz, J.J., Garcia Nieto, P.J., Alvarez Rabanal, F.P. and Suarez Sierra, J.L., Optimization of an acoustic test chamber involving the fluid-structure interaction by FEM and experimental validation, *Meccanica*, 2010, 45, 705–722.
- [22] Nguyen, V.B., 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, UK, 2013.
- [23] Clough, R.W. and Penzien, J., *Dynamics of Structures*, 2nd Edition, McGraw-Hill Education, 1993.