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IN-SITU MEASUREMENT OF MATERIAL PROPERTIES OF GYPSUM BOARD WALLS

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Abstract

The dynamic behaviour of lightweight framed gypsum board walls is very complicated due to its frequency dependency. Basically, it is determined by the material properties of the structural members – the gypsum board and the studs – and the way of their assembly.

In a test series the dynamic response of the leaf of different gypsum board walls is investigated and the wave numbers of free bending waves are measured in-situ. From the bending wave numbers it is possible to estimate the frequency dependent stiffness properties of the structure.

The test walls are geometrically almost identical, but differ in their structural details, like for instance the stud spacing and the number of layers of gypsum board. Since the stiffness properties of the used materials are known, respectively are also determined experimentally, it is possible to compare them with the measured properties of the leafs of the walls and define frequency ranges where structural members participate differently in the dynamic response of the leaf.

The obtained results are very useful for the understanding of the dynamics of lightweight framed structures and can further be used for modeling or predicting the dynamic response, sound radiation, etc of gypsum board walls.

INTRODUCTION

Currently a research project is conducted at the Acoustics Laboratory of the Eindhoven University of Technology about flanking transmission of sound through junctions of lightweight building elements, like framed double leaf gypsum board walls. The main goal of this research is to adapt the so-called direct method of prEN ISO 10848 to junctions of this type of building elements. The method uses structure borne sound measurements to determine the vibration reduction index K_{ij}. K_{ij} is important input data for the prediction model of EN 12354 to estimate the sound transmission via the

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flanking paths in buildings.

Recently it was shown by Schoenwald et al. that there are two possibilities to estimate the K_{ij} and respectively the flanking sound reduction index R_{ij} from the velocity level difference of two coupled building elements with a high coincidence frequency f_c. First it is possible to take in the prediction the direct resonant transmission into account and second to introduce a correction for the difference between the free and forced radiation efficiency below the coincidence frequency. However, a good knowledge over the dynamics of the structure in the range below the coincidence frequency is necessary to solve the problem and to apply either of both solutions.

Therefore test series are carried out to investigate the influence of structural changes at test walls on the measured material properties as well as a to determine the material properties of their structural members, like studs and gypsum boards.

In this paper the results of the measurement of the stiffness properties are presented. Two measurement techniques have been applied for different frequency ranges – the modal analysis for very low frequencies and the phase gradient method for a comparatively large frequency range that is relevant for building acoustics.

MEASUREMENT TECHNIQUES

Experimental Modal Analsis

For the modal analysis at the gypsum board wall a 11-Channel FFT-Analyser Type ‘Pulse 10’ from Brüel and Kjaer is used for data acquisition and the software package ME’scopeVES from Vibrant Technology for the modal analysis. The frequency response functions (FRF) were measured in the frequency range blow 400 Hz with a frequency resolution of 0,25 Hz using the Single Input – Multiple Output (SIMO) technique. The structure was excited with a roving impulse hammer at equally spaced points on a 0,20 m wide grid. On one board in the center of the wall the grid width was reduced to 0,15 m to get a better spatial resolution. As reference the output signals of two 3-dimensional accelerometers were used. The modal participation of the reference points was check before the test and one accelerometer attached on each side of the wall.

For the tests at gypsum board beam samples an older 8-channel FFT-analyser Type 2035 from Brüel and Kjaer with an frequency resolution of 800 lines in an frequency range below 1600 Hz was used for the data acquisition. The FRFs were measured with an roving impulse hammer and only one accelerometer as reference.

Wavenumber Measurement - Phase Gradient Method

Different methods for measuring the stiffness properties of plane structures in-situ are described by Roelens et al.. The simplest of the methods described also by Nightingale et al. is used for this test series to measure the real part of the wavenumber, hence forward wavenumber, and the bending stiffness respectively.

The real part of the wavenumber $\underline{k}_B$ of a free propagating plane bending wave in a homogenous, isotropic medium is given by the spatial derivative of the phase angle ϕ in propagation direction. The derivative can be approximated by measuring the phase change $\Delta\phi$ per unit distance Δr between two arbitrary observation points in the propagation direction of the wave:

$$k_B = \mathrm{Re}\left(\bar{k}_B\right) = \frac{\partial \phi}{\partial r} \approx \frac{\Delta \phi}{\Delta r} \tag{1}$$

A plane propagating wave in a real plane structure can be assumed in the direct field of a point source when the phase difference is measured between points that lie on a straight line through a point source.

Thus, the structure is excited by a shaker at one point with random or pseudo-random noise. The acceleration signal at the excitation point was measured with an impedance head and simultaneously with a second accelerometer the acceleration signal at equally spaced points on a straight line. The phase difference between the roving and excitation point was determined by calculating the cross spectrum between the two signals for each measurement position using the CPB-analyzer of the 'Pulse 10' measurement system. The spacing of the positions on the measurement paths was 0,05 m and 0,10 m depending on the frequency range and thus the bending wavelength in the gypsum board.

Unfortunately, it is only possible to measure the relative phase difference in the range of -180° and 180° between two signals. Thus, afterwards the phase information has to be unwrapped for each frequency to get the absolute phase difference with respect to distance to the source. This post analysis can be done with a simple macro in an Excel-spreadsheet.

The absolute phase change depending on the distance to the source will have a linear character in the direct field of the source and a rapidly varying unsystematic phase change in the reverberant field. The phase gradient is found by estimating the slope of the graphs with a linear regression analysis of the measurement points in the direct field.

The excitation points and measurement paths are listed in Table 1 for the test walls. Hereby it has to be noted that all excitation points lie on the length axis. At the vertical lines the results from the path above and the path below the excitation point are averaged. Further also the results along the length axis are averaged due to the marginal differences of the results.

Table 1: Excitation points and measurement paths at the test walls

Notation	Excitation position	Orientation of path
Line A	Leftmost stud	Horizontal, length axis
Line B	Rightmost stud	Horizontal, length axis
Line C	Between 2 studs	Vertical, height axis
Line D	Stud at center bay	Vertical, along stud with joint of board
Line E	Stud at center bay	Vertical, along stud no joint of board

TEST SETUPS

Gypsum Board Walls

Two geometrical almost identical gypsum board walls are built in a former reverberation chamber at the Eindhoven University of Technology.

The length of both walls is 4,20 m and their height is 2,60 m. One consists of a common metal frame (metal studs: UW/CW 75 x 0,6 mm, Notation MS) and the other one of a wooden frame (wood studs: 69 mm x 45 mm, Notation WF). The spacing of the studs is 0,60 m and 0,30 m respectively. Common gypsum board (2,60 m x 0,60 m x 12,5 mm) is used for the leafs. The boards are connected with screws to the frame and in case of doubling of the leafs no further connections exist between the two layers. The screw spacing is 0,30 m and 0,60 m respectively. The joints of the gypsum boards are taped and filled. Lightweight mineral wool (flow resistance > 5 kNs/m^4) with a thickness of 60 mm is placed in the cavities as absorbent.

The test walls are connected to adjacent structures using standard construction details with elastic interlayer and point connections. The lower edge of the specimens is placed on the heavy concrete floor of the test chamber. The upper edge of the test specimens is free. One vertical edge of each wall is connected to the concrete walls of the test chamber. The other vertical edge is fixed at a rectangular hollow steel column that filled with sand to increase its mass.

In course of the study the test walls are built in steps and structural modifications are made to investigate their influence on the dynamic response of the wall. Four regarded situations are shown in Table 2.

Table 2: Structural modifications at the test specimens

Notation		Modification
S2	Frame Cladding	Stud spacing 0,30 m Only one side, single
S4	Frame Cladding	Stud spacing 0,60 m Both sides, single
S6	Frame Cladding	Stud spacing 0,60 m Excited double, other single
S8	Frame Cladding	Stud spacing 0,60 m, double screw spacing Excited double, other single

Gypsum board and metal stud

Two different set-ups are used to determine the stiffness properties of gypsum board. Using modal analysis 33,5 cm long beam samples were cut along the length and width axis from a 12,5 mm thick gypsum board and simply supported at their ends. The length of the beams was chosen so that it was possible to determine the eigenfrequencies in the building acoustic relevant frequency range (Barateiro).

In a second set-up for the phase gradient method two gypsum boards were hanging at some points suspended with rubber bands in an open test hall of the acoustics laboratory. The resonance frequency of the mass-spring system was low and thus the suspensions have no significant influence on the dynamic response of the boards. The plates were excited in the center and the phase difference measured along the length and height axis of the plate (Leth et al.).

Wavenumber measurements also were carried out at one of the metal channel used as studs for the walls. The stud was excited at a free end with a shaker and the other end was fixed in a box with sand to increase the damping of the channel.

MEASUREMENT RESULTS

Experimental Modal Analysis at the Wall Set-up

Exemplarily, the imaginary part of the FRFs of the experimental modal analysis of situation S4 of the metal stud wall are shown in Figure 1 in the frequency range below 160 Hz. The first mode of the complete wall was found to be at 5,4 Hz. The mode shapes of the three low order modes are shown in Figure 2. The resonance peak at 33 Hz was identified as the first mode of the gypsum boards between the studs. The eigenfrequencies of those fit well to the one calculated for a simply supported gypsum board of size 0,6 m x 2,6 m and are indicated in Figure 1 by their order.

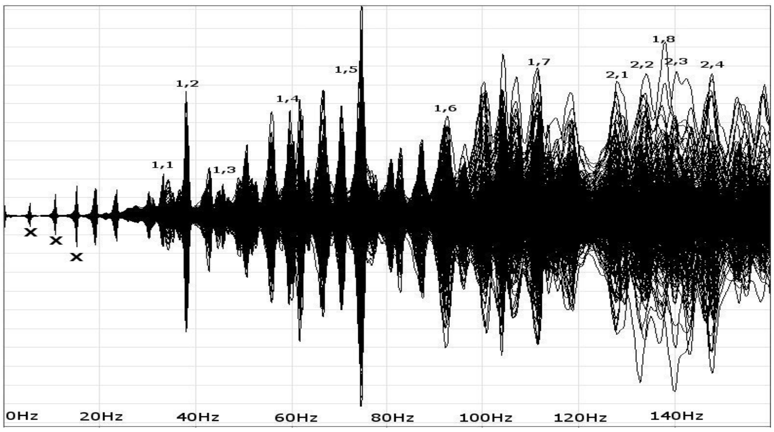

Figure 1 – Imaginary part of FRFs of MS.S4 (0 – 160 Hz; X – modes sown in Figure 2)

Already below 100 Hz the number of modes of a gypsum board wall is relatively high due to the circumstance that the wall is vibrating as one complete structure as well as the leaves between the studs independently. Above 100 Hz an identification of single modes and mode shapes becomes difficult. In this range the lower limit of the modal density and modal overlap of the wall is given by a simply supported gypsum board with the dimensions of the bays between two adjacent studs.

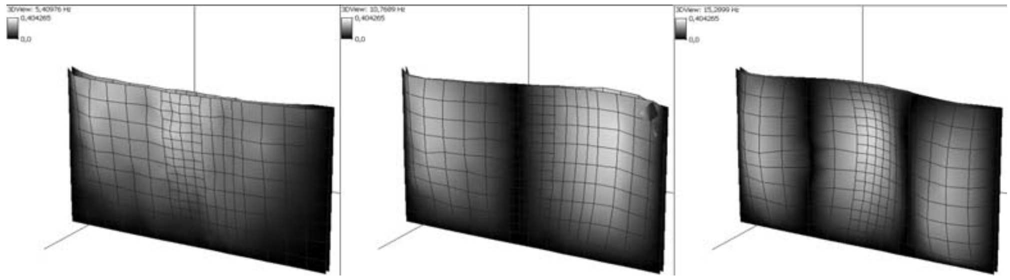

Figure 2 – Mode shapes of the first three modes of MS.S4

Wavenumber Measurements at the Walls

The real part of the wavenumber spectra are shown in Figure 3A for the different structural members of the wall. The wavenumber spectra are computed in this case using the average material properties that are determined experimentally at two different plate samples along the main axis. The Young's modulus along the length axis was found to be 2,6 GN/m² and along the width axis 2,28 GN/m². Thus, the boards seem to be slightly orthotropic. The standard deviation of the mean modulus of the results at different samples and paths was smaller than this difference. The average Young's modulus found from the eigenfrequencies at beams samples of these boards was estimated to be 6,0 MN/m². The deviation of the Young's modulus determined from different eigenfrequencies even measured at the same beams sample had a great deviation, thus it was not possible to show the orthotropy of the boards. The reason for the deviation of the results is the difficulty to realize ideal simply-supported boundary conditions at the ends of the beams.

The wavenumbers measured at the metal channel show different regimes. Below 500 Hz the bending stiffness is bigger than the one of the boards, thus the wavenumbers are smaller, but increase rapidly above 500 Hz. This increase is caused by wave propagation in the flanks of the channel. The wavenumbers of the wooden studs were simply calculated because of their simple geometry.

In Figure 3B the wavenumbers along the length axis of the walls are shown. The wavenumbers are averaged for the situations S2 and S4 with a single layer of gypsum board, since it was found that the distance of the studs has no influence on the stiffness in the direction perpendicular to them. Further the material of the studs and the doubling of the gypsum board does not increase the bending stiffness in this case in the regarded frequency range.

In Figure 3C and Figure 3E the wavenumbers that are measured on a path parallel to the height axis of the walls along the center line of one bay right in the middle between two studs are shown for the different frames. In both cases only a small influence at low frequencies is investigated with the standard stud spacing of 0,6 m. In the case of the reduced spacing the stiffness increases below 630 Hz and approaches the one of the studs below 125 Hz in the case of the wooden frame. The transition begins, when the stud spacing is approximately half of the bending wavelength of the leaf (0,60 m at 125 Hz) in direction perpendicular to the studs and ends when it equals approximately the stud spacing (0,3 m at 500 Hz). Once again as expected a doubling of the gypsum board does not increase the stiffness of the leafs of the walls.

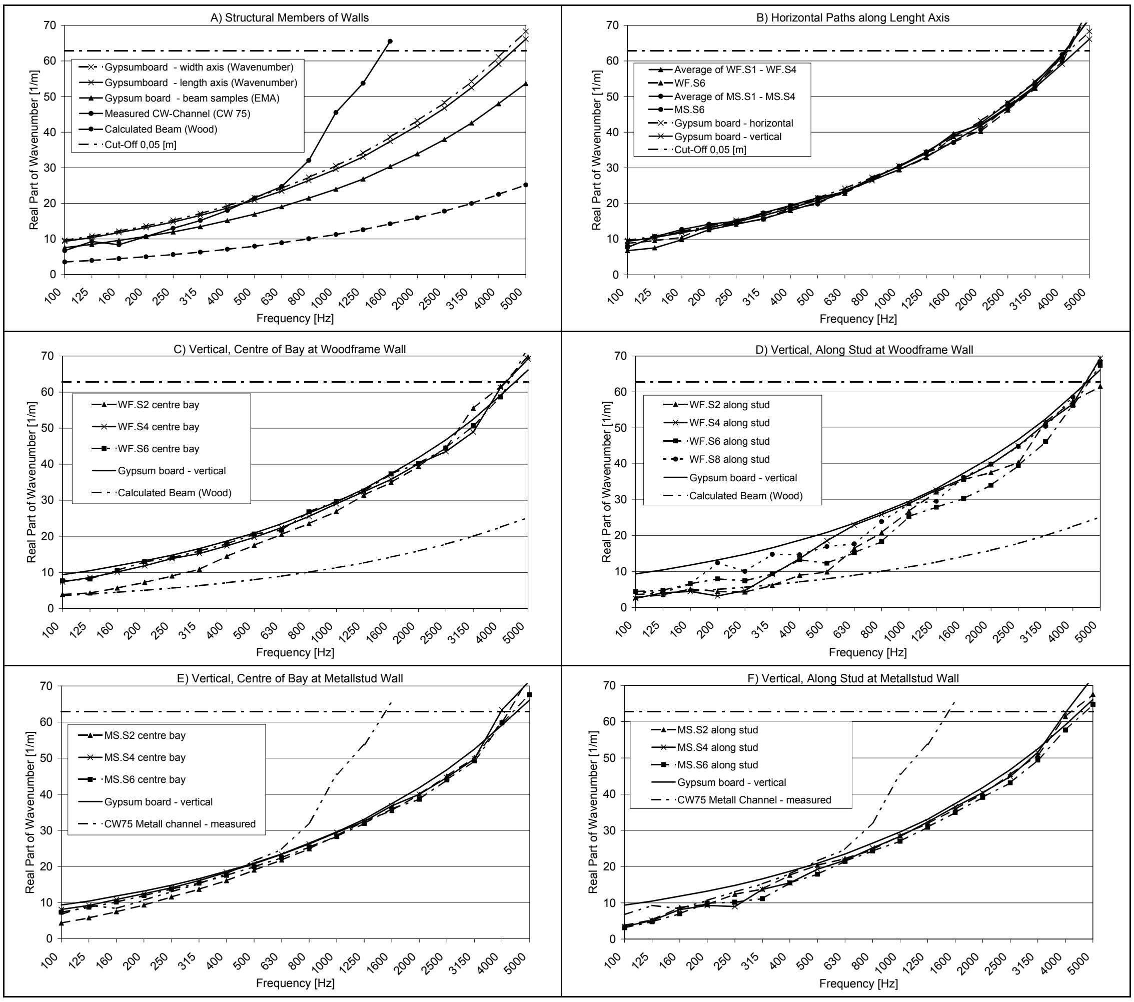

Figure 3 – Wavenumber spectra of gypsum walls and their components along different paths

In Figure 3D and Figure 3F the results for the measurement parallel to the height axis along studs are shown. In this case no significant difference was found in the regarded frequency range for paths along studs in the middle of a gypsum board and along studs where also joints of gypsum boards are located and thus were averaged. In the case of the wooden frame the graphs for the situations with 0,3 m screw spacing approach the wavenumbers of the stud below app. 200 Hz well. Here the screw spacing is smaller than a half bending wavelength in the leafs. Transition occurs above 630 Hz when the bending wavelength is bigger than the screw spacing and at the single layers the stiffness approaches the one of the gypsum board. For a screw spacing of 0,6 m this transition frequency shifts to 160 Hz. In the case of a double layer the wavenumbers stay also below the one of the single gypsum board above the upper transition frequency and follow with certain bias. Reason here for is not the stiffness of the stud itself, but the connection of the two layers gypsum board due to screws.

At the metal frame wall the transition of the screw spacing incidentally falls to the same frequency, where the channel stiffness becomes weaker than the one of the leafs. In this case all curves follow the stiffness of the channel below 500 Hz well, above again the double layer is slightly stiffer than the single layer.

CONCLUSIONS

The measurement of the stiffness properties with the phase gradient method is a valuable tool to determine the dynamic behaviour of lightweight, double leaf structures with a high modal density and modal overlap as well as of their structural members in a wide frequency range, whereas experimental modal analysis can only be used in the very low frequency range.

Further the bending stiffness of the structural members of some test walls were measured. The dependence of the real part of wavenumbers of plane propagating waves in the leafs of the walls on these material properties and structural details were shown. General it can be said that the stud and screw spacing determines the frequency range were the different structural members dominate the stiffness of the complete structure. The wall is orthotropic and dominated by the stiffness of the studs in the direction parallel to them when the stud spacing is less than half a bending wave in the direction perpendicular to them. Further the plate has a rib stiffened character with line reinforcements in the frequency range where the screw spacing is less than half a bending wavelength in the cladding parallel to the studs. As expected a doubling of the gypsum board of the leafs with point connections between the two layers at the studs increases the bending stiffness of the leaf slightly only along the studs.

REFERENCES

Periodical: Nightingale, T.R.T.; Halliwell, R.E.; Pernica, G. , “Estimating in-situ material properties of a wood joist floor: Part 1 – Measurements of the real part of bending wavenumber and modulus of elasticity”, Building Acoustics, **11**, 1-27 (2004)

Periodical: Roelens, I., Nuytten, F.; Bosmans, I.; Vermeir, G.; “In-situ measurement of the stiffness properties of building components”, Applied Acoustics, **52**, 289-309 (1997)

Other: Barateiro, H.; “Using experimental modal analysis to characterize the response of a lightweight leaf structure”, Eindhoven University of Technology, BPS-04.43.A (2004)

Other: van Leth, M.; Ritmijer, M.; ‘Bepaling van de verliesfactor en de buiggolflengte van gipskartonplaten’, Eindhoven University of Technology, BPS-master project (2005)

Other: Schoenwald, S.; Gerretsen, E.; Martin, H.J.; ‘Aspects of the measurement of Kij at junctions of lightweight assembled structures’. Procceedings of CFA-DAGA 2004, Strasbourg, 175-176 (2004)