SOUND TRANSMISSION THROUGH CROSS-JOINTS IN MULTI-FAMILY HOUSES WITH LIGHTWEIGHT, DOUBLE STRUCTURES AND STEEL SUPPORTING STRUCTURES – TRANSMISSION MODELS

PACS REFERENCE: 43.40.At

Koopman, Arnold; Van Gogh, Willem; Bron-van der Jagt, Susanne
TNO Building and Construction Research
P.O. Box 49
2600 AA Delft
The Netherlands
Tel: +31 15 2763215
Fax: +31 15 2763018
E-mail: a.koopman@bouw.tno.nl

ABSTRACT

In the Netherlands new building concepts with removable inner walls and installations are developed for multi-family houses. Lightweight, double structures as separating floors and walls and steel structures are applied. In order to fulfil the noise requirements, it is necessary to restrict the sound transmission through cross-joints and steel structures. For a future building a FEM model has been made of some cross-joints. Vibration reduction indices of these joints are calculated. This paper deals with the model and gives calculation results for several design variants of cross-joints.

Another part of this research concerns measurements of the transmission in experimental set-ups and is described in a separate paper. Besides, that paper explains the background of this research in more detail and gives prediction results of the airborne and impact sound insulation between apartments.

INTRODUCTION

In this research the sound transmission through cross-joints in multi-family houses consisting of lightweight building structures and steel supporting structures has been investigated. The research has been focussed on the sound transmission of the path floor-joint-floor, because this path determines the airborne sound insulation between two apartments next to each other. No vibration reduction index data concerning this path were available before this research.

The research consists of two parts, which are both aimed to determine the vibration reduction indices of the cross-joints. The vibration reduction indices have been measured in experimental set-ups. The background of this research, the measurements and the predictions of the airborne and impact sound insulation between apartments are described in detail in a separate paper. For the predictions the vibration reduction indices, as determined with the FEM model and in the experimental set-ups, have been applied.

This paper describes the conditions and properties of the FEM model and the model results.

SOUND TRANSMISSION

As is explained in the other paper about this research, the sound transmission path concrete floor element – steel supporting structure – concrete floor element determines the airborne sound insulation between apartments in the considered multi-family building. Figure 1 shows the cross-joint with this transmission path in detail.

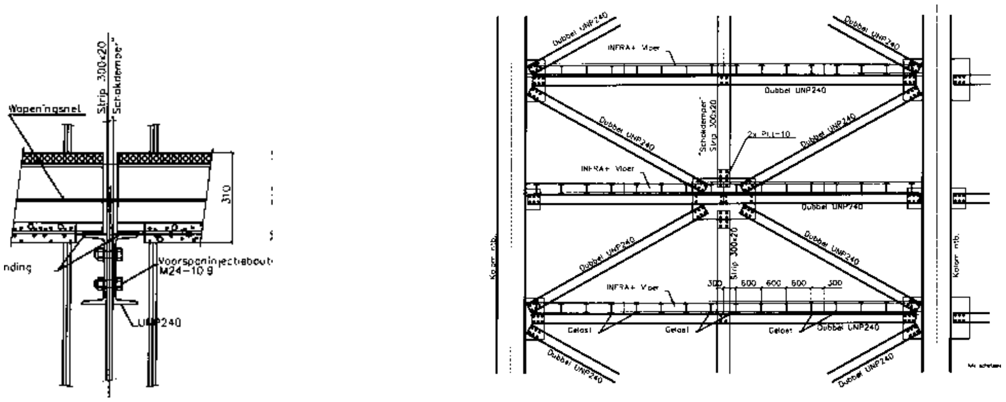

Figure 1 Cross-joint

FEM MODEL

For making a prediction of the vibration transfer through the building joint numeric calculations are carried out with the finite element program DIANA. An overview of the model is given in Figure 2.

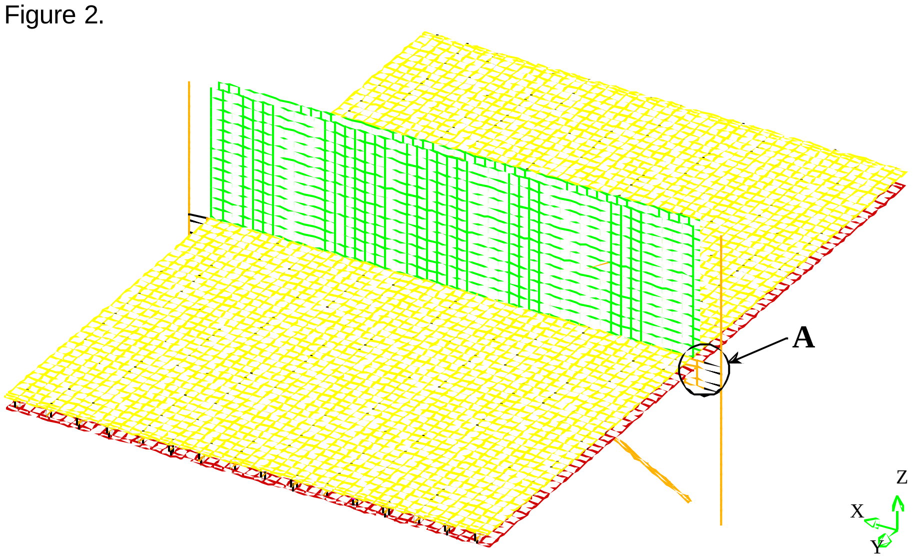

Figure 2 Schematic view of the model

All steel beams in the stability wall, except the girders of the A+ floors (UNP girders), are modelled with two-node, three-dimensional class-I beam elements. Basic variables are the translations u_x, u_y and u_z and the rotations ϕ_x, ϕ_y, and ϕ_z. A class-I beam element is a classical beam element (based on the Bernoulli theory) with directly integrated cross-sections. A 2-point Gauβ integration along the beam axis is used for these elements.

The UNP girders are modelled with an eight-node quadrilateral isoparametric curved shell element. The basic variables in de the nodes of the curved shell element are the translation u_x, u_y and u_z in the global X Y Z directions and the rotations ϕ_x and ϕ_y, respectively around the x and –y axes in the plane of the element. The default integration scheme of this element, 2x2x2 integration, is used.

Shell elements are also used for modelling the steel plates in the junctions of the girders with the columns and the crossed windbracing, for the gypsum board walls, the concrete plate of the A+ floor (lower floor: ceiling of the level below) and fibre-cement floor (upper floor).

The rubbers for disconnecting the floors on both sides of the stability wall are modelled with twenty-node isoparametric solid brick elements. The basic variables in the nodes of solid elements are the translations u_x, u_y and u_z in the local directions. The default integration scheme for these elements, 3x3x3 Gauβ integration, is used. The rubbers are situated between the UNP girders and the steel plates in the junctions, see also Figure 3.

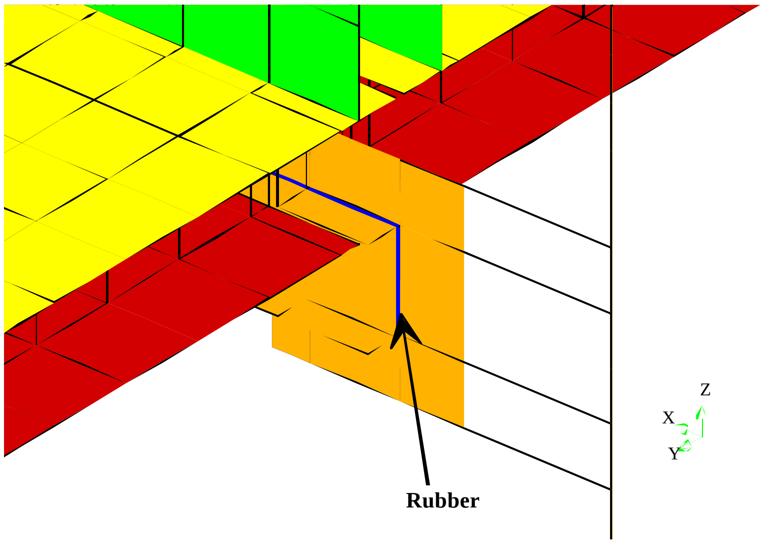

Figure 3 Detail of the model by the junction of the UNP girders and the column (Detail A in Figure 2)

The IPE-beams in the A+ floor are modelled with beam elements, which are line elements. These line elements are situated in the neutral line of the IPE-beams. They have to have a rigid connection with the curved shell elements of the lower (concrete) floor and the spring elements used for modelling the rubber between the IPE beams and the upper floor. The situation of these elements is respectively in the bottom and the top of the IPE beams. These rigid connections are modelled with Class-I beam elements with an infinite high modulus of elasticity (100 times the elasticity modulus of steel) and a large cross section (1.0 by 1.0 meter).

The rubber between IPE240 beams of the A+ floor and the upper floor (existing of fibre-cement plates) are modelled with two-node translation spring elements. Basic variables of these elements are the translation, the elongation and the axial force. Per connection between IPE240 beams and the upper floor three spring elements are used, knowing:

- 1 spring element to model the axial stiffness of the rubber;
- 2 spring elements to model the shear stiffness of the rubber in two directions perpendicular to the axial direction of the rubber.

Material Properties

The material property of steel elements, concrete plate of the A+ floor, the fiber-cement top floor and the rubber between the UNP girders and the steel plates in the junctions are summarised in Table 1.

Table 1 Properties of the materials used in the model

	Steel	Concrete	Fiber-cement	Gypsum Wall	Rubber (joints)
Modulus of elasticity (N/m^2)	$2,1\ 10^{11}$	$3,85\ 10^{10}$	$6,75\ 10^{9}$	$1,25\ 10^{9}$	$1,0\ 10^{7}$
Poisson's ratio (--)	0,3	0,15	0,3	0,3	0,3
Density (kg/m^3)	7800	2500	1250	1108	900
Critical damping (%)	0,3	3	1,0	1,0	14

The rubbers between the fiber-cement plates (top soil) and the A+ floor are modelled with three spring elements per connection: one for the axial stiffness ($k_a = 7{,}23\ 10^5$ N/m) and two for the shear stiffness ($k_s = 3{,}23\ 10^5$ N/m). These stiffnesses are based on a distance between the connections of the top soil with the IPE beams of the A+ floor on one beam of 20 cm.

Element Length

The length of the elements is set on 20 cm. This is a factor 5 lower than the shortest wavelength of bending waves at 400 Hz found in the construction. The wavelengths have been derived from plate and beam theories [1].

Boundary Conditions
For the outside borders, where the modelled part of the construction connects to the rest of the building, boundary conditions has to be set.
All column and windbracing ends are clamped: there is no rotation or translation.
The ends of the IPE-beams of the floor have no translation and only have rotation in the Y-direction (along the long axis of the beam).
The vertical edges of the gypsum walls are clamped in the X and Y direction, and they can therefore only translate and rotate in the Z-direction.
Any other edges and ends are free.

Solver Algorithm
The solution procedure for the system of equations is a direct solution method (Newmark), using linear transient analysis. This analysis runs in the time domain and linear behaviour is assumed.

MODEL RESULTS

With an impact force the numerical model of the building joint is excited. The impact is a vertical point force at a random place on the lower floor (ceiling). Vibrations occur, travel towards the edges, get reflected and at the joints get transmitted to the other floor, the receiving side. In both floors a more or less diffuse vibration field is building up and damping out. The 'measurement' set-up in the model and post processing is similar to measurement set-ups and processing for real situations where transmission losses are determined, to facilitate comparison.
From the experiment two parameters are determined: the difference in vibration level between the floors on either side of the joint and the decay time of the floor. How these two parameters are used for the calculation of sound insulation is explained in the next chapter.
The vibration level of a floor is determined by integrating the vibration field over space (X and Y) and time. The next 4 figures show how vibration radiates from the point of impact towards the edges and the joints and how it is transmitted to the next floor. Examinations learned that vibration is mainly transmitted through the column joints, and hardly through the windbracing joint in the middle. This knowledge is useful when looking for ways to reduce the transmission.

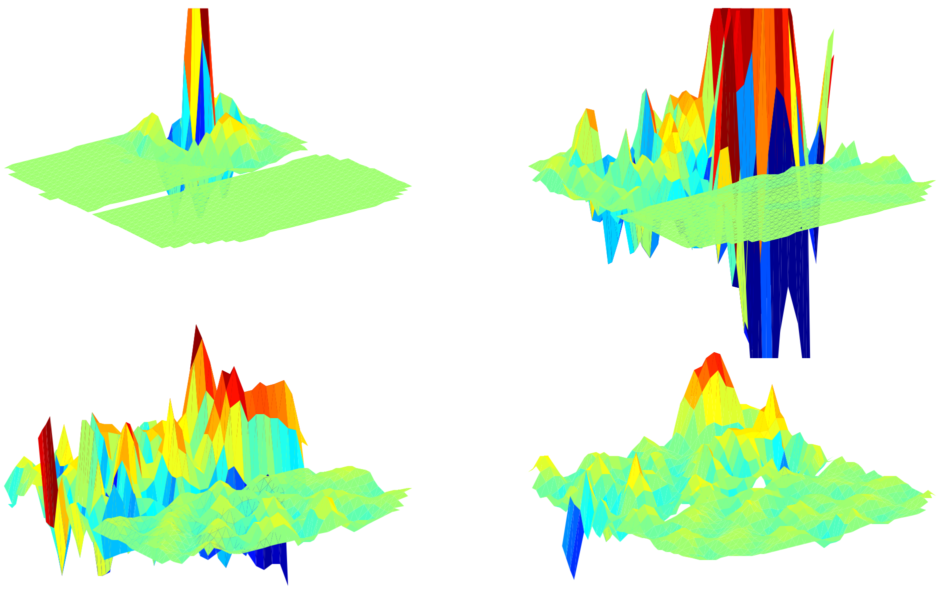

Figure 4 Vibration velocity, filtered between 160 en 300 Hz, at four stages: after 5, 15, 30 and 60 ms (variant 3)

Three variants have been modelled:

1 Fixed connections at the column and windbracing joints;
2 Application of cork-rubber at all the joints in order to achieve uncoupling;
3 Stiffening of the column, mainly in the torsional direction, with a fixed connection there and cork-rubber at the windbracing joint.

The first variant is the most desirable one, from the construction point of view. However, it proofed to be vibrational unsound, and that is why the second option came up. That one does indeed suffice, but has important constructional drawbacks. The third variant solved that. The results are shown in figure 5.

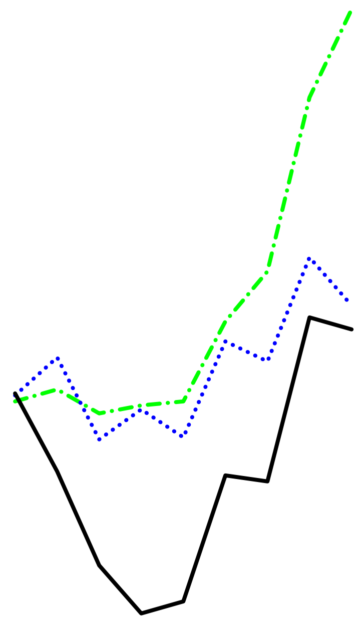

Figure 5 Vibration level difference for each of the three variants 1, 2 and 3

The first variant shows a serious coupling between the two floors between 160 en 250 Hz. It is not totally understood why this happens at these frequencies. It is suspected that mode-coupling, occurring due the symmetry of the system, has an optimal effect there. Applying rubber to decouple the floors clearly works from 125 Hz and above, solving the problem around 200 Hz and giving a substantial bonus at the higher frequencies (variant 2). Taking away the rubber at the column joints and instead making the columns stiffer spoils it for these higher frequencies but still works for the 160 - 250 Hz range.

Integrating the vibration field of both floors over the spatial dimensions gives a decay curve over time from which a reverberation time (decay time) is derived. Pulse excitation is not an optimal source for determining decay time, but this is (partly) helped by use of backward integration. Table 2 shows the decay time, expressed as T60, the time it takes for the level to drop 60 dB. The 500 Hz octave band is less reliable, because in certain structural elements the bending wavelength gets in the order of magnitude of the element length of the FEM model. The decrease of reverberation time with increasing frequency seems quite normal though. The three modelled construction variants all gave the same results.

Tabel 2 Decay time

Band [Hz]	100	125	160	200	250	315	400	500	615
T60 [s]	0,6	0,6	0,6	0,6	0,5	0,5	0,4	0,4	0,4

PREDICTION OF AIRBORNE SOUND INSULATION

The prediction method of the sound insulation is explained in detail in the other paper about this research. Based on the calculation results in figure 5 and table 2, an airborne sound insulation $D_{nT;A}$ of 51-52 dB(A) has been predicted for a representative situation in the considered building.

CONCLUSION

This research shows that FEM can be applied as a useful 'design' tool, in order to predict the sound transmission through cross-joints in the design stage of a future building. This paper describes the conditions and properties of the FEM model for a cross-joint in this building. The building consists of lightweight building structures and steel supporting structures. The sound transmission of the path floor-joint-floor determines the airborne sound insulation. This research has been focussed on this transmission path.

The FEM calculation results show that the sound transmission of the considered path can be restricted enough, as long as there is a complete separation or effective 'decoupling' (by rubber) of the floor elements.

Because the FEM model showed promising prediction results concerning the airborne sound insulation between apartments, an experimental set-up has been built. In this set-up vibration reduction indices have been measured. The backgrounds of this research, the measurements and the predictions are described in detail in a separate paper.

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