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Innovative building systems to improve the acoustical quality in lightweight masonry constructions: Application of resilient joints at junctions - PART 1: analysis of the experimental results

Charlotte Crispin[a], Bart Ingelaere[a] and Gerrit Vermeir[b]

[a]BBRI, rue du Lombard, 42, B-1000 Brussel, Belgium
[b]Lab. ATF, Katholieke Universiteit Leuven, Celestijnenlaan 200D, B-3001 Leuven, Belgium
charlotte.crispin@bbri.be

The more severe acoustic requirements imposed by the new Belgian standard for dwellings are a real challenge for the building professionals (architects, contractors, building elements manufacturers and suppliers, etc) and more particularly for the market of lightweight materials. An important brick producer in partnership with the BBRI has succeeded to propose efficient acoustic solutions for these kinds of materials by treating in particular the flanking transmission. Indeed, to obtain high sound insulations, the structural transmission paths of noise through the flanking walls cannot be neglected any more. By the application of resilient rubber interlayers at the junctions, these transmission paths are nearly eliminated. A large number of measurements was carried out in order to study in detail the effect of these flexible joints on the sound transmission. These measurements were made in a specially designed laboratory where vibration reduction indexes can be measured for all types of connections and for different loads. We present, in this paper, the measurement survey and the analysis of the results.

1 Introduction

The more severe acoustic requirements imposed by the new Belgian standard for dwellings are a real challenge for the market of lightweight bricks. The Wienerberger Group asked BBRI (Belgian Building Research Institute) to find efficient acoustic solutions for these kinds of materials.

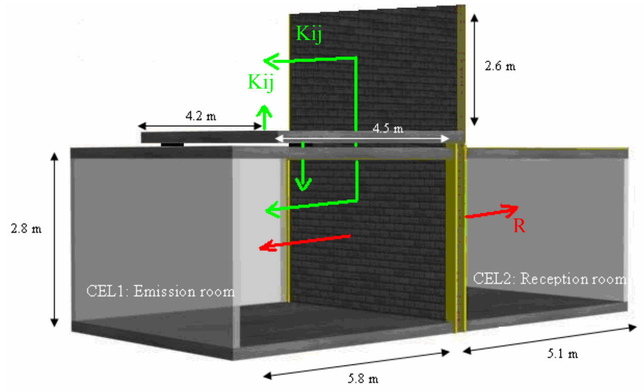
The reduction of the direct horizontal sound transmission can be easily reached by a cavity wall and the direct vertical transmission by a heavy floor with a floating floor. The reduction of the horizontal and vertical structure-borne transmission at junctions is obtained by the application of resilient joints. The resilient joints provide an efficient mean to reduce the flanking transmission paths. However these important improvements of them must be studied because a lot of effects are yet unclear:

- The influence of the joint compression on the K_{ij};
- The wave conversion at the joint;
- The effect of preload;
- The effect of a plaster bridges;
- The change of the energy distribution between the walls and floors when the resilient joint is inserted.

In order to study in detail the efficiency of these buildings systems and to obtain input data for prediction models, a large number of measurements were carried out. These measurements were made in the experimental site of Wienerberger in Beerse (Belgium). The setup is conform to the standard EN ISO 140-3 (1995) dedicated to the measurement of the sound reduction index and to the standard EN ISO 10848 dedicated to the measurement of the vibration reduction index K_{ij}.

2 Test arrangement

Two cells are mounted in the experimental site of Wienerberger in Beerse (figure 1). The thickness of the flanking walls of the test cells is about 0.185 m. These walls are composed with bricks (ρ = 1600 kg/m³). The floor is a concrete slab (ρ = 2300 kg/m³) with a thickness of 0.4 m and the ceiling is composed of hollowcore concrete slabs with a structural topping (total thickness = 0.19 m, ρ = 2300 kg/m³). The two cells are completely decoupled avoiding flanking transmissions. This particular setup allows the measurement of the sound reduction index R of the separating wall and the vibration reduction index K_{ij}. A large space is left open in the ceiling of CEL 1 to avoid perturbation of the vibration field on the floor constituting the T-junction for the K_{ij} measurement.



Emission room volume = 69.3 m³

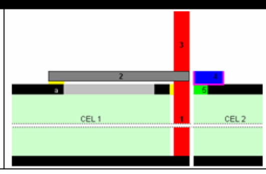
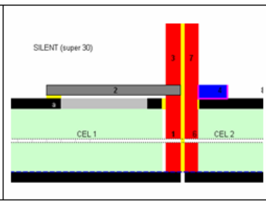
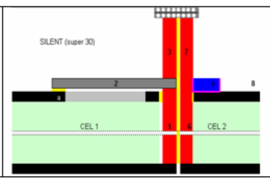
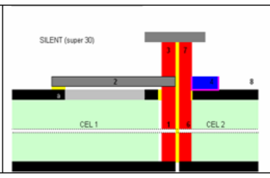
Reception volume = 62.5 m³

Separation wall surface = 11.24 m²

Fig. 1 Test arrangement

3 Systems tested

The table below (Table 1) summarizes the systems tested.

Test number	Tested system	Description
TEST 01		**A rigid T-junction**: the vertical walls (1,3) are made of bricks (density : 1108 kg/m³, thickness : 0.14 m) and interrupted by perpendicular hollowcore slabs (density : 1575 kg/m³, thickness : 0.20 m). The wall 1 is plastered on the CEL1 side. This junction constitutes our reference.
TEST 02		A cavity wall without any connection between the two leaves. The walls 1 and 3 are interrupted by the hollowcore slabs (floor 2) creating a T junction. The walls 6 and 7 are not interrupted creating a line junction. The density of the brick walls is 1108 kg/m³ and the thickness of the walls is 0.14 m. The cavity has a thickness of 0.03 m and is filled with mineral wool. The walls 1 and 6 are plastered.
TEST 03		The same composition as TEST02 but the walls 3 and 7 are joined at the top to simulate a structural connection via a foundation.
TEST 04		The same construction as the TEST 03 but in this case walls 3 and 7 are shorter (1 m instead of 2.6 m).

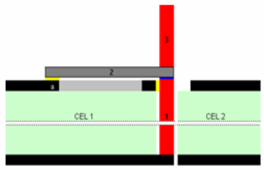
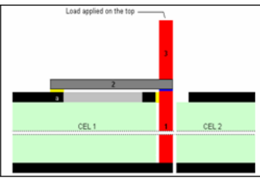
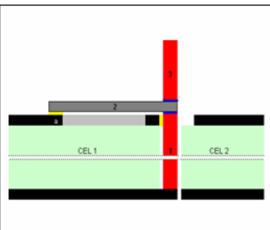
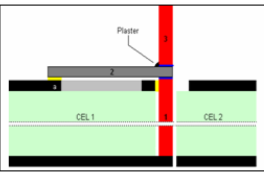
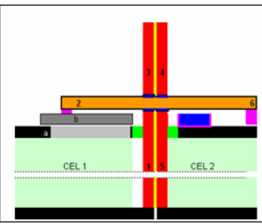
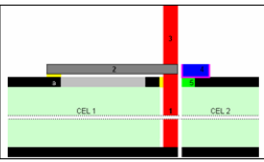
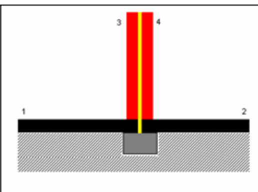
TEST 05		A T-junction **with flexible interlayer**: the vertical walls are made of bricks (density: 1108 kg/m³, thickness: 0.14 m) and interrupted by horizontal hollowcore slabs. The resilient joint is placed between the slabs and wall 1. The resilient joint is a resinbonded rubber with a thickness of 0.01 m and a width of 0.14 m. Wall n°1 is plastered on the CEL1 side.
TEST 06		The same junction as TEST05. We have applied in this case **different loads on the top** to simulate storeys by a system of steel beams and pneumatic jacks
TEST 07		A T-junction with **two flexible interlayers**: the vertical walls are made of bricks (density: 1108 kg/m³, thickness: 0.14m) and they are interrupted by perpendicular hollowcore slabs. Wall n°1 is plastered on the CEL1 side. A resilient joint is placed between the slabs and wall 1. The other one is placed between the slabs and wall 3. The resilient joint is a resinbonded rubber from CDM with a thickness of 0.01 m and a width of 0.14 m.
TEST 07b		The same junction as TEST 07 but a structural bridge is added to simulate a plaster band on the upper joint. The vertical walls are loaded with a pressure of 10 bars in the pneumatic jacks.
TEST 09		**A cross junction** composed of a continuous concrete floor and a double brick wall (density and thickness of bricks: 1108 kg/m³ and 0.14 m). A resilient joint is inserted between the brick walls and the floor. The resilient joint is a resinbonded rubber with a thickness of 0.01 m and a width of 0.14 m. The brick walls are not plastered. The cavity between the brick walls is filled with mineral wool and measures ± 0.03 m.
TEST 10		A rigid T-junction: the vertical walls (1 and 3) are made of bricks (density: 1650 kg/m³, thickness: 0.175 m) and interrupted by perpendicular hollowcore slabs (density: 1575 kg/m³, thickness: 0.20 m). So, a rigid T-junction with heavier walls as those fromTEST01.
FOUND 01		The vertical walls are composed of bricks (density: 1108 kg/m³ and thickness: 0.14 m). The cavity is filled with mineral wool (thickness: 0.03 m). The concrete floor has a thickness of 0.12 m and a density of 2300 kg/m³. The floor is interrupted but joined by a common foundation. This test measures the improvement of the K_{ij} by decoupling the ground floor slabs on a common foundation.

Table 1 Presentation of the tested systems

4 Measurement of the sound reduction index R

Figure 2 presents the results of sound reduction index measurements per 1/3 octave bands according to EN ISO 140-3:1995. The results show typical curves for a simple wall, a cavity wall and a cavity wall with connection at the perimeter. So, a detail analysis will not be presented here. Only the result of TEST10 needs some particular attention because the critical frequency f_c, is observed at 80 Hz as expected but surprisingly, the slope falls down slightly around 400 Hz and meets the curve of TEST01. This can be explained by the local weaknesses of the wall at the vertical joints between bricks not filled with mortar. The R_w is only 47 dB instead of about 52 dB as expected in theory.

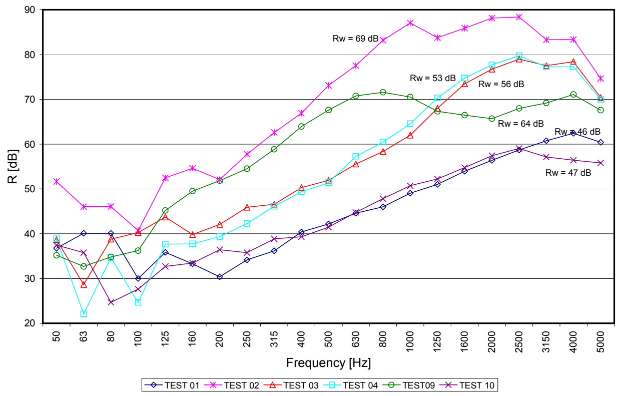


Fig.2 Sound reduction index of tests 01, 02, 03, 04, 09 and 10

5 Measurement of the vibration reduction index K_{ij}

The graphs below present the measurements of the vibration reduction index K_{ij} obtained according to the standard EN ISO 10848-1 and the draft prEN10848-4. The legends below the graphs give firstly the transmission path, secondly the number of the test and thirdly the load applied on wall 3 (in bars). Example: K13_07_10 gives the K_{ij} for the transmission path 13 of TEST 07 and with a load of 10 bars applied on wall3.

5.1 Effect of resilient joints on the structural transmission

5.1.1 Measurement in line

Figure 3 presents the vibration reduction index K_{ij} for the path **in line** and compares the results for a junction without joint (rigid junction, TEST01), with one joint (TEST05 and TEST06) and with 2 joints (TEST07).

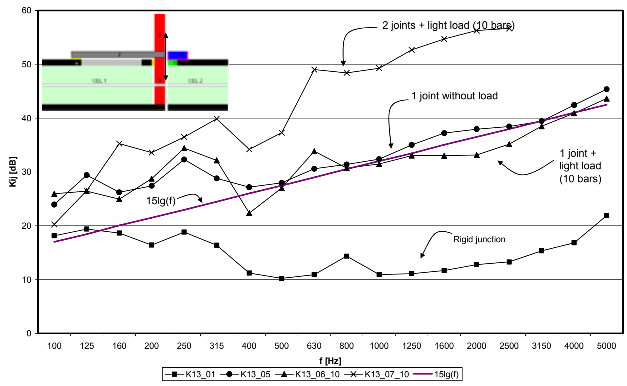


Fig.3 K_{ij} for an inline transmission path in a T-junction (without joint, one joint and two joints)

The rigid junction (TEST01)

The K_{ij} for a rigid junction normally doesn't depend on the frequency though we can see higher values in low and high frequencies. The high K_{ij} values observed below 400 Hz cannot be explained only by the poor modal overlap factor due to a poor number of modes in this frequency range. An important conversion of the bending waves to "in-plane" waves at the junction is also a reason which might explain the high K_{ij} value at low frequencies. The single value calculated as the average of the K_{ij} between 200 and 1250 Hz is **13.4 dB**. The predicted value according to the standard 12354-1 is 12.7 dB.

Junction with one flexible interlayer (TEST05 and TEST06)

Two curves are presented. The first (with bullet) shows the results for a junction without load applied on the top of wall 3. We can see a distinct improvement of the K_{ij} compared to the junction without joint. The improvement is about 10 dB at low frequencies and 20 dB in the high frequencies. The K_{ij} increases by 15 lg(f). The second curve (with triangle) presents the results with a slightly loaded wall (10 bars). On this graph we can see the same tendency as for the results without load: an improvement by 15lgf. The poor modal overlap factor and the important conversion of the bending waves to in-plane waves is also well observed on the graph below 400 Hz where the K_{ij} is much higher than expected. The gap and the peak observed at 400 and 630 Hz for the test with light load, could be explained by the steel beam used for loading wall 3 (see figures 5.a and 5.b) which possibly disturbs the "in-plane" wave field.

Junction with 2 flexible interlayers (TEST07)

Compared to the junction with one joint, a further improvement of the K_{ij} is observed. The K_{ij} increases by 25 lg(f) instead of 20lg(f) as given in theory [5]. We see again K_{ij} values of below 400 Hz and around 630 Hz higher than expected.

5.1.2 Measurement in the angle

Figure 4 presents the vibration reduction index K_{ij} for the path **in angle** and compares the results with a junction with one joint (TEST05 and TEST06), with 2 joints (TEST07) and without joint (rigid junction, TEST01).

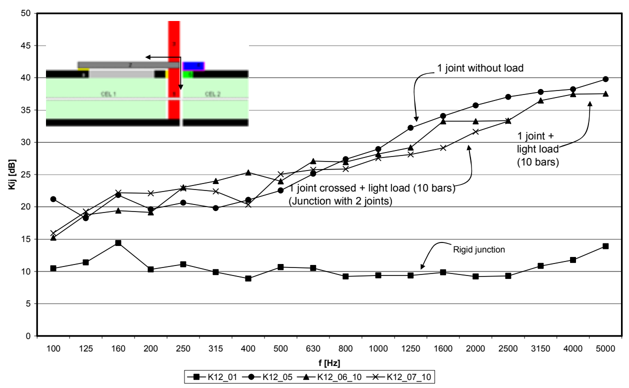


Fig.4 K_{ij} for an angle transmission path in a T-junction (without joint, one joint and two joints)

For the rigid junction, the K_{ij} is quite constant and the single value (i.e. the average of the K_{ij} between 200 and 1250 Hz) is **9.9 dB**. The predicted value according to the standard EN ISO 12354-1 is 6.7 dB.

The curves for the junction with one joint (with and without load, triangled respectively bulleted on the graph) show an increase by 20lgf instead of 10lgf as given in theory. The curve for the junction with 2 joints (cross on the graph) shows an increase by 15lgf. This means that, in high frequencies (up to 800 Hz in the graph), the energy which cannot cross the second resilient joint and spread out over wall 3, is send in to floor 2. So, the K_{ij} is lower than in the case of one joint.

5.2 Effect of a load

The graphs below (figures 6 and 7) present the effect of the joint compression on the K_{ij}. The compression of the joint to simulate storeys has been carried out by a particular mounting (see figures 5.a and 5.b). A free steel beam is placed on the top of wall 3. Four hydraulic jacks are inserted between this free beam and an upper steel framework attached to the ground without any connection with the setup. The pressure applied by the hydraulic jacks loads wall 3 and compresses the joint. The conversion of the pressure in the hydraulic jacks to the load applied on the wall 3 is given in table 2.

bars	kN/m
10	5.5
50	19.3
100	36.6
110	40.0
150	53.8
190	67.7

Table 2 Conversion pressure-load

Fig. 5.a System of steel beams to load the walls

Fig. 5.b Hydraulic jack

5.2.1 Measurement in line for the junction with one resilient joint

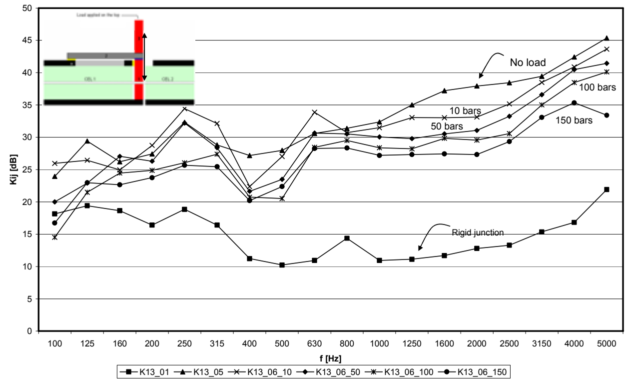


Fig.6 K_{ij} for an in line transmission path in a T-junction with one flexible joint (TEST06). Different loads are applied on the joint.

The effect of the load on the resilient joint is well observed for all frequencies. When the load increases, the K_{ij} falls. Roughly, the curves fall by 2dB at each frequency when a load is added. This is explained by the increase of the joint stiffness when the load increases. In spite of the fact that the joint is highly compressed, the vibration reduction index remains considerably higher compared to the rigid junction. Again, we observe unexpected high K_{ij} below 400 Hz and at 630 Hz (see paragraph 5.1.1). A supplementary study is carried out to demonstrate the link between the joint stiffness and the K_{ij} value. For this study, we have developed a particular setup to measure the dynamic stiffness of the resilient joint with heavy loads (to simulate multiple storeys) in the audio frequency range (50 to 5000 Hz). This setup is inspired by the standard EN ISO 10846 (Part1 to 5) [3].

5.2.2 Measurement in the angle for the junction with one resilient joint

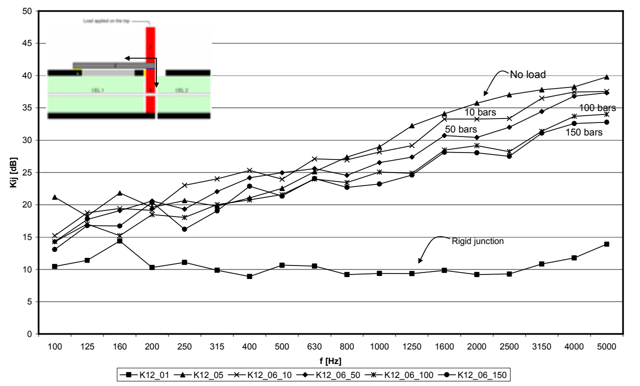


Fig.7 K_{ij} for an angle transmission path in a T-junction with one joint (TEST06). Different loads are applied on the joint.

The effect of the load is well observed above 500 Hz. Roughly, the curves fall by 2dB at each frequency when a load is added. As for the case in line, in spite of the fact that the joint is highly compressed, the vibration reduction index remains considerably higher compared to the rigid junction proving the great efficiency of the resilient joint.

The results for the junction with two flexible joints will not be presented in this paper. The effect of the compression on this junction is similar to the results for the junction with one joint. The full report is property of the Wienerberger Group and can be consulted by simple request.

5.3 Effect of a plaster bridge

The graph below (figure 8) presents the effect of a plaster bridge.

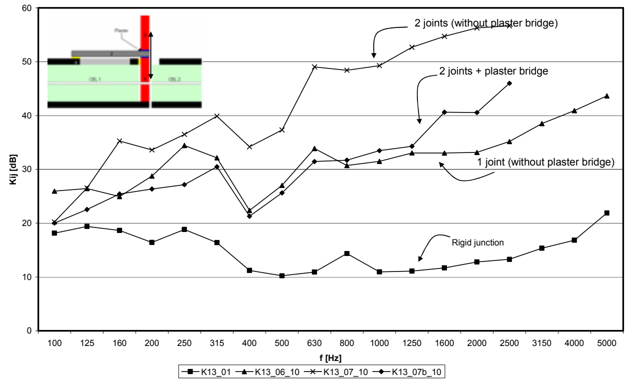


Fig.8 K_{ij} for an in line transmission path in a T-junction with two joints and a plaster bridge (TEST07b)

This significant test shows that a simple connection by a coat of plaster can cancel out the positive effect of the joint. We can see on the graph that a plaster bridge realized on the junction with two resilient joints (TEST07) on the upper flexible joint brings us back to the results with only one joint (TEST06) except for the high frequencies.

5.4 Effect of the foundation on the structural transmission

At the ground floor, the horizontal transmission is strongly dependent on the structural transmission paths through the foundation. The graph below (figure 9) compares the vibration reduction index of the structural path from one leaf of the cavity wall to the other for different foundation types.

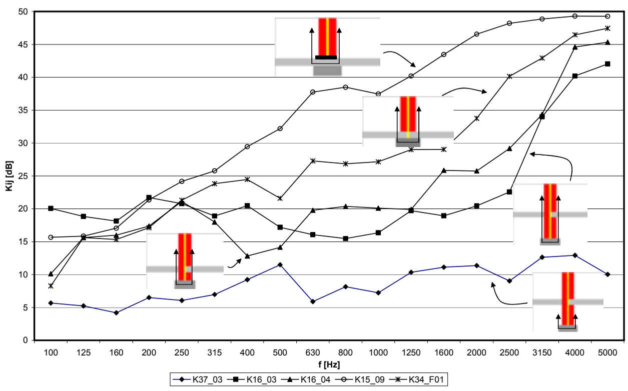


Fig.9 K_{ij} for transmission paths through foundations

As expected, the highest K_{ij} is the one with resilient joints (K15_09). In this case, the structural path wall-wall is almost entirely suppressed. The case where the ground floor slab is not continuous at the foundation (K34_F01) also gives a fair attenuation of the structural transmission path. The height of the underfloor space doesn't play an important role regarding to the K_{ij} level (see K16_03 and K16_04).

5.5 The change of the energy distribution between the elements

As R.J.M. Craik and A.G. Osipov wrote in their article [1], when resilient layers are inserted into a building, they attenuate sound but do not normally remove any acoustic energy from the building. I.e. the insertion of a resilient joint does not remove the energy but sends it into another direction. As we can see on the figure 10, the insertion of the joint sends only slightly energy back into another direction. On the graph below, we compare the K_{ij} in angle when the energy can spread in the coplanar wall to the case when the energy is stopped by a resilient joint. The comparison shows that the reorientation of the energy is slightly noticeable above 500 Hz where the K_{ij} falls down by about 1 dB as the energy cannot spread out into the other wall. Below 500 Hz we cannot do any correct interpretation because the modal overlap factor is too low.

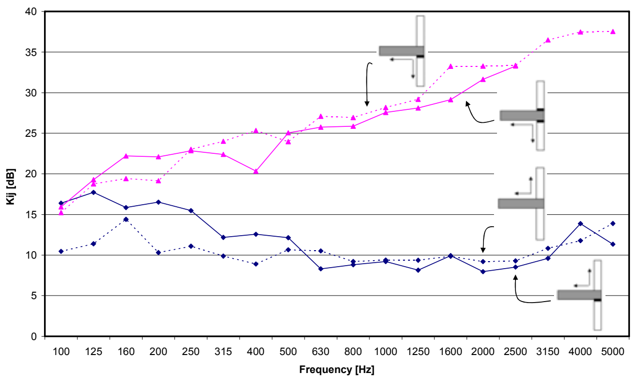


Fig.10 Influence of the resilient joint on the energy redistribution

5.6 Effect of a preload

A test has been carried out to estimate the effect of a compression of the joint during a long period. A load of 190 bars has been applied on the top of wall 2 (TEST06) during one week. The measurements don't show any difference.

6 Conclusion

When we use a cavity wall as partition wall, it is the structure-borne transmission via the common floors (ceiling or foundation) which is dominant for the horizontal transmission between apartments. Vertically, the flanking transmission through the bricks walls contribute also significantly to the global sound transmission. The use of resilient joints at the junctions and foundation is a practical mean to reduce these structural paths efficiently. We have observed, by this measurement survey, the important improvement of the K_{ij} obtained with a resinbonded rubber from CDM. An increase of the load increases the stiffness of the rubber and leads to a fall of the K_{ij} on the entire frequency range but it remains considerably higher compared to the rigid junction. A supplementary study is carried out in the BBRI laboratory to investigate the relation between the stiffness of the joint and the K_{ij}. For this study, we have developed a particular setup to measure the dynamic stiffness of the resilient joint with heavy loads (to simulate multiple storeys) over the audio frequency range (50 to 5000 Hz). Others tests have permitted to suppress the fear of uncontrolled reorientation of the energy when a resilient joint is inserted as well as a negative effect on the K_{ij} of a long period of load. On the other hand the application of this flexible interlayer is very tricky since a light plaster bridge can remove the benefit of the interlayer. This important measurement survey was very useful as input data in prediction models since no data are available for junction with flexible interlayer at foundations and since the empirical formula given in the standard EN ISO 12354-1 (2000) for common junctions are inaccurate.

Acknowledgments

The authors wish to acknowledge the technical and financial assistance of the Wienerberger group and the IWT (Institute for the Promotion of Innovation by Science and Technology in Flanders).

References

[1] R.J.M. Craik and A.G. Osipov, Structural isolation of walls using elastic interlayers., Applied Acoustics 46, 233-249 (1995)

[2] EN ISO 140-3:1995 Acoustics - Measurement of sound insulation in buildings and of building elements - Part 3: Laboratory measurements of airborne sound insulation of building elements (ISO 140-3:1995)

[3] EN ISO 10846-1:1998 Acoustics and vibration - Laboratory measurement of vibro-acoustic transfer properties of resilient elements - Part 1: Principles and guidelines (ISO 10846-1:1997)

[4] EN ISO 10848-1:2006 Acoustics - Laboratory measurement of the flanking transmission of airborne and impact sound between adjoining rooms - Part 1: Frame document (ISO 10848-1:2006)

[5] D.B. Pedersen, Estimation of vibration attenuation through junctions of building structures. Applied Acoustics 46, 285-305 (1995)

[6] prEN ISO 10848-4 Acoustics - Laboratory measurement of the flanking transmission of airborne and impact noise between adjoining rooms - Part 4: All other cases