Simplified prediction of the vibration reduction indices of double wall junctions

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Abstract

Heavyweight cavity walls are commonly used as party wall between row houses and between dwellings in apartment buildings in Belgium. The double wall junctions complicate the prediction of flanking transmission. In this paper, empirical rules for the vibration reduction indices of rigid double wall T- and X-junctions are proposed. They are determined from Monte Carlo simulations carried out with a statistical model that was previously validated by laboratory measurements. In general, a double wall junction can be replaced by an equivalent single wall junction in flanking transmission models. The EN ISO 12354 approximation of a double wall T-junction by an equivalent single wall X-junction proves justified. For double wall X-junctions, the thickness of the equivalent single walls should be either the thickness of a single leaf or the total thickness of both double wall leafs, depending on the transmission path of interest.

Keywords: Sound, Insulation, Flanking

1 INTRODUCTION

The vibration reduction index K_{ij} is an important input quantity in building acoustical models for flanking transmission. The standard ISO 12354-1 [1] gives empirical models based on measurements and simulations for single plate junctions. According to the standard, a double wall T-junction (called Π-junction in this paper) can be approximated by a single wall X-junction. No model is however given for double wall X-junctions (further called H-junction), whereas this type of junction is commonly encountered in Belgium.

The vibration transmission across double wall junctions has been analyzed by means of measurements [2, 3] and simulations [4, 5, 6, 7]. Both measurement [2] and simulation [5] results have proven that an equivalent single wall X-junction can give good estimates for the vibration reduction indices of double wall junctions. Because the experimental and numerical validation was only performed for a few particular case studies, little is known about the general validity and accuracy of these single wall approximations. Crispin *et al.* [4] have developed new expressions for the K_{ij} of H-junctions based on a large number of FEM calculations. The K_{ij}-expressions are function of the PC-ratio [1] which incorporates both the surface mass ratio and the bending stiffness ratio of the plates. The difficulty of determining the bending stiffness currently limits the applicability of these expressions.

Because simplified, empirical formulae as a function of mass ratio are available for the vibration reduction indices of different types of single wall junctions [1], this paper investigates whether double wall Π- and H-junctions can be modeled as equivalent single wall junctions to estimate their vibration reduction indices.

The figures in table 2 show diagrams of the Π- and H-junctions analyzed. Only symmetric Π- and H-junctions are considered in this paper. This means that the properties of plate 1 and plate 2 are the same, as well as the properties of plates 3 to 6.

For the double wall Π-junction, the following equivalent single wall junction has been investigated:

- X'-junction where the single walls have the same thickness and density as one of the cavity leafs of the double wall.

For the double wall H-junction, three equivalent single wall X-junctions have been investigated:

- X'-junction where the single walls have the same thickness and density as one of the cavity leafs of the double wall (blue results in figure 2)
- X"-junction where the single walls have double the thickness (i.e. the total thickness of the cavity leafs) and the same density as one of the cavity leafs of the double wall (red results in figure 2)
- X"'-junction where the single walls have the same thickness and double the density as one of the cavity leafs of the double wall (green results in figure 2).

To check the validity limits and general accuracy of the prediction rules, an extensive set of simulations has been performed.

2 SIMULATIONS

2.1 SEA model

The vibration transmission across the single and double wall junctions is modeled using an SEA model. While the influence of the modal behaviour of the plates may be important, like shown by finite element models [3, 4], spectral finite element models [7] and wave based models [3, 6], SEA modeling is suitable to investigate general trends. The SEA model for the double wall junctions is described in detail in [5]. The model assumes homogeneous, acoustically thin plates and unpinned junction lines. Each plate is represented by three subsystems to incorporate bending, quasi-longitudinal, and in-plane transverse waves. The coupling loss factors are determined from wave theory for semi-infinite plates under the assumption of diffuse vibration fields. An offset has been taken into account for the double walls, equal to half the thickness of the continuous floor or wall, as this proved important when validating the model with measurement results [3].

2.2 Input for Monte Carlo simulations

The direction average velocity level difference has been calculated for 16 different floors/walls (table 1), resulting in a set of 240 Π- and H-junctions. Originally, the model was used to investigate horizontal Π- and H-junctions composed of concrete floors and different types of double walls. Afterwards, the analysis was extended to Π- and H-junctions representing a vertical junction of single and double walls. In this way, also mass ratio's $m_3/m_1 \gg 1$ are included in the investigation. As the cavity thickness does not significantly influence the vibration reduction index [5], it was kept constant at 5 cm.

Table 1. Plate properties

	Thickness t [cm]	Density ρ [kg/m^3]	Young's modulus E [$\times 10^9$ Pa]	Poisson's ratio ν [-]	Loss factor η [-]
Concrete	12; 20; 28*	2500	33	0.2	0.015
Concrete bricks	9; 14	1700	20	0.2	0.015
Aerated concrete	10; 15	650	1.8	0.2	0.015
Sandlimestone	15; 24	1800	16	0.2	0.015
Sandlimestone brickwork	15	1300	11	0.2	0.015
Gypsum blocks (lightweight)	10	900	5.4	0.2	0.015
Gypsum blocks (heavyweight)	10	1100	6.6	0.2	0.015
Masonry bricks (lightweight)	9; 14	800	2.8	0.2	0.015
Masonry bricks (heavyweight)	9; 14	1200	3.7	0.2	0.015

* not used for the double walls (plates 3-6)

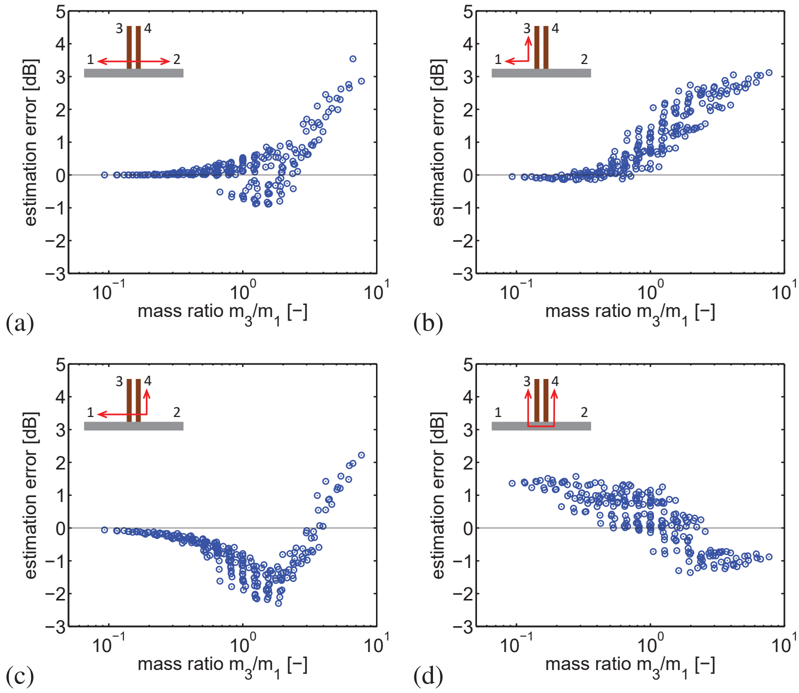


Figure 1. Estimation error as a function of the mass ratio m_3/m_1 for the average vibration reduction indices over $200-1250\,\mathrm{Hz}$ of the double wall Π-junction, when modeled as an equivalent single wall X-junction.

2.3 Simulation results

2.3.1 Double wall Π-junction

The double wall Π-junction can be relatively well approximated by an equivalent single wall X-junction of which the walls have the same mass as the cavity leafs of the double wall. Figure 1 shows the estimation error (i.e. $K_{ij,X'} - K_{ij,\Pi}$) for the average vibration reduction index over the frequency bands $200-1250\,\mathrm{Hz}$ as a function of the mass ratio m_3/m_1 for the different flanking paths.

For the transmission paths 1-2 (figure 1a), 1-3 (figure 1b) and 1-4 (figure 1c), the estimation error is negligible when the double wall leafs are much lighter than the single walls ($m_3/m_1 \ll 1$). The discrepancy between the Π- and X'-junction becomes larger for increasing mass ratio m_3/m_1. For the path 1-3 (figure 1b) the equivalent single wall X-junction gives an overestimation of the average vibration reduction index up to 3 dB. The average vibration reduction index of path 1-4 (figure 1c) is estimated by the equivalent X'-junction with an accuracy of 2 dB. It can be noted that the difference $K_{ij,X'} - K_{ij,\Pi}$ is always larger for the path 1-3 than for the path 1-4, because the vibration reduction index $K_{14,\Pi}$ is always larger than $K_{13,\Pi}$ and the same estimation $K_{13,X'}$ is used. For the transmission path 3-4 between the double wall leafs (figure 1d), the estimation error decreases from $+1.5\,\mathrm{dB}$ (i.e. an overestimation) for $m_3/m_1 \ll 1$ to approximately $-1\,\mathrm{dB}$ (i.e. an underestimation) for $m_3/m_1 \gg 1$.

2.3.2 Double wall H-junction

Figure 2 shows the estimation errors for the average vibration reduction indices for the three equivalent single wall X-junctions used as approximation for the double wall H-junction in function of the mass ratio m_3/m_1.

Generally, the X-junction that uses an equivalent single wall with double the thickness of the double wall leafs (red) does not give a good estimation of the vibration reduction index when the transmission path includes at

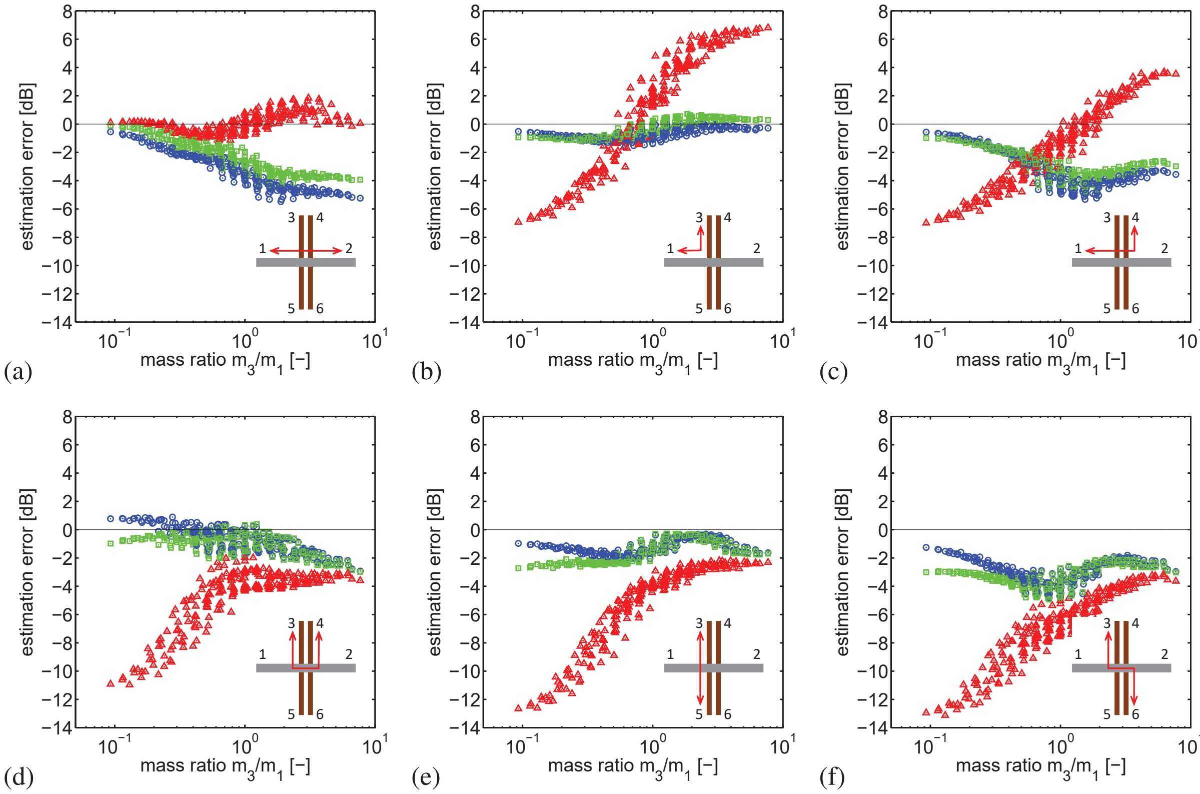


Figure 2. Estimation error as a function of the mass ratio m_3/m_1 for the average vibration reduction indices over $200-1250\,\text{Hz}$ of the double wall H-junction, when modeled as an equivalent X-junction with single walls having the same thickness/density (blue), double thickness (red) or double density (green) compared to a single cavity wall leaf of the H-junction.

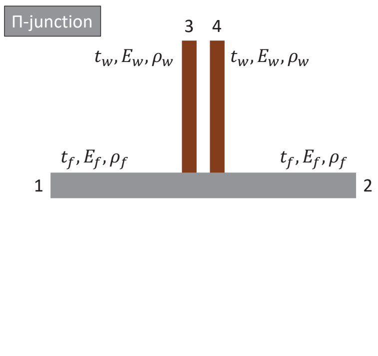
least one double wall leaf (figures 2b-2f). The vibration reduction index is largely underestimated for small mass ratio's m_3/m_1. When the mass ratio increases, the underestimation becomes smaller for the transmission paths including two double wall leafs (figures 2d-2f). For the transmission paths including only one double leaf wall (figures 2b-2c), the equivalent X-junction with double thickness gives an overestimation of the vibration reduction index when $m_3/m_1 > 1$.

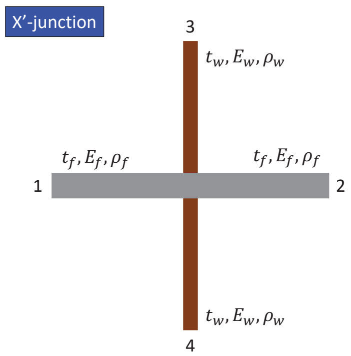
The transmission paths that include at least one double leaf wall can be best approximated by the equivalent X-junctions with same thickness/density (blue) or double density (green) (figures 2b-2f). On average, the transmission path 1-3 (figure 2b) is underestimated by 1 dB by the equivalent X-junction with same thickness/density. For the transmission paths 3-4 (figure 2d) and 3-5 (figure 2e), the vibration reduction indices are generally underestimated by 1 to 2 dB. For the transmission paths 1-4 (figure 2c) and 3-6 (figure 2f), the models with same thickness/density (blue) or double density (green) give a slight underestimation for small mass ratio's m_3/m_1, but the average K_{ij} is underestimated by up to 5 dB for mass ratio's close to 1.

2.4 Prediction rules

For Belgian construction practices, the cases for which the double wall leafs are lighter than the continuous plate of floor ($m_3/m_1 < 1$) are the most relevant. Table 2 gives empirical prediction rules that are derived from the Monte Carlo simulation results in the range $m_3/m_1 < 2$. The aim is to provide prediction rules as simple as

Table 2. Prediction rules for double wall Π− and H-junctions with $m_3/m_1 < 2$

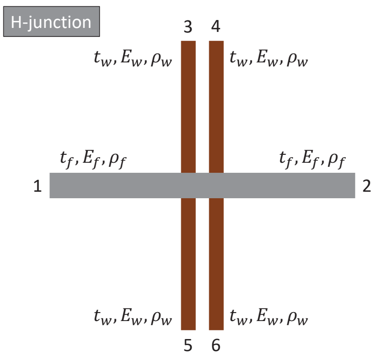


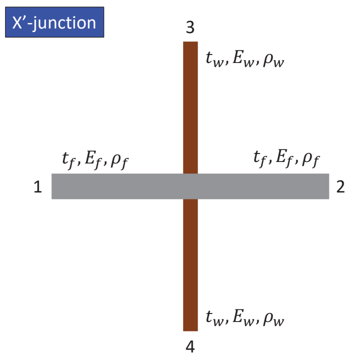


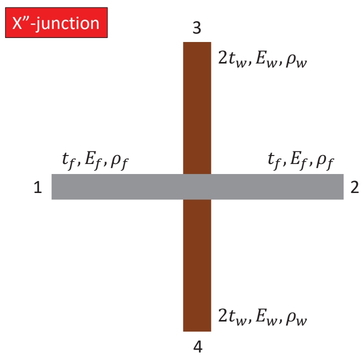
$$K_{12,\Pi} = K_{12,X'}$$

$$K_{13,\Pi} = K_{14,\Pi} = K_{13,X'}$$

$$K_{34,\Pi} = K_{34,X'}$$







$$K_{12,H} = K_{12,X''}$$

$$K_{13,H} = K_{13,X'} + 1\,\text{dB}$$

$$K_{14,H} = \max \begin{cases} K_{13,X'} + 1\,\text{dB} \\ K_{13,X''} \end{cases}$$

$$K_{34,H} = K_{34,X'}$$

$$K_{35,H} = K_{34,X'} + 1\,\text{dB}$$

$$K_{36,H} = K_{34,X'} + 2\,\text{dB}$$

possible while limiting the estimation errors. Especially a large overestimation of the vibration reduction index needs to be avoided for robust design practice.

For the double wall Π-junction, the rules of table 2 concur with the approximation given in annex J of ISO 12354-1 [1]. While these rules generally give accurate estimations for the vibration reduction indices $K_{ij,\Pi}$ when $m_3/m_1 < 2$ (with a maximum overestimation of 1 dB), the overestimation is more significant when $m_3 \gg m_1$. For transmission path $1-3$, the overestimation can already reach 2 dB when $m_3/m_1 > 1$.

For the double wall H-junction, the newly developed prediction rules give a maximum overestimation of 1 dB when $m_3/m_1 < 2$. The underestimation can be larger, with values up to 3 dB in some specific cases. The transmission paths $1-4$ and $3-6$ proves most difficult to predict, as all three equivalent X-junction give large

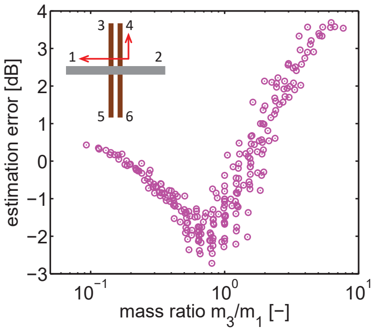


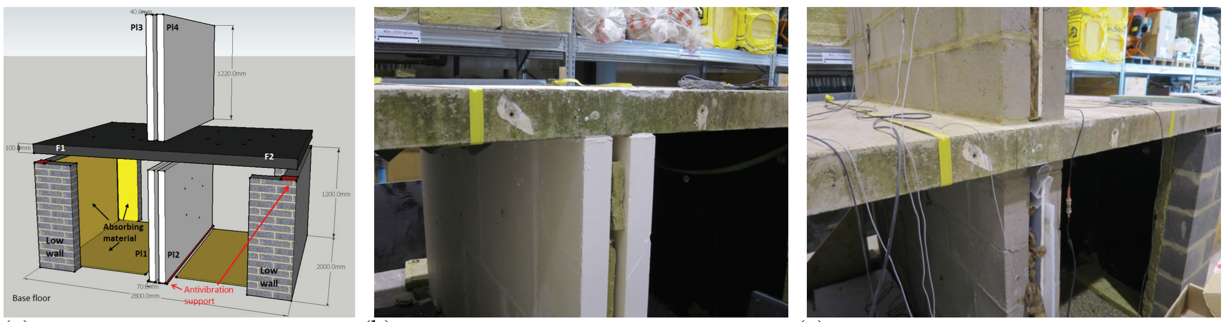
Figure 3. Estimation error as a function of the mass ratio m_3/m_1 for the average vibration reduction indices $K_{14,H}$ over $200-1250$ Hz of the double wall H-junction when using the estimation of table 2

underestimations when $m_3 < m_1$ (figures 2c and 2f). To minimize the underestimation of $K_{14,H}$, it is suggested to use the maximum of (i) the K_{ij}-value for the case with same thickness/density (blue) plus 1dB and (ii) the K_{ij}-value for the case with double thickness (red). By use of this new proposal, the underestimation can be limited to 3 dB (figure 3). For the path $3-6$, it is suggested to use the K_{ij}-value for the equivalent X'-junction with same thickness/density augmented by 2 dB.

3 EXPERIMENTAL VALIDATION

To validate the models and prediction rules of table 2, vibration reduction index measurements have been carried out on a half scaled test bench (figure 4a). A first series of measurements (figure 4b) was performed on junctions composed of a continuous concrete floor ($t_f = 0.10$ m, $m_1 = 230$ kg/m^2) and single and double gypsum block walls ($t_w = 0.07$ m, $m_3 = 65$ kg/m^2) [3]. A second series (figure 4c) was performed on junctions with a continuous concrete floor ($t_f = 0.10$ m, $m_1 = 230$ kg/m^2) and concrete block walls ($t_w = 0.09$ m, $m_3 = 198$ kg/m^2). The measured average vibration reduction indices over the frequency range 400 Hz $-$ 2.5 kHz (corresponding to 200 Hz-1250 Hz in real scale) for the double wall junctions are summarized in table 3, together with the estimated values from the measured vibration reduction indices for the equivalent single wall X'-junction and the estimation errors. Because an equivalent X"-junction with double thickness walls has not been measured, the prediction rules for paths $1-2$ and $1-4$ of the H-junction cannot be validated.

In general, the vibration reduction indices of the gypsum block double wall junctions are slightly overestimated



(a) (b) (c)

Figure 4. Measurement set-up of a gypsum block double wall Π-junction (b) and a concrete block double wall H-junction (c) on a half scaled test bench for vibration transmission measurements [3].

(on average 1.2 dB), while the simulations suggest a better agreement for this small mass ratio of $m_3/m_1 = 0.28$. The largest estimation error is found for the wall-wall path $K_{34,\Pi}$. This could be expected as the simulations also indicate that the prediction rule for $K_{34,\Pi}$ gives an overestimation for the smaller mass ratio's.

The absolute values of the estimation error are larger for the concrete block double wall junctions, but generally on the safe side (i.e. an underestimation of the vibration reduction index). This larger uncertainty is in accordance with the larger spread in the simulation results around this mass ratio $m_3/m_1 = 0.86$.

Table 3. Measurement results (arithmetic average of K_{ij} between 400 Hz and 2.5 kHz)

Gypsum blocks			Concrete blocks		
double wall measurement	estimation from $K_{ij,X'}$ measurement	over-estimation	double wall measurement	estimation from $K_{ij,X'}$ measurement	over-estimation
$K_{12,\Pi} = 6.8$ dB	$K_{12,X'} = 8.0$ dB	+1.1 dB	$K_{12,\Pi} = 6.4$ dB	$K_{12,X'} = 8.4$ dB	+2.0 dB
$K_{13,\Pi} = 15.1$ dB	$K_{13,X'} = 16.4$ dB	+1.3 dB	$K_{13,\Pi} = 11.1$ dB	$K_{13,X'} = 11.0$ dB	−0.2 dB
$K_{14,\Pi} = 15.9$ dB	$K_{13,X'} = 16.4$ dB	+0.5 dB	$K_{14,\Pi} = 12.1$ dB	$K_{13,X'} = 11.0$ dB	−1.2 dB
$K_{34,\Pi} = 18.2$ dB	$K_{34,X'} = 21.7$ dB	+3.5 dB	$K_{34,\Pi} = 14.8$ dB	$K_{34,X'} = 14.4$ dB	−0.4 dB
$K_{13,H} = 16.2$ dB	$K_{13,X'} + 1 = 17.4$ dB	+1.1 dB	$K_{13,H} = 14.6$ dB	$K_{13,X'} + 1 = 12.0$ dB	−2.6 dB
$K_{15,H} = 18.3$ dB	$K_{14,X'} + 1 = 20.0$ dB	+1.7 dB	$K_{15,H} = 12.7$ dB	$K_{14,X'} + 1 = 13.5$ dB	+0.8 dB
$K_{34,H} = 20.5$ dB	$K_{34,X'} = 21.7$ dB	+1.2 dB	$K_{34,H} = 18.5$ dB	$K_{34,X'} = 14.4$ dB	−4.1 dB
$K_{35,H} = 22.1$ dB	$K_{34,X'} + 1 = 22.7$ dB	+0.6 dB	$K_{35,H} = 17.3$ dB	$K_{34,X'} + 1 = 15.4$ dB	−1.9 dB
$K_{36,H} = 23.6$ dB	$K_{34,X'} + 2 = 23.7$ dB	+0.1 dB	$K_{36,H} = 18.4$ dB	$K_{34,X'} + 2 = 16.4$ dB	−1.9 dB

4 SUMMARY AND CONCLUSIONS

Simplified formulae are proposed for the vibration reduction index of rigid double wall Π- and H-junctions. They allow to estimate the vibration reduction index of double wall junctions using existing semi-empirical formulae for rigid, single wall junctions. The empirical rules are determined from Monte Carlo simulations carried out with a statistical model. The simulation results indicate that the estimations are most accurate when the mass ratio m_3/m_1 is small, meaning that the double wall junction can be well represented by an equivalent single wall junction as long as the double wall leafs are relatively light compared to the continuous single floor or wall. The simplified formulae have been validated by two sets of vibration reduction index measurements. For the double gypsum block walls, the rules give an average overestimation of the double wall vibration reduction index of 1.2 dB. For the double concrete block walls, the vibration reduction index is generally underestimated with an average absolute estimation error of 1.7 dB. Future research should investigate whether these estimations can also be used for asymmetric junctions and junctions including elastic interlayers.

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