Low audio frequency vibration performance of common isolation configurations for bolted connections

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ABSTRACT

Resiliently treated bolted connections are being increasingly utilised as the demand for high density housing is combined with the increasing requirements of acoustic comfort for occupants. The typical design of a bolted connection is for an oversized hole in the equipment bracket or cleat combined with a sandwiched elastomeric pad with resilient sleeve and washer to prevent any metal on metal contact. However, the use of a sleeve and washer, which often contain different stiffness characteristics to the pad, will compromise the theoretical attenuation through the connection and the expected performance loss is difficult to calculate due to a number of variables. In this paper, the vibration transfer through a bolted connection between a steel beam and concrete structure was investigated at low audio frequencies using a number of commonly used isolation configurations, along with correct and incorrect installation. An out of balance motor with variable speed was used to excite the beam at low frequencies, and a large speaker used at a higher frequency. In order to minimise flanking paths, the end of the beam with the bolted connection was placed on the structure, and the other end supported on a separate structure. Vibration levels were measured both on the steel beam and on the concrete structure directly adjacent to the connection, in order to determine the level of vibration transfer and the frequency domain characteristics relative to a rigid connection.

1 INTRODUCTION

The use of resilient material between structural connections to reduce vibration transmission is a common treatment in Australia and New Zealand. The main purpose is to prevent low audio range frequency structure-borne noise being regenerated in an adjacent space due to a source of vibration. Examples of such sources may be rain noise on a roof or mechanical equipment impacts such as those from a carstacker.

Designing a flexible connection that still provides the necessary restraint required presents a number of challenges. Bolted connections can be implemented without creating metal-on-metal contact which would bridge the connection; however this often requires the use of stiffer resilient components to be practically implemented. Figure 1 displays a typical isolated bolt detail using an isolation sleeve and rubber washer.

The arrangement in Figure 1 is an inexpensive solution that prevents rigid contact between the equipment base plate and the bolt with the use of a flexible sleeve around the bolt inserted into an oversized hole in the equipment base plate, and a flexible washer under the steel washer. The effect that an isolated bolt has on vibration transmission performance is hard to quantify due to a number of factors, including connection design, installation procedure, flexibility of the sleeve and washer material, and the tightening torque required. An isolated bolted connection can easily be compromised by inappropriate design of the connection for the application, or incorrect installation. Resonant frequencies of the structural steel will also affect the vibration transmission through the connection.

The stiffness of a typical pad used in this application will result in a natural frequency of approximately 15-25 Hz when loaded correctly. According to single degree of freedom vibration isolation theory, significant transmission reduction would be expected to occur from input frequencies above 40 Hz, and the inherent damping in a typical building structure is expected to significantly reduce the ideal transmission at frequencies higher than 80 Hz (Thornely-Taylor, 2017).

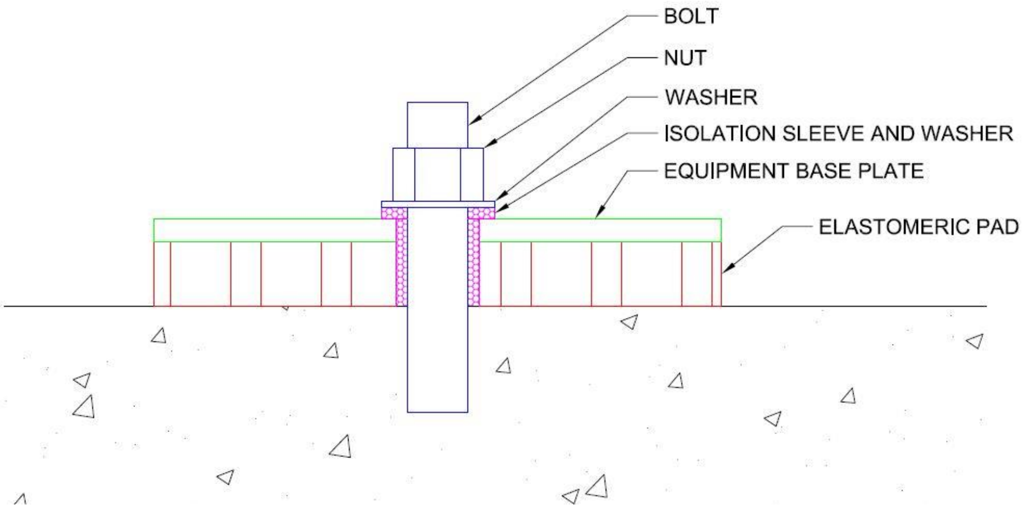

Figure 1: Typical isolated bolt detail

The transfer of vibration through a bolted connection was investigated using a steel beam fixed to a concrete slab via a drop in anchor. Several different connection designs were tested in order to investigate the effect common configurations and installations would have on vibration transfer.

2 METHODOLOGY

The basic test configuration consisted of the steel parallel flange channel (PFC) supported at both ends only. At one end the PFC is fixed to the slab through a single bolt, and the other end rested on a block placed off the slab. The isolation material was placed between the PFC and slab at the bolted connection. One accelerometer was placed adjacent to the bolted connection on the concrete slab, and a second accelerometer adjacent to the bolted connection on the PFC. The beam had structural mass of approximately 36 kg, and additional non-structural mass of 75 kg was placed towards the bolted connection end in order to provide the necessary loading on the pad but prevent the fundamental bending mode of the beam from being in close proximity to the expected pad resonance.

Individual vibration measurements were taken in 1/3rd octaves, at forcing frequencies of 40 Hz, 50 Hz and 80 Hz for all test configurations. A variable speed, out of balance motor was used for the 40 Hz and 50 Hz tests, and a loud speaker with an acoustic enclosure (to minimise flanking paths) for the 80 Hz tests. Accelerometers were placed above and below the resilient connection. Acceleration was measured in the direction of pad compression only, as typically the connection will be designed to isolate forces applied in the compression direction. The ribbed geometry of the pad allows control of the bulging and compressive stiffness, however this results in greatly reduced shearing strength and stiffness. A simplified section view of the pad geometry is shown in Figure 2, and the test setup can be seen in Figure 3 and 4.

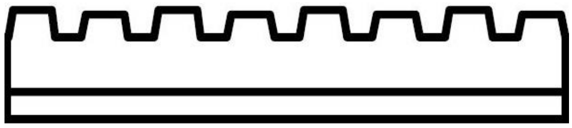

Figure 2: Simplified cross section of elastomeric pad geometry

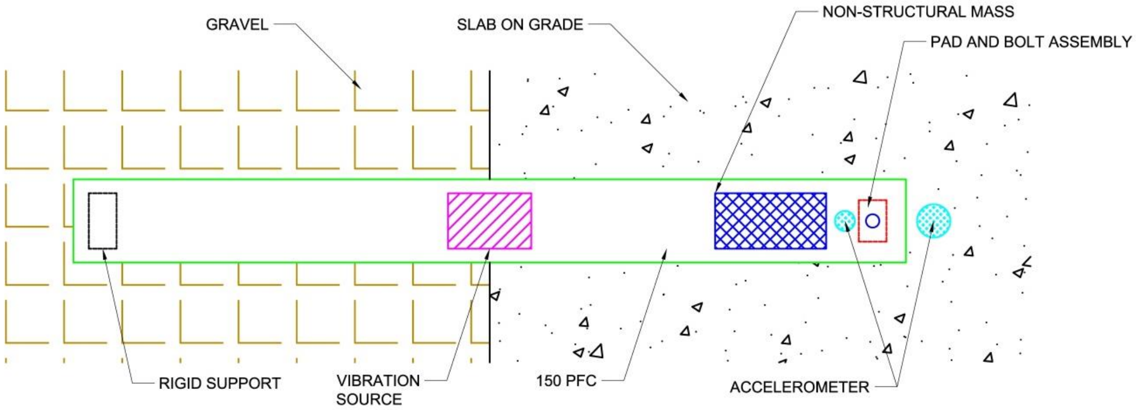

Figure 3: Plan view of configuration

Figure 4: Test setup with acoustic enclosure and accelerometer positions

It was expected that the results would be affected by the resonant frequencies of the beam due to both multiple degree of freedom effects and the likelihood of one or more beam resonances occurring in close proximity with the driven frequencies. A true laboratory test of the transmission through the pad and bolted connection would remove the existence of the beam and have the bolted connection under a stiff plate with the source mounted directly on top. However, this would overstate the performance of the pads for the application, and the effects that occur due to resonances of the beam are a realistic component of this isolation system in practice. To further investigate these effects, a simulated modal analysis was conducted of the beam in one test configuration (Section 4.2).

Placing the opposite end of the PFC off the slab minimised the vibration transfer between the free end of the beam and the concrete slab. Vibration levels were measured at multiple locations in the concrete slab between the bolted connection and the edge of the slab to determine the amount of vibration in the slab due to ground based flanking paths, rather than through the bolted connection. It was found that flanking vibration was not a significant source of vibration in the slab at the point of measurement.

3 TEST CONFIGURATIONS

A total of six different connection configurations were tested for this paper, each configuration is shown in Figure 5.

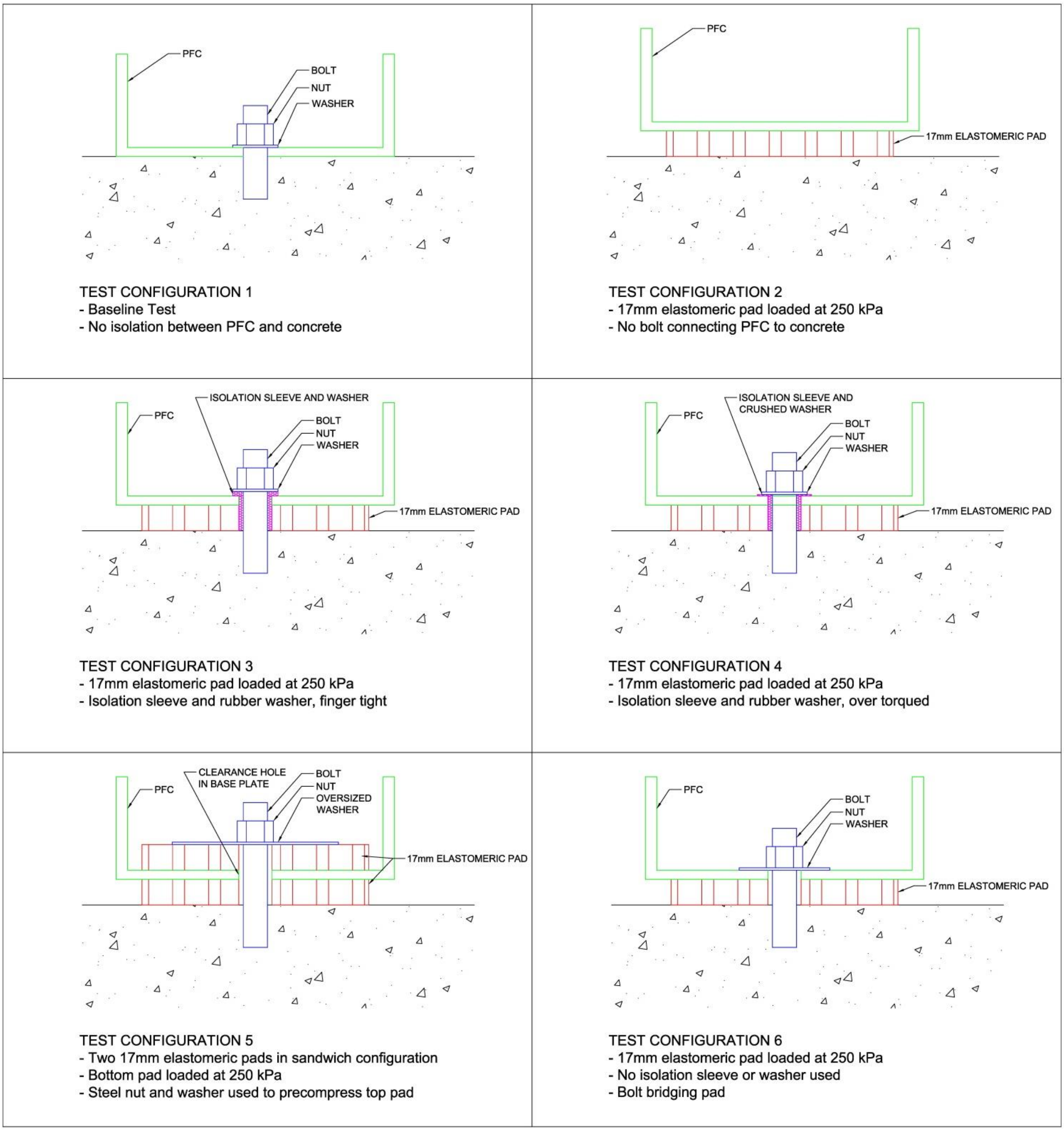

Figure 5: Section view and description of each connection configuration

It was expected that maximum vibration transmission levels would be observed in the baseline test (configuration 1), and minimum transmission levels for configuration 2, which with the absence of the bolt, washer and sleeve has no stiffer components to compromise the connection. Configuration 3 with the isolation sleeve installed with minimal pressure on the resilient washer was expected to perform similarly to configuration 2. Configurations 4 and 6 represent poor installation and configuration 5 replaces the resilient washer with a second pad. The addition of a second pad of the same size doubles the effective stiffness of the isolation system when compared to using one pad only. This configuration is required for isolating connections through vertical surfaces, or fixing to a soffit.

4 RESULTS AND ANALYSIS

4.1 Theoretical and Practical Attenuation

To illustrate the beam effects, the theoretical damped vibration transmission can be calculated using Equation 1. While this equation is not appropriate in a multiple degree of freedom problem such as the test setup configured here, it provides a simplified reference due to its frequent application in the vibration control field.

$$T = \sqrt{\frac{1+\left(2\zeta\frac{f}{fn}\right)^2}{\left(1-\left(\frac{f}{fn}\right)^2\right)^2+\left(2\zeta\frac{f}{fn}\right)^2}} \quad (1)$$

f: *Driven Frequency*
f_n: *Isolator Natural Frequency*
ζ: *Damping Ratio*

The 17mm pad used has a known natural frequency of approximately 24 Hz in the compression axis under 250 kPa, and a damping factor of 0.13. Using Equation 1 above, the theoretical vibration transmission percentage through the pad only is shown in Table 1 for the frequencies tested, and compared to the measured vibration levels for each test configuration, normalised to the baseline test. In all cases, a clear peak of vibration levels could be observed on either side of the bolted connection at the input frequency's 1/3rd octave band.

Table 1: Vibration transmission percentage for each test configuration

Test Configuration	40 Hz	50 Hz	80 Hz
Theoretical (Equation 1)	59.6%	33.6%	13.0%
1 - Baseline	100.0%	100.0%	100.0%
2 - 17mm Pad - Not Bolted	16.9%	22.7%	16.4%
3 - 17mm Pad - Bolted with IS	28.4%	29.6%	16.1%
4 - 17mm Pad - Bolted with crushed IS	63.9%	83.1%	46.2%
5 - 17mm Pad Sandwich - Bolted	36.7%	38.5%	27.6%
6 - 17mm Pad - Bridged Bolt	81.4%	102.1%	41.9%

The trend in transmission percentages between test configurations are in line with what would be expected, with configuration 2 (no bolt) providing the most effective isolation, and varying increased vibration transmission levels for all other configurations. Of particular interest are the results of the crushed isolation sleeve and the bridged bolt, with both configurations showing a significant increase in transmission levels compared to the correctly isolated configurations 2, 3 and 5.

Low vibration transmission values with respect to theoretical were observed for the 40 Hz tests for configurations 2, 3 and 5. The 50 Hz tests transmission percentages were also lower than expected when compared to the theoretical transmission for configurations 2 and 3, while the 80 Hz results were closer to the values calculated with Equation 1.

Determining the cause of the better than theoretically predicted isolation performance in the 40 Hz tests is outside the scope of this paper; however it is likely due to the interaction between the input forcing frequencies and the PFC's mode shapes, as well as the baseline configuration having a shifted set of natural frequencies due to the removal of the degree of freedom provided by the pad. Additionally, normalization of the baseline test, which is useful when assessing relative performance, infers that there is no attenuation through a rigidly bolted connection.

The vibration attenuation results for all test configurations relative to the baseline test are shown in Table 2.

Table 2: Vibration attenuation results for each configuration

Test Configuration	Attenuation compared to Baseline (dB)		
	40 Hz	50 Hz	80 Hz
1 - Baseline	-	-	-
2 - 17mm Pad - Not Bolted	15.4	12.9	15.7
3 - 17mm Pad - Bolted with IS	10.9	10.6	15.7
4 - 17mm Pad - Bolted with crushed IS	3.9	1.6	7.0
5 - 17mm Pad Sandwich – Bolted	8.7	8.3	11.2
6 - 17mm Pad - Bridged Bolt	1.8	-0.2	7.6

The results show the expected trend in terms of vibration transfer, with the highest attenuation achieved by having no mechanical fixing between the PFC and concrete, followed by the correct installation of a bolted connection using an isolation sleeve. Overtightening of an isolation sleeve, or not using one at all, results in little isolation at 40 and 50 Hz, with attenuation only slightly better than if no pad was used at all.

The performance at 80 Hz is significantly better in all test configurations when compared with the performance at 40 and 50 Hz. Values were more consistent with equation 1 for configuration 2 and 3.

In the case of the correctly installed isolation sleeve in configuration 3, the nut has been tightened to finger tight only. The isolation sleeve and washer prevents the bolted connection from bridging the pad by having a flexible material between the bolt and the PFC, with no rigid contact between the bolt and the PFC. When the pad is located on a horizontal surface, gravity forces the isolated mass to load the pad into compression, as such no more than light pressure from a self-locking nut onto the resilient washer is required. The level of vibration transfer through this connection configuration is higher than for configuration 2, but is significantly lower than for similar configurations where either there is no isolation sleeve and a bridging bolt, or the isolation sleeve has been over tightened.

The results for configurations 4 and 6 demonstrate the importance of preventing rigid contact within a bolted connection when a pad is used for vibration isolation. Despite the presence of the pad, the attenuation of vibration levels in these two configurations is minimal at 40 and 50 Hz compared to the baseline test, consisting of no isolation element at all. Overtightening of the isolation sleeve and washer, or the use of no sleeve at all results in a rigid connection between the PFC and nut, allowing significantly increased vibration transfer between the PFC and concrete slab.

Configuration 5, comprising of the PFC sandwiched between two isolation pads is a common configuration when pads are mounted vertically, or where the connection needs to provide restraint against uplift. However, this configuration effectively doubles the stiffness of the isolation system in configuration 2 and 3, and hence vibration transfer is expected to increase. This is shown in the results, with attenuation levels slightly below that of configuration 3, but still significantly above the configurations where a rigid connection has been formed through the incorrect installation or omission of an isolation sleeve and rubber washer. Configuration 5 is also less susceptible to overtightening of the connection resulting in a significant drop in isolation effectiveness.

4.2 Modal Analysis Results

A simulated modal analysis of configuration 2 was conducted using Strand7 to investigate the indicative effects of beam resonances on results. Beam resonance locations on the frequency spectrum will vary with every installation; however structural beam modes will commonly occur in a similar range of values and pattern to the test case investigated here. As with the accelerometer data, the direction of interest for the output is the axis of pad compression.

The following parameters were employed to simulate the test configuration shown in Figure 3.

- 150 PFC beam supported at two ends
- First end fixed in translation and rotation in yaw and roll but free to pitch.
- Second end supported on spring element - spring element connected to fixed node

- Spring element dynamic stiffness of 2.17 kN/mm
- Spring element damping ratio of 0.13
- Non-structural mass of 75 kg added in approximate replication of test conditions.
- Vibration source located at the centre of beam

Modal analysis results are shown in Table 3 with mass participation percentage in the vertical direction. Torsional modes and modes with zero participation in the direction of interest (vertical) were ignored.

Table 3: Modal Analysis results

Mode No.	Frequency (Hz)	Mass participation (vertical direction)
1	15	76.5%
2	38	13.5%
3	57	4.2%
4	127	1%

From Table 3, the coupling of the pad and beam has seen the first mode shift down from 24 Hz, the expected pad resonance in a one-degree of freedom system, to 15 Hz. The bending modes of the beam strongly influence the second and third modes.

A harmonic response analysis of the fixed node's reaction force under the spring element enabled simulation of the influence of system's modes on the level of force likely to be transmitted through to the connected structure at a given frequency. The magnitude of reaction shown at each data point in Figure 6 is arbitrary, as the input force at each frequency was constant.

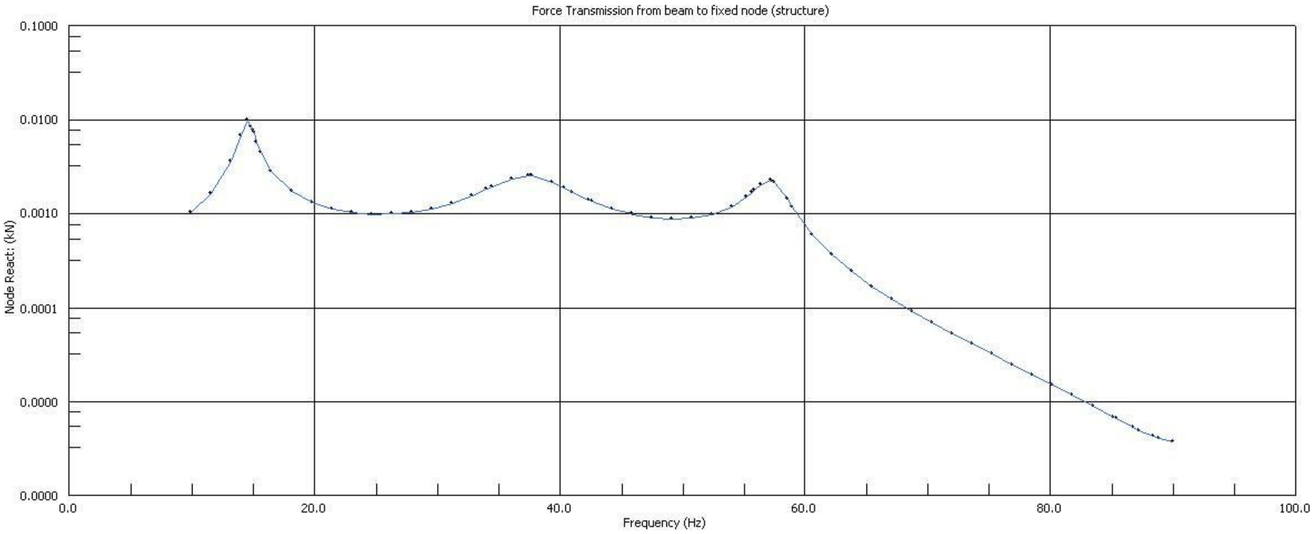

Figure 6: Reaction force at fixed node under spring element from beam excitation

The location of peaks in the transmission graph above was expected to vary with the results of the physical test setup due to differences in damping and non-structural mass properties. The existence of peaks near the test input frequencies of 40 Hz and 50 Hz demonstrates how the transmission at these two frequencies could be similar, as measured during testing, and in contrast to Equation 1, where a higher ratio of driven to isolator natural frequency will always result in lower transmission once the ratio exceeds 1. The drop-off in force transmission at 80 Hz was expected from the mode locations, however the relative value of force transmitted at 80 Hz to 40 and 50 Hz was many times lower than values listed in Table 1, qualified to some extent by the existence of background vibration levels and airborne influences in testing, further discussed in 4.3.

4.3 Airborne Effects

The 80 Hz tests were initially conducted using a loudspeaker placed on the PFC. This arrangement allows airborne noise to affect the results by causing vibrations in the slab that are not due to the vibration of the beam. In order to measure the vibration in the slab from the airborne transmission path, the PFC arrangement was modified to allow the loudspeaker to be placed in the same position relative to the accelerometer, but with the PFC cantilevered out from the non-bolted end, with no contact between it and the slab. These vibration levels were then compared with the results from configuration 2, which was expected to produce the lowest levels of vibration transfer of all configurations. It was found that the vibration levels in the slab due to airborne effects were significant when compared with the transfer through the bolt, and an acoustic enclosure around the loudspeaker was constructed to minimize this effect. The acoustic enclosure consisted of a 19mm plywood box with 50mm acoustic insulation lining the inside, and surrounded five sides of the loud speaker. For ease of removal, the bottom of the enclosure remained open; however acoustic insulation was used under the enclosure to minimise flanking transmission. The acoustic enclosure test setup can be seen in Figure 4.

A repeat of the airborne effects test was performed with the acoustic enclosure, and the vibration increase measured by the accelerometer on the slab from connecting the beam to the slab through bolted connection end of the PFC compared to airborne effects only is shown in Table 4.

Table 4: Vibration level increase due to transfer through bolted connection

Test Configuration	Acceleration Increase Due to Connection, 80 Hz (dB)
1 – Hard-bolted	20
2 - 17mm Pad - Not Bolted	10
3 - 17mm Pad - Bolted with IS	13
4 - 17mm Pad - Bolted with crushed IS	15
5 - 17mm Pad Sandwich - Bolted	15
6 - 17mm Pad - Bridged Bolt	17

The results with the acoustic enclose show that vibration levels due to transfer through the connection are at least 10 dB above background vibration levels for all configurations, with background vibration levels taken to include the effects of airborne transmission. This is sufficiently above background levels that the airborne transmission path for the 80 Hz tests can be ignored. The background vibration levels were also taken for the 40 Hz and 50 Hz tests where an out of balance motor was used as the input, and all configurations resulted in a vibration level at least 40 dB above background levels.

5 CONCLUSION

Vibration transfer levels at low range audio frequencies were measured through an isolated bolted connection under a number of test configurations, representing common installation conditions. The lowest transfer levels were found in the ideal case, with no bolt used, and a slight drop off in isolation performance if an isolation sleeve and washer was used in conjunction with a bolt and installed correctly. A significant increase in vibration transfer was observed for test configurations where the system was effectively bridged, either through poor installation or connection design, with vibration levels similar to that of a hard bolted connection. The use of a sandwich pad configuration was also investigated, with vibration transmission measured to be worse than that of the correctly installed single pad configurations, but well above that of the over torqued or bridged test configurations. This is likely due to the additional stiffness that the second pad adds to the system compared to the single pad configurations.

The theoretical vibration transfer through an elastomeric pad was also calculated for the tested frequencies and compared with the measured results, with a large discrepancy present. This variance between measured and theoretical results is not unexpected given the testing setup, which was designed to simulate realistic bolted connections rather than to eliminate all possible variables in order to approach the ideal case. The modal shapes of the testing configuration and resonant frequencies were investigated using FEA to discuss possible causes for the difference between the theoretical and measured results.

The results presented in this paper show the importance of correctly designing and implementing isolated bolted connections in order to provide effective isolation. A poorly designed or installed isolated connection results in vibration transfer levels similar to a hard bolted connection.

REFERENCES

Thornely-Taylor, Rupert. 2017. 'Evaluating Uncertainty in the Prediction of the Performance of Base-Isolation Systems Designed to Reduce Groundborne Noise in Buildings' *24th International Congress on Sound and Vibration*. London, United Kingdom