Mitigation of Train-Induced Floor Vibrations in Multi-Story Buildings Using a Blocking Floor

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ABSTRACT

A new method is developed for reducing train–induced floor vibrations in buildings. Vibration transmitted through building columns to the upper floors can be mitigated by considerably increasing the thickness of a lower floor, which is named the “blocking floor”. This can be a desirable and inexpensive solution for vibration mitigation. The work presented by this paper shows the ability of an impedance-based wave propagation model to capture the blocking floor behavior by comparing the analytical predictions of the velocity rations with the measured velocity ratios in the frequency domain. A 4-story scale model building was designed and constructed for measuring floor vibrations induced by excitations at the base. The effectiveness of using different blocking floors with different thicknesses in the scale model to mitigate vibrations was examined. Additionally, a sandwich floor with an integral damping layer was added to the scale model building to examine the effect of enhanced energy dissipation in the blocking floor slab.

INTRODUCTION

In recent years, the exploitation of air-rights construction has resulted in buildings being subjected to potentially disturbing vibrations from urban rail lines and roadways. Building owners and engineers are concerned about occupant complaints related to structure-borne noise and vibration. Human hearing is in the range of 20 Hz to 20 kHz that varies based on age and environmental conditions. Similar concerns exists for laboratory buildings that contain sensitive equipment. Until recently no simple predictive model exists to predict how vibrations will dissipate as they travel up in a building.

Previous researchers at Tufts University and Acentech, Inc. (Sanayei et al., 2008 and Hughes et al., 2008) have developed a model to predict structure-borne wave propagation vibration in buildings. It was shown in the mathematical model that a ‘blocking floor’ with increased thickness of reinforced concrete floor can substantially
impede vibrations. This approach to vibration mitigation is attractive to designers and owners because it can be achieved with standard construction elements and without jeopardizing the building’s lateral resistance to wind loads. Additionally, for structures where transfer trusses are necessary near the base of the building, these transfer levels may be leveraged as blocking floors without much additional expense.

Tufts University and Acentech Incorporated have developed a simplified one-dimensional mathematical model to predict vibration levels within multi-story buildings (Sanayei et al., 2008). Comparing this mathematical model with data obtained at the TD Banknorth Garden (a 9-story steel framed sports arena) and 675 Massachusetts Avenue in Cambridge Massachusetts (a 15-story reinforced concrete structure), they observed more attenuation in the measure data than what was accounted for in the mathematical model. Additionally, it was shown that the presence of a thicker and heavier floor slab and a deep girder on the third floor in the TD Banknorth Garden provided enhanced impedance that led to a large gap between the second and third floor velocity ratios. These observations stimulated the current work on blocking floors.

A scale model building was designed and constructed by Hughes et al. (2008) at Tufts University for the purpose of testing and modeling the vertical propagation of structure-borne vibrations. The scale model was a 4-story, two-bay by two-bay building, 60” by 60”, with medium density fiberboard (MDF) floors supported by aluminum columns and beams. The scale building model was excited at the base of the center column using a Brüel & Kjær Type 4808 vibration exciter. The direction of the excitation was axially into the column and floor vertical accelerations were measured at the center of each floor on the column. Floor-to-floor attenuation measured in the scale model building was compared to attenuation predictions. The feasibility of mitigating vibration on upper floors by considerably thickening a lower floor was examined. In order to create a thicker first floor, two additional MDF layers were added to the first floor of the scale model building. It was determined and confirmed through mathematical modeling that full continuity was not achieved between all three layers and the bond between MDF layers was not sufficiently rigid so that the overall blocking floor did not behave as a single layer undergoing simple bending, there was a measureable decrease in vibration levels on upper floors.

In the present research a new scale model building was constructed for (a) further investigation of using a full continuous solid blocking floor on a lower level to mitigate vibrations on higher floors, (b) improvement of the physical scale model building at the connections and the composite floor, (b) improvement of the mathematical model using infinite and finite floors.

COMPONENT AND SYSTEM IMPEDANCE MODELING

The mathematical model used to predict vibration propagation models columns as two-node axial wave propagating rods and floors as infinite plates where propagating waves do not reflect (Sanayei et al., 2008). Hughes et al. (2008) added beam elements as transverse bending wave propagating mediums to the infinite plates. Additionally, finite floor slabs were modeled as simply supported, thin, rectangular plates excited by point
forces and approximated in terms of an infinite modal summation using the Bernoulli-Euler beam theory.

For impedance modeling, the dynamic behavior of beams and slabs were included as frequency dependent effective mass with real and imaginary parts. The energy dissipation in all structural elements was represented by a complex modulus with a structural loss factor. The complex stiffness matrix for the system includes the self mass of columns and the effective mass of other attached elements added to the wave propagating column as energy dissipating elements. Infinite or finite beams and floors are interconnected by finite columns. Point force impedance can be expressed as the force to velocity ratio in frequency domain by:

\[ Z = \frac{F}{v} = \frac{kx}{v} = \frac{m_{\text{eff}}a}{v} = \frac{m_{\text{eff}}x(i\omega)^2}{x(i\omega)} = i\omega m_{\text{eff}} \]  

(1)

where variables \( Z, k, m, x, v, a, \) and \( \omega \) represent impedance, stiffness, effective mass, displacement, velocity, acceleration, and circular frequency, respectively. The effective mass represents the dynamic behavior of beams and slabs. The capability of structural components to dissipate energy is represented by the equivalent dynamic stiffness, \( k \):

\[ k = (i\omega)^2 m_{\text{eff}} \]  

(2)

For the whole system, the global dynamic stiffness matrix includes the dynamic stiffness contributed by column and slab elements. The frequency dependent steady state responses of the system subjected to harmonic loading are represented in (3) and (4) by Clough and Penzien (2003).

\[ [K_{\text{col}}] - \omega^2[M_{\text{eff}}] \{U\} = \{F\} \]  

(3)

\[ \{U\} = [K_{\text{col}} - \omega^2 M_{\text{eff}}]^{-1}\{F\} \]  

(4)

where variables, \( F \) and \( U \), are applied forces at column to slab connections at the center column and the corresponding measured displacements; \([K_{\text{col}} - \omega^2 M_{\text{eff}}]\) represents the dynamic system stiffness of the structure.

**Blocking Floor Theory**

As shown by Hughes et al. (2008), the effective mass contributed by the thicker MDF slab (2.25”), which is 3-times thicker than the standard, is roughly 20 dB more than a typical slab (0.75”). The driving point impedance of an infinite plate using the simple bending theory is

\[ Z_{\text{slab}} = 8\sqrt{D}\sqrt{\rho t} = 8t^2 \sqrt{\frac{E}{12(1-\nu^2)}} \sqrt{\rho} \]  

(5)

where variables, \( D, t, E, \) and \( \nu \), are plate modulus, thickness, Young’s modulus & Poisson’s ratio.

\[ D = \frac{Et^3}{12(1-\nu^2)} \]  

(6)

The impedance increases proportional to \( t^2 \), which causes higher vibration attenuation and reduces vibration levels on upper floors. The mathematical model showed that by thickening the first floor, the dynamic properties for the entire system may lead to
decreased vibrations at all floors. Therefore, both the added mass and the added stiffness of thicker floor slabs will be more effective in vibration mitigation. According to Equation 5, added stiffness plays a more significant role than added mass.

**DESIGN OF A SCALE MODEL BUILDING**

In this research, a new five story scale building was constructed for floor vibration testing, FIGURE 1 and FIGURE 2. The slabs used in the scale model buildings were 1,219.2 mm x 1,828.8 mm x 19.05 mm (48” x 72” x 0.75”) medium and low density fiberboards. Aluminum columns were 80/20 Model 25-2525 with a length of 381 mm (15”). The column-slab connections consisted of 8 L-shape 80/20 brackets fixed above and below floor slabs, instead of 4 L-shape brackets fixed below slabs used by Hughes et al. (2008), to provide the best coupling between the floors and columns. The dynamic behavior of the connections was modeled as lumped masses on the column applied one per floor. At higher frequencies, above 1 kHz, the dynamic system response became mass controlled and sensitive to any additional mass lumped on the excited center column. It was crucial to add the masses of the connections to the dynamic stiffness matrix of the system.

![FIGURE 1. SCALE MODEL BUILDING WITH 0.75 INCH MDF ON ALL FLOORS](image1)

![FIGURE 2. LABORATORY SCALE MODEL BUILDING (DIMENSIONS IN INCHES)](image2)

**Impedance Matching**

The scale laboratory model was designed to have the same impedance ratios as a full scale four story building. Properties used for the full scale building were 240 mm (9.45”) for the thickness of the first floor reinforced concrete slab and 120 mm (4.725”) for the higher floors. A W14x90 structural steel column was used for all columns of the full
scale building. Using similar impedance ratios for the scale model building resulted in using a 38 mm (1.5”) thick MDF slab for as the blocking floor and 19 mm (0.75”) thick slabs for all other floors. Aluminum columns of the scale model building were 2.54 mm x 2.54 mm (1” x 1”). Infinite impedance theory is used for comparison of full scale and small scale buildings as shown in TABLE 1 and TABLE 2. These tables illustrate that the impedance ratios for components in the scale model buildings are sufficiently close to a typical full scale building with and without blocking floors so that transmission behavior in the scale models is representative of full scale buildings. Column and slab sizes determined using impedance matching will result in frequency scaling of about 1/10 for the full scale building in comparison to the scale building (Hughes et al., 2008). Therefore a vibration test of the scale model building within the range of 10 to 5 kHz corresponds approximately to 1 to 500 Hz for the typical full scale building.

### TABLE 1. IMPEDANCE COMPARISON OF FULL SCALE AND SCALE MODEL BUILDINGS USING 0.75 INCH THICK MDF

<table>
<thead>
<tr>
<th>Impedance</th>
<th>Full Scale Building</th>
<th>Scale Model Building</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SI (N/m s⁻¹)</td>
<td>US (lb/in s⁻¹)</td>
</tr>
<tr>
<td>Slab</td>
<td>2.62 x 10³</td>
<td>3.02 x 10³</td>
</tr>
<tr>
<td>Column</td>
<td>6.78 x 10⁵</td>
<td>7.81 x 10³</td>
</tr>
<tr>
<td>slab/column Ratio</td>
<td>0.39</td>
<td>0.39</td>
</tr>
</tbody>
</table>

### TABLE 2. IMPEDANCE COMPARISON OF FULL SCALE AND SCALE MODEL BUILDINGS USING 1.5 INCH THICK MDF

<table>
<thead>
<tr>
<th>Impedance</th>
<th>Full Scale Building</th>
<th>Scale Model Building</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SI (N/m s⁻¹)</td>
<td>US (lb/in s⁻¹)</td>
</tr>
<tr>
<td>Slab</td>
<td>9.93 x 10³</td>
<td>1.14 x 10³</td>
</tr>
<tr>
<td>Column</td>
<td>6.78 x 10⁵</td>
<td>7.81 x 10³</td>
</tr>
<tr>
<td>slab/column Ratio</td>
<td>1.47</td>
<td>1.47</td>
</tr>
</tbody>
</table>

### Sandwich Beam Testing

For the purpose of building a sandwich floor in a scale model building, sandwich beams are tested in a free-free beam configuration. In order to examine the mechanism of energy dissipation of a sandwich structure, one layer of shear damping material (3M ISD 112 Damping Polymer) was placed in between two MDF beams. Several 36” long and 2” wide solid and sandwich MDF beams were fabricated and tested. The measure data is used to identify damping properties in a simpler setup. The
sandwich beam properties and damping values will be used to simulate highly dissipative floor element. Test configuration is shown in FIGURE 3. The experimental configuration is as follows: the shaker, SU-3-4 adaptor, Brüel & Kjær type 8230 force transducer, 10/32 rod through the MDF beam, and Brüel & Kjær Type 4384 accelerometer.

Experimental results are presented and discussed for the driving point impedances of damped composite beams made up of a thin viscoelastic layer sandwiched between two elastic layers. The effect of a damping layer is expected to suppress resonant peaks and control excessive vibrations. When the damping layer is constrained on both sides, the extensional stiffness of the damping layer is negligible and shear damping exceeds the extensional damping. Thus, shear mechanism is the predominant damping mechanism. The amplitudes of vibration resonances and anti-resonances are controlled by damping. In order to ensure continuous contact between layers and make the damping layer fully engaged in energy dissipation, they are compressed together using 32 mm (1.25”) drywall screws. Screws are spaced at intervals of 152.4 mm (6”) and 304.8 mm (12”) respectively. Screws may help transfer interface shear between constraining layers, increase flexural rigidity and reduce shear deformation of the damping layer and sandwich beam behavior, which may have a negative effect on energy dissipation.

FIGURE 4. Measured Driving Point Impedances of Sandwich Beams

FIGURE 4 shows measured impedances from sandwich beam tests using two 0.75” MDF beams with ISD 112, and the same setup with 3 screws and 7 screws. The results are also compared to a solid 1.5” MDF beam. Below 1 kHz, composite beams with 3 or 7 screws shows increased damping at resonance frequencies by 10 dB. However, above 1 kHz, structural damping is higher than before because screws help squeeze three layers
together and allow more shear deformation to occur in the damping layer. Although screws reduce the effect of the damping layer at low frequencies, damping is still significantly increased. Structural loss factor was at least five times the original compared to the results from the test of the solid beam with the same thickness for the frequency range from 10 Hz to 5 kHz (FIGURE 4). Sandwich structure is proved to be an effective way to increase damping in the current test configuration.

**Scale Building Model**

For the scale model building, Carpet tape is selected as the shear damping material for the sandwich floor because of its similar properties to ISD 112, inexpensive price, large size, and continuity, which is easier to handle than commercial damping materials. Two layers of MDF were bounded together with one layer of carpet tape using 32 mm (1.25”) drywall screws to ensure continuous contact between sandwiched layers. Additionally, 50.8 mm (2”) 10-32 machine screws were bolted at 12” on centers through 3 layers.

A Brüel & Kjær Permanent Magnetic Vibration Exciter Type 4808 was connected to the base of the center column. A white noise signal was generated as the excitation source with a 50 kHz sampling rate and a sampling block of 50,000 data points. The length of each set of data is 1 second and the frequency resolution is 1 Hz. A Hanning window was applied to each set of one-second measured data in the time domain. The measured acceleration was transformed to the frequency domain using FFT function in Matlab.

Acceleration measurements were made in the vertical direction on the center column at each floor, as well as at the column base. Vibration attenuation in the system is represented by velocity ratios of velocities on upper floors to those at column base. Measurements taken in the scale model buildings are compared to the predictions using Bernoulli-Euler plate theory to describe the input impedance of the floor at the column connection to validate the mathematical model for the scale model buildings with and without blocking floors.

The equation used to obtain velocity ratios is

$$VdB = 20 \log \frac{v_i}{v_B}$$  \hspace{1cm} (7)

where $v_i$ is the measured velocity on the $i^{th}$ upper floors and $v_B$ is the measured velocity at the base of the center column.

Predictions of velocity ratios for three scale model buildings using three first floor configurations are compared in FIGURE 5 and FIGURE 6. First floor slab configurations are: (a) 0.75” thick MDF, (b) 1.5” thick sandwich plate, and (c) 1.5” thick solid MDF. Floors 2, 3, and 4 have the same 0.75” thick MDF slabs. It is shown that at high frequencies, above 1 kHz, thicker blocking floors are expected to mitigate vibration on upper floors by 1-5 dB, which induced the idea of using a blocking floor at a lower level in a building for vibration mitigation at higher level floors.
Testing of Scale Model Building with 1.5 inch Thick Solid Floor

Measured velocity ratios in the two scale model buildings with 0.75” and 1.5” thick MDF slabs are compared with each other in FIGURE 7. Moreover, in FIGURE 8, a 200-point moving averaging is used to average the normalized measured data in order to smooth the results for measuring the average reduction in vibration levels. Below 1 kHz, there is not much difference between the two measurements. At high frequencies, the blocking floor reduced velocity ratios and behaved as expected. There is 3-4 dB difference in velocity ratios at the frequency region from 1 kHz to 3 kHz. Above 4 kHz, the 1.5” thick blocking floor provided less impedance than the 0.75” thick MDF floor did. This phenomenon might be due to lack of sufficient stiffness of the 8-small-bracket connection to engage the column with the blocking floor slab.
FIGURE 7. MEASURED VELOCITY RATIOS FOR 0.75" & 1.5" BLOCKING FLOOR: (a) 1ST FLOOR, (b) 2ND FLOOR, (c) 3RD FLOOR, (d) 4TH FLOOR

FIGURE 8. EXPANSION OF HIGH FREQUENCY REGION OF FIGURE 7: (a) 1ST FLOOR, (b) 2ND FLOOR, (c) 3RD FLOOR, (d) 4TH FLOOR

Testing of Scale Model Building with 1.5 inch Thick Sandwich Floor

Scale model measurements using 1.5” thick MDF floor and sandwich floor are compared in FIGURE 9. It shows that the sandwich floor successfully reduces the amplitudes of vibration resonances in the overall frequency range. The increased damping in the sandwich floor smoothed fluctuations in the velocity ratios due to floor resonances. The measured velocity ratios show that the discontinuity between those two MDF layers of the sandwich floor did not reduce the total plate bending stiffness because the screws at 12” on centers helped restrain the relative horizontal displacement of two MDF layers and sufficiently transferred shear stresses. The velocity ratios of these two building models indicate that the 1.5” sandwich floor provided almost the same impedance as the 1.5” MDF solid floor. Meanwhile, the damping layer significantly increased the damping of the composite layer, which leads to smooth responses from 100 Hz to 5 kHz.
Based on the three scale model building tests with the 0.75” thick MDF floor, the 1.5” thick solid floor, and the 1.5” thick sandwich floor, adding the blocking floor is an effective solution to vibration mitigation from 1 kHz to 3 kHz at all floors of the scale model building. Moreover, the sandwich floor has the expected higher level of vibration energy dissipation caused by its damping layer. As expected, the machine screws have almost no negative effect on vibration attenuation. Their role is to provide composite action between the two layers. The scale model building was tested within the range of 10 to 5 kHz that corresponds to 1 to 500 Hz for the typical full scale building used in this research (Hughes et al., 2008). The frequency range of interest for train induced floor vibration in full scale buildings is normally within the above range (Martin et al., 1978).
CONCLUSIONS

A 4-story scale model building was constructed for measuring floor vibrations transmitted into the building from the foundation through columns. All predictions successfully captured their corresponding measured data. The 1.5” thick MDF floor has the anticipated effect on vibration mitigation and reduced velocity ratio levels by 3-4 dB from 1 kHz to 3 kHz at all floors of the scale model building. A sandwich floor is effective in vibration control of resonant amplitudes on all floors of a scale model building.

For full scale buildings, it might be possible to have thicker floors at several lower levels (e.g., parking levels) to mitigate vibration levels at higher occupied floors. It may also be possible to leverage transfer levels as blocking floors. However, there are several challenges in making the blocking floor theory a practical reality. Due to the complexity of real buildings, scale model buildings differ from real buildings in many aspects. These differences include existence of partition walls, load bearing walls, stair ways, floor beams and girders which lead to higher levels of energy dissipation. It is difficult to estimate the effect of a blocking floor in real buildings without full scale testing and whether a blocking floor can mitigate floor vibration in the frequency range of interest. For future work, it is recommended to conduct full scale testing of several buildings.

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