Measurement and prediction of train-induced vibrations in a full-scale building

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Abstract

Buildings located close to transportation corridors experience structure-borne sound and vibration due to passing traffic which can be disruptive to operation of sensitive equipment in manufacturing, and medical facilities. Structure-borne sound and vibrations, when high may also be annoying to human occupants in residential, office, and commercial buildings. Hence, there is a growing need for cost effective sound and vibration predictions to evaluate the need for mitigation.

The research focuses on in-situ testing of a full-scale building for verification of a previously developed impedance-based methodology and to create a prediction model to study ground-borne vibrations in the test building. A mitigation methodology was also examined using the verified prediction model.

Impedance modeling involves the propagation of axial waves through columns combined with the impedance of the intermediate floor slabs. The vibration transmission in the building was characterized and predicted using a single column model with attached floors.

Train-induced floor vibrations in an existing four-story building in Boston were measured and compared with predictions of the impedance model. The impedance model predictions closely matched with the measured floor responses.

A previously suggested mitigation method was investigated analytically using the impedance model. A thickened floor referred as the “blocking floor” was used on the lower elevation of the building and the reduction in vibration at the upper floors of the building was compared for various thicknesses of the blocking floor, to study its efficiency. The blocking floor has high impedance and reflects a major portion of the vibration transmitting in the columns preventing it from reaching the upper floors. The blocking floor was found to mitigate the transmission of ground-borne vibrations to upper floors.

1. Introduction

In major cities around the world, urbanization and rising land prices have been driving an increase in real estate development adjacent to, and above in some cases, railway lines and other transportation corridors. Structure-borne sound and vibrations from traffic can not only be annoying to human occupants, they can also be disruptive to the operation of manufacturing facilities, medical facilities, and research laboratories. As awareness of structure-borne sound and vibrations issues grow among developers, owners, designers, and building occupants, there is a corresponding increase in demand for cost effective sound and vibration predictions to evaluate the need for mitigation. If designers could predict the vibration response of buildings with reasonable accuracy, cost-effective vibration mitigation strategies could be incorporated into initial stages of structural design.

1.1. Background

Transmission of train-induced ground borne vibrations can be broadly classified into three different stages. The vibration generation at the source, ground borne transmission and the vibration transmission from the ground into the building and within the building. Previous researchers have investigated in detail to
identify the source of vibration from railway lines and to find possible solutions to mitigate the effect of train-induced vibrations in buildings. Cox and Wang [1] summarized the track geometry and the rail head roughness as possible causes of vibration. Vibrations transmit from the rail to the track structure and then to the surrounding ground, propagate through the ground and eventually entering into the building through the foundations and transmitting to the upper floors.

The characteristics, frequency range and magnitude, of train-induced vibrations have been well identified by researchers. Vibration energy levels are observed to be in the frequency range of 10–250 Hz [2]. One of the challenges is to develop a methodology to predict floor vibration levels in a building based on the ground-borne vibration input at the base of the building, at the foundation level. A prediction model will also facilitate the study and comparison of different design alternatives for floor vibration mitigation.

Current guidelines for predicting train-induced vibrations in buildings, published by FTA [19], rely on a heuristic predictive model. The FTA’s recommendations for estimating floor-to-floor vibration attenuation are −2 dB per floor (1–5 floors above grade) and −1 dB per floor (5–10 floors above grade). However offsetting this attenuation are resonances of the building structure, particularly the floors, walls and ceilings which will create amplification in the vibration levels.

There have been several attempts to develop predictive finite element models ([3,4]). However, a detailed finite element model required to accurately replicate the dynamic behavior of the building from low to high frequency ranges is not available at initial stages of design.

Study of train-induced floor vibrations and its mitigation is an area of ongoing research at Tufts University and Acentech Inc. We have developed a simplified impedance-based analytical model for train-induced vibration predictions [5]. An axial wave propagation model with a single column and associated floors was considered to predict floor vibration levels based on measured ground-borne vibration input at the base of the column. The impedance of columns and slabs representing stiffness, mass and damping properties constitute the basic elements of the model. The prediction model was validated using tests on a four-story scale model building and the robustness and efficiency of the modeling technique was demonstrated by comparison with finite element models [6].

Mitigation of train-induced vibration has been investigated by various researchers by considering methods applied at the source or along the transmission path or at the building structure. Reducing wheel and rail irregularities, noise isolation pads [7], soil replacement below tracks [8], and specialized track structure design [9] have been found to reduce level of vibrations transmitted from the track to the surrounding ground. The use of open and filled trenches [10], wave barrier of lime-cement columns [11] and gas cushion screens [12] have been investigated and found to be effective in reducing vibration transmission between the railway track and nearby buildings. Base isolation in buildings using resilient foundations or elastomeric bearings [13], compacted sand fill below foundation [14] were also found effective in reducing vibration transmission into buildings.

The researchers at Tufts University and Acentech Inc. have investigated the use of a thickened “blocking floor” for vibration mitigation at the building. The blocking floor has high impedance and reflects down a major portion of the vibrations transmitting from the columns to the upper floors. Use of lower floors of the building as a blocking floor for mitigation of ground-borne vibrations was successfully investigated using a four-story scale model building designed and constructed at Tufts University with and without the blocking floor [15].

1.2. Scope of research

A continuation of the earlier work at Tufts University in the areas of vibration prediction and mitigation, the original contributions of this research are (1) verification of train-induced vibration characteristics and its propagation within a full-scale building (2) to study the axial wave propagation between floors through columns, examination of impedance of complex floor systems and verification of composite slab properties using in-situ impact hammer testing (3) prediction of train-induced ground-borne vibrations using the impedance model and comparison with measured response of the actual building (4) examination of the blocking floor concept using the verified impedance model.

2. Impedance model

Impedance modeling involves the propagation of axial waves through columns combined with the impedance of the intermediate floor slabs. A previously developed impedance-based prediction model representing a single column and the connected floors was used to simulate the dynamic behavior of the test building and predict floor responses to train-induced vibration input measured at the base of a column. The train-induced vibrations at a floor are the sum of the incoherent contributions from individual columns surrounding the floor. Hence, a single column-floor model can be treated as an independent system to represent the vibration transmission in the building. A detailed explanation and validation for the same is provided in Section 5.

Impedance represents stiffness, mass and damping properties of the system. The finite column segment between floors is represented as impedances at the top and bottom of the column and the impedance of the floor slabs are included at the junction between column segments above and below.

A summary of the impedance-based modeling concept, the associated wave propagation equations, and the blocking floor theory that are used in this paper is presented in this section for completeness. Previous research [15] has shown that axial vibrations are the dominant mode of ground-borne vibration transmission in columns to upper floors of the building, hence the analysis presented here is limited to transmission due to axial wave propagation in columns.

The axial wave propagation model shown in Fig. 1 is considered to represent a typical column segment. Where, \( f_1 \) and \( f_2 \) represent the axial forces and \( u_1 \) and \( u_2 \) represent the axial displacements at the ends of the column segment, which are frequency dependent.

The dynamic relationship between forces and displacements at the ends of the column segment is represented by the dynamic stiffness matrix of the column given by Eq. (1). It accounts for the stiffness, mass, and damping properties of the column.

\[
[k] = \rho A c \left( \frac{\omega}{\sin(\beta L)} \right) \begin{bmatrix} \cos(\beta L) & -1 \\ -1 & \cos(\beta L) \end{bmatrix}
\]

where \( L \) is the length of the column, \( A \) is the cross-sectional area of the column, \( \omega \) is the driving frequency, \( \beta \) is the wave number defined in terms of the wave speed, \( c \) and material density, \( \rho \) [16] and given by Eqs. (2) and (3).

\[
\beta = \frac{\omega}{c} = \omega \sqrt{\frac{\rho}{E}}
\]

where, \( E \) is the Young's modulus of elasticity, \( A \) is the cross-sectional area of the column, \( \rho \) is the density, and \( c \) is the wave speed in the column.

\[ u_2 \]

\[ E, A, L, \rho \]

\[ u_1 \]

\[ f_2 \]

\[ f_1 \]

Fig. 1. Axial wave propagation model for a column segment.
where $E$ is the complex modulus of elasticity of the column defined by Eq. (4).

$$E = E(1 + i\eta)$$

where $E$ is modulus of elasticity of the column and $\eta$ is the material loss factor.

Axial vibrations in the columns induces bending deformations in the floors at the connections. The axial load transmitted through the column is transferred as a point load to the floors which are modeled as thin infinite plates as per Kirchhoff plate theory. The point impedance of thin plates is resistive. Energy propagates away from the drive point at the column interface. This drive point impedance is defined by Cremer et al. [16] and given in Eq. (5) representing stiffness, mass, and damping properties of the floor.

$$z = 8\sqrt{\rho Dh}$$

where $\rho$ is the slab material density, $h$ is the slab thickness and $D$ is the bending stiffness of the slab given by Eq. (6).

$$D = \frac{Eh^3}{12(1-v^2)}$$

where $v$ is the Poisson’s ratio of the slab material and $E$ is the complex modulus of elasticity of the slab. The dynamic mass of the floor depends on the driving frequency and is given by Eq. (7).

$$m = \frac{z}{i\omega}$$

Fig. 2 shows the simplified one-column impedance model of the four-story full-scale building used for testing. The model consists of four axial degrees of freedom, one per floor in the axial direction.

The dynamic stiffness matrices of the column elements, Eq. (1), are assembled into global matrix $[K]$ and the dynamic mass of the floors, Eq. (7), are assembled into global matrix $[M]$. The stiffness and the mass matrices are functions of frequency. The excitation is represented by the load vector $\{F\}$ and the steady state response of the system is shown as $\{U\}$. The system relationship is represented by Eq. (8), [17].

$$[K]\{U\} - \omega^2[M]\{U\} = \{F\}$$

For train-induced excitations, the load vector of external forces $\{F\}$ comprises of a non-zero force at the column base and zero external forces at all other floors as shown in Fig. 2. Since the model considers force input at the column base, the grade slab and the foundation system are not included in the impedance model. The frequency dependent steady state response for all floors is given by Eq. (9) and the corresponding velocity given by Eq. (10).

$$\{U\} = [K - \omega^2M]^{-1}\{F\}$$

$$\{V\} = i\omega\{U\}$$

If the forces at the column base are known, the frequency dependent response is determined using Eq. (9). In the case of measured vibrations at the column base, velocity ratios established between various floors with reference to the base are used in conjunction with the measured floor vibrations at the column base. This is explained in detail in Section 6.

### 3. Test building

A four-story building in Boston, Massachusetts was selected to develop and verify the predictive capability of the impedance-based analytical model considered in this research. Four floors of the building were considered for the test plan and identified from bottom to top as loading dock, plaza floor, second floor, and third floor. Two tracks of the commuter rail line pass through the building tunnel at the loading dock level. Fig. 3 shows a train exiting the test building.

The test structure selected is a convention center with large open halls and a limited number of partition walls, an ideal choice for creating a simplified model as the alternate vibration propagation paths are avoided and vertical transmission of vibrations is mainly through the columns. The building, originally constructed in the 1960s and substantially renovated in the 1980s, contains a mix of concrete and steel-frame construction, one-way slabs on wide-flange beams and two-way waffle slabs. The superstructure is founded on pile caps that distribute load to steel piles. The main structural columns are located on a square grid of size 9.144 m (30 ft). To ensure stronger train-induced excitation and avoid floor vibrations.
complexities, a column located close to the train tracks and away from any masonry walls or large floor openings was selected. Fig. 4 shows the plan and section of the building identifying the test column. The foundation system below the column consists of an isolated pile cap supported on four steel-encased concrete, end bearing piles.

3.1. Modeling of composite columns

The chosen column consists of three finite segments between the four floors. The two lower segments between loading dock-plaza floor and plaza floor-second floor are reinforced concrete and the third segment between second floor and third floor is steel section encased in concrete, hence a composite column model is considered for these segments. The train-induced vertical vibration is assumed to be uniform across the cross-section of the composite column. The concrete and steel portions are assumed to experience the same axial motion corresponding to the train-induced vibration with no shear slippage occurring between them. The dynamic stiffness of a column defined in Eq. (1) depends on the material wave speed and the area density of the column. Hence an equivalent wave speed and equivalent area density are considered for the composite column cross-section as per Eqs. (11) and (12), respectively.

\[
\epsilon_{eq} = \frac{A_s E_s + A_c E_c}{\rho_s A_s + \rho_c A_c} \tag{11}
\]

\[
(\rho A)_{eq} = \rho_s A_s + \rho_c A_c \tag{12}
\]

Eqs. (11) and (12) use composite column material properties that are; the density of reinforcing bars or steel section \(\rho_s\), density of concrete \(\rho_c\), cross-sectional area of steel \(A_s\), cross-sectional area of concrete \(A_c\), complex elastic modulus of reinforcing bars or steel section \(E_s\) and complex elastic modulus of concrete \(E_c\).

3.2. Modeling of composite slabs

The plaza and second floor have concrete waffle slab construction. The waffle slab consists of 0.4826 m \(\times\) 0.4826 m \((19' \times 19')\) domes at every 0.6096 m (2 ft) with 0.0889 m (3.5') thick slab and 0.0254 m (1') topping layer. The third floor, a composite slab with light-weight concrete over metal decking is supported on a grid of steel beams and girders spanning in perpendicular directions, hence composite slab models are considered for these floors. The impedance, \(z\), of the floor slab defined in Eq. (5) and the bending stiffness of the slab, \(D\) defined in Eq. (6) can also be represented as shown in Eqs. (13) and (14).

\[
z = 8\sqrt{\rho D h_m} \tag{13}
\]

\[
D = \frac{E h_k^3}{12(1-\nu^2)} \tag{14}
\]

where \(h_k\) and \(h_m\) are respectively the slab thicknesses considering an equivalent homogeneous flat plate with the same plate bending stiffness and mass of the actual composite slab.

For the plaza and second floors, equivalent flat slab thicknesses \(h_k\) and \(h_m\) were computed based on waffle slab properties available in CRSI design handbook [18]. For the third floor, equivalent flat slab thicknesses were computed for the floor system considering contribution of the concrete slab, steel beams and girders.

Tables 1 and 2 summarize the properties of relevant structural elements of the building which serve as building blocks for the impedance model. \(\nu\) is the Poisson’s ratio of the material, \(E\) is the modulus of elasticity of the material, \(\rho\) is the density of the material and \(\eta\) is the material loss factor.

In Table 1, all three column segments have the same gross cross-sectional area, however the reinforcement contents of the reinforced concrete sections are different. The equivalent wave speed is dependent on the complex modulus of elasticity and hence has an imaginary component related to damping, which results in a decay during propagation. Damping is accounted by material loss factor, \(\eta\), the values for which are obtained from standard literature. In Table 2, the waffle slabs are normal weight concrete and the third floor is lightweight concrete over metal decking. In these tables LD is abbreviation for Loading dock, PL is Plaza level, SF is Second floor, and TF is Third floor.

4. Measurement of floor impedance

Impact hammer tests were performed at several locations on each floor level to study the individual floor responses. The impedance associated with a constant impedance, analytical floor which best represents the measured floor response is considered as the impedance of the floor in the analytical model.

The excitation force is an impulse generated by striking the impact hammer on the floor slab at a location away from the column and floor beams. The resulting force spectrum is fairly constant in the frequency range of 10 Hz to 300 Hz. The corresponding response of the floor is measured using an accelerometer placed

![Fig. 4. Test building plan and section.](image-url)
adjacent to the point of excitation. The response is an exponentially decaying function and depends on the impedance of the system. The measurements are recorded and analyzed using a dynamic signal analyzer. The test equipment is shown in Fig. 5.

Fig. 6 shows the comparison between measured transfer function cross spectra or accelerance defined using Eq. (15) and analytical accelerance spectra calculated for a constant impedance floor slab using Eq. (16).

\[
\text{Accelerance}(f) = \frac{\text{Floor response acceleration}(f)}{\text{Excitation force}(f)}
\]

\[
\text{Accelerance}(f) = \frac{i\omega}{2\pi f}
\]

Floor impedance \( z \) for a thin floor in bending is constant, therefore the accelerance is directly proportional to frequency and hence is seen as a straight line with constant slope in dB scale in Fig. 6.

Fig. 6 shows accelerance of four floor slabs with three different construction types. The loading dock accelerance is shown in Fig. 6(a). It is a normal-weight concrete grade slab. It shows that for most frequencies the constant analytical impedance behavior associated with an infinite flat plate approximates the measured accelerance of the loading dock grade slab. The plaza floor and the second floor accelerance are shown in Fig. 6(b) and (c), respectively. These are normal-weight concrete waffle slabs. The accelerance computed analytically fairly replicates the measured accelerance plots on the corresponding floors. The analytical graph line for each floor follows the trend associated with the best fit line through the measured data points, which represents the actual impedance of the waffle floor slabs. Measurements of these two floors above 200 Hz were not considered for comparison due to low coherence. The third floor accelerance is shown in Fig. 6(d). It is a light-weight concrete slab on metal deck supported on a grid of steel beams and girders. The agreement between the analytical slab model behavior and the measurements is good. The analytical slab model at this location considers only the concrete slab portion. The lower accelerance observed in the measurements below 30 Hz and above 150 Hz, can be associated to the presence of the metal deck, surrounding beams and girders which increased the local stiffness of the slab at the test location.

Comparison of the analytical and measured accelerance plots indicate that the slab impedance models used for modeling of all four floors with different construction types, replicate the measurements. Hence the idealized constant impedances of these floors are computed using Eqs. (5) and (13) and utilized in the impedance model of the building to represent the floor behavior.

### 5. Train-induced vibration measurements in the building

Train-induced floor vibrations were measured to study the characteristics of the train-induced excitation at the base of the building and its propagation to higher floors. The measurements were also used to validate the impedance modeling assumptions and to verify the prediction model developed in this research. Vibrations were measured simultaneously on all floors using accelerometers placed near the column floor junctions. Fig. 7 shows the test setup for measuring vertical components of the train-induced vibrations.

Train passage events were identified by reviewing the vibration time histories, removing events that were significantly corrupted by vibration from other sources such as vehicular traffic and moving equipment. Ambient measurements collected provide a sense of the robustness of the measured data. Thirty second long ambient measurements were simultaneously recorded from all accelerometers in each setup. Train pass by were transient events varying from 15 to 25 s in duration. Sampling rate of 2000 Hz was used for train-induced vibration measurements. The time histories were processed in one second intervals to obtain a “peak hold” or maximum value of the spectra at each frequency during the train passage. The acceleration spectrum obtained was converted to the corresponding floor vibration velocity in decibel scale using a reference velocity of \( 1 \times 10^{-8} \text{ m/s} \) recommended by FTA [19]. FTA also recommends one-third octave band frequency spectra to represent the detailed analysis of building response and performance of vibration mitigation methods. One-third octave band were computed by summing narrow band spectral energies lying within each one third octave band. The velocity levels obtained are represented in decibel scale. A set of measurements for five train passage events were recorded and the mean of the processed levels is shown in Fig. 7(b).
vibration amplitudes was used as the measured floor vibration velocity on each floor.

The train-induced measurements recorded at the base of the test column serve as the source of vibration input for validation of the impedance model considered in this research. Fig. 8 shows the measurements recorded at the column base using a tri-axial test setup.

The solid lines represent the train-induced vibration measurements and the dotted lines represent the ambient vibration measurements. It is seen that the important part of the train-induced vibration spectrum lies between 30 and 200 Hz with a broad peak around 50 Hz. Researchers ([12,20]) have also reported similar conclusions regarding the frequency range of interest for train-induced vibrations based on a large number of measurements carried out along railway lines in Boston and Stockholm, respectively. The ambient vibration measurements were well below the train-induced vibrations in the frequency range 40–150 Hz. Measurements recorded below 30 Hz in this test setup were ignored due to significant ambient noise present in the building associated with moving equipment, vehicles, and the ventilation system. The vertical component of vibration at the base of the test-column was observed to be lower than the horizontal components.

Train-induced vibrations originate from the interaction between the train wheel and track. Individual wheel sets act as independent sources of vibration. Two adjacent columns in a building which are equidistant from the rail track, receive vibrations primarily generated at different sources of the rail track and from different wheel sets. The sources of vibration at the base of two adjacent columns are statistically independent of each other and so is the vibration that propagates up through them. A
statistical analysis performed on the vibrations measured due to a train passage event, on the same floor at two adjacent column locations verified this phenomenon. The coherence between measurements from two adjacent columns is shown in Fig. 9.

A high signal to noise ratio observed in these train-induced vibrations suggest robust measurements. Low coherence observed indicates that the measurements are statistically independent. Also, high frequency waves in slabs do not travel far from their sources at the column-slab connection [15], reducing the influence of the vibrations observed at one column location over the vibrations measured at the adjacent column location. Hence, a one column mathematical impedance model shown in Fig. 2 can be treated as an independent system to represent the propagation of train-induced vibrations in the building.

6. Train-induced vibration predictions using impedance model

Train-induced floor vibration velocity can be predicted on each floor at the column junction using Eqs. (9) and (10). This however requires measurement of the force at the base of the test column due to train-induced excitation, which was not essentially feasible. The vibration relationship between floors in the impedance model was established by the application of a unit harmonic load at the foundation level. The vibration relationship is the velocity ratio between the vibration at an upper floor at the junction with the column relative to the vibration at the loading dock adjacent to the same column. The vibration velocity levels obtained were used to predict the train-induced vibrations on upper floors by multiplying them with the train-induced vibration velocity measured on the loading dock floor at the base of the column.

The ambient vibration measurements, measured train-induced floor vibration velocities and the corresponding predictions from the impedance model are shown in Fig. 10.

High signal to noise ratio observed for the train-induced vibration measurements indicate robust measurements in the frequency range of interest. The measured vibration velocity levels at the loading dock level serve as the input to velocity ratios from the impedance model in computing the velocity spectra at the upper floors. Comparison of the measured floor vibrations levels below 50 Hz at all floors reveal similar amplitudes, indicating that the higher floors have the same motion as measured at the column base. Below 50 Hz, a reasonably good match is observed between the predictions and measurements on higher floors. Above 50 Hz,
the floor vibration predictions on higher floors tend to deviate from the measurements. In the impedance model, the resonant behavior of the columns was observed at 70 Hz and above.

The impedance model is a simplified representation of the complex building system. A difference in interpretation of the actual behavior of the composite columns would in turn affect the floor vibration predictions and may have been a possible reason for the deviation in the predictions observed at higher frequencies. A sensitivity analysis performed on the impedance model by considering various structural and material parameters was not successful in identifying a definite cause for the variation observed in the results. The authors acknowledge that a measurement error at the loading dock level could also potentially result in significantly lower vibration levels measured at the loading dock floor. The impedance model considers the loading dock floor as an input for vibration predictions at upper floors of the building. A lower input to the model would result in underestimating the floor vibration levels on upper floors. The impedance model considers a single column with the associated floors as a statistically independent system with no influence from the adjacent columns. However, the transmission across the floors from the surrounding columns, although not very high for columns spaced further apart, can influence the response measured at the column considered for the test. This modeling error can lead to underestimation of the single column response subjected base excitations.

Overall, the reasonable match observed between the predictions and the measured floor velocities in the frequency range of interest from 10 Hz to 250 Hz, shows the capability of the impedance-based analytical model to predict the floor vibration velocities of a real building subjected to train-induced excitations.

7. Impedance modeling as a potential floor vibration prediction tool

For a building located close to a train-induced vibration source, impedance modeling can offer a simplified and computationally efficient approach to predict vibration levels at various floors with reasonable accuracy. Considering a target area of interest in the building, only column and floor dimensions, material properties, boundary conditions and vibration measurements at the base of the column are required to assemble the impedance model of the test building.

For new buildings impedance modeling has the potential to predict train-induced floor vibrations based on open field measurements. The authors acknowledge that open field measurements potentially differ from the actual vibration levels that would be observed at the grade slab level after the building has been constructed [2], in particular at the base of a column and away from the column on the grade slab. The vibrations at the base of a column in the constructed building would also be influenced by the column and foundation system. The effect of these factors needs to be investigated further.

The impedance model developed for an existing building can be used for studying retrofit scenarios and for comparison of different design alternatives to mitigate ground-borne floor vibrations. In general building owners are interested in prediction of floor vibrations anywhere on the floors in addition to locations near columns. Train-induced vibration predictions using the impedance model are obtained for a floor at a location near the column. The total response of the floor is a sum of incoherent contributions from individual columns surrounding the floor. Hence, the total response at an arbitrary point on the floor can be obtained by considering the sum of the vibration energy contributions from

Fig. 11. Predicted reduction of floor vibrations as a function of plaza floor thickness.
individual columns. The transfer functions between the nearest four columns and the point on the floor are multiplied with the response measured at the respective column locations and the vibration energy contributions are summed up. For existing buildings, the transfer function can be estimated using impact hammer tests on the floor, with excitation at the individual columns and the corresponding responses at the same point of the floor in the bay between the four columns.

8. Train-induced floor vibration mitigation using blocking floor

The impedance model can also be used to study mitigation measures to reduce train-induced floor vibration levels. The impedance of a floor slab, defined by Eq. (5), increases with the square of the floor thickness. Increasing the thickness of a single floor in the model significantly increases its impedance with the potential to reduce the vibration velocity level on that floor and the floors above as vibration energy is reflected by the thickened “blocking floor” back down towards the foundation. The method is more effective when lower floors of the building above ground are treated as blocking floors. This way it reduces the vibrations on all floors above and also keeps the heavy floor as close as possible to the ground. Two different cases of the analytical model of the test building with the plaza floor slab thickened by two times $2x$ and three times $3x$ in the impedance model were considered to observe the sensitivity to this phenomenon. The reader should note that only the plaza floor which is the lowest floor above ground in the building is thickened. The train-induced floor vibration predictions using the impedance model with and without the blocking floors are compared in Fig. 11.

These predictions were obtained by varying only the plaza floor thickness. Hence the order of magnitude of the results shown in Fig. 11 can be used for a relative comparison between the cases analyzed. Comparison of the results from the three cases reveals the effectiveness of the thickened plaza floor to reduce the train-induced vibration levels on the higher floors of the building. The floor vibrations levels above 30 Hz on the plaza and higher floor levels are lowered by 5 dB or more for the $2x$ case and 10 dB or more for the $3x$ case when compared to the vibration levels without the blocking floor action. Hence, a thicker lower floor can provide significant floor vibration mitigation at the blocking floor and the floors above.

The observations indicate that the blocking floor has the potential to mitigate vibration transmission to floors above the blocking floor level. A thickened blocking floor is a simple method that can be easily integrated into the design of the structure with less impact on the overall design, construction and cost of the building. In many buildings lower floors which functionally serve as parking garages are thicker and designing them as blocking floors would be an easier and cost-effective train-induced vibration mitigation solution.

The blocking floor is a floor with high impedance that is a combination of higher stiffness, damping, and mass properties. Floor systems such as waffle slabs or composite slabs offer higher bending stiffness that are more efficient for their use as a blocking floor.

9. Conclusions

An impedance-based analytical model was used to simulate the dynamic behavior of a four-story full-scale building and to predict the floor responses to train-induced vibration. The predictions were compared to the measured building responses. A floor vibration mitigation methodology was also evaluated using the developed impedance model.

The following conclusions have been made from the findings of the research presented in this paper:

1. Train-induced vibrations measured at the base of the test column serve as ground-borne vibration input into the building. The important part of the train-induced vibration spectrum was found to lie between 30 and 200 Hz with a broad peak around 50 Hz.
2. Individual column responses to train-induced vibrations were found to be statistically independent, justifying the use of a single column analytical model with floor impedances to represent the building.
3. Waffle slab and concrete slab on metal deck floors can be modeled based on standard composite floor approaches, in that the measured accelerance values for the floors agreed well with composite model predictions.
4. Impedance-based modeling offers a simple and quick approach for reasonably accurate prediction of train-induced vibration with small computational requirements.
5. Based on the impedance model, blocking floor used at a lower level above ground, has the potential to reduce train-induced vibration levels on higher floors of the building.

10. Future work

The results from this work form the foundation for future full-scale building investigations. The continuation of this research will include the following:

1. Study relationship between open field measurements and measurements after construction of the building, both at column locations and away from columns on grade slabs.
2. Study vibration prediction on building floors away from columns based on vibration contributions from the surrounding columns.
3. Full-scale testing of buildings to study the effectiveness of blocking floor concept as a floor vibration mitigation methodology.
4. Development of design guidelines for the prediction and mitigation of building vibrations.

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