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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

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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, $f1$ and $f2$ represent the axial forces and $u1$ and $u2$ 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.

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

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

$$\beta = \frac{\omega}{c} = \omega\sqrt{\frac{\rho}{E}} \tag{2}$$

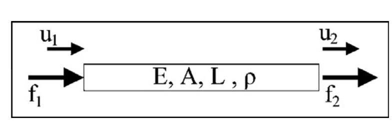

Fig. 1. Axial wave propagation model for a column segment.