Simplified Assessment of Forklift-Induced Floor Vibrations

Tuan Nguyen[1], Nicholas Haritos[2], Emad F Gad[3] and John L Wilson[4]

1. Research Fellow, Faculty of Engineering and Industrial Sciences, Swinburne University of Technology, Hawthorn, 3122, Australia
   Email: tuannguyen@swin.edu.au
2. Corresponding Author. Adjunct Professor, Faculty of Engineering and Industrial Sciences, Swinburne University of Technology, Hawthorn, 3122, Australia
   Email: nharitos@swin.edu.au
3. Professor in Structural Engineering, Faculty of Engineering and Industrial Sciences, Swinburne University of Technology, Hawthorn, 3122, Australia
   Email: egad@swin.edu.au
4. Dean, Faculty of Engineering and Industrial Sciences, Swinburne University of Technology, Hawthorn, 3122, Australia
   Email: jwilson@swin.edu.au

Abstract

A substantial amount of research has been reported in the literature on floor vibrations due to human excitations. However, there is a paucity of significant literature concerning vehicle-structure interaction on ramps and floors in buildings with areas for storage and/or industrial activities. Knowledge of vehicle-structure interaction effects from delivery vehicles and forklifts on building floor systems in the design of such buildings attains a high level of importance when acceptability levels of floor vibrations are particularly stringent such as in the case of research facilities and hospitals.

This paper explores the application of a semi-analytical model for dealing with the up/down motion of a forklift mast with payload for inducing floor vibrations from forklifts. Particular emphasis is placed on the results obtained from the conduct of in-situ experiments aimed at capturing details of this interaction to assist with verification/suitability of the model. The in-situ experiments include the performance of Experimental Modal Analysis of the potentially problematic zones of the flooring system of a hospital under construction.

Keywords: Floor vibration, vehicle-structure interaction, acceptability limits, excitation models

1. INTRODUCTION

Vibration of floor systems has been extensively researched essentially only with respect to human-induced excitation, in line with the development of numerical and experimental techniques for floor vibration assessment and the introduction of acceptance criteria (European Commission 2006; Reynolds and Pavic 2006; Zivanovic et al. 2007; Nguyen et al. 2012). In addition, studies of vehicle-induced vibrations in buildings have been virtually restricted to those for ground-borne vibrations associated with nearby road traffic or railway systems (Crispino and D'apuzzo 2001; Hao et al. 2001; Pridham 2009; Sanayei et al. 2014).

On another note, delivery vehicles and forklifts working on floor areas such as loading docks have the potential to induce disturbing vibrations not only to these areas but also to nearby floors within the same building. However, there is a paucity of significant research or guidance that deals with modelling and assessing the direct excitation of floor systems in buildings by either relatively slow moving delivery vehicles or forklifts. Pan et al. (2001) performed numerical investigations of the dynamic response to moving trucks of a production floor in a multi-storey factory building with elevated access. The research focussed on the vehicle dynamic load originating from road roughness and the effect of considering the deflections of the supporting structures in a vehicle-structure interaction model. The Eurocode EN1 (2002) proposed a simple quasi-static approach to account for forklift-induced loads when designing areas for storage and industrial activities. The dynamic effect is considered by simply multiplying the static vertical axle load weight by a dynamic factor of 1.4 for pneumatic tyres or 2.0 for solid tyres, applied to the floor at the front wheel locations only. Ehland at al. (2010) introduced 3-DOF and 2-DOF dynamic load models for forklifts in which some key parameters were obtained from testing of four forklift trucks. Both pitch and bounce modes were included in the proposed dynamic load which was the product of a mass matrix and an acceleration vector. More recently, Haritos et al. (2013) have developed several preliminary semi-analytical models for dealing with a set of identified vehicle-floor interaction scenarios for inducing floor vibrations from forklifts. Brownjohn et al. (2014) have conducted experimental modal analysis (EMA) and measurement of operational vibration levels of a number of floors in a multi-storey industrial complex. The floors were subjected to various excitation sources including heavy machinery, forklift operating and human walking. The most critical scenario was found to be associated with forklifts with stiff tyres travelling on rough concrete with construction joints.

This paper examines the dynamic behaviour of a forklift truck and the response to resultant actions on a real floor system, concentrating on the up/down mast motion induced vibrations. A companion paper, (Douglas et al 2014) provides an overview of the full complement of testing performed on this floor system. Observations from the floor and forklift testing have assisted in at least partially verifying simplified analytical models for forklift-induced loads, which would be useful to the vibration design of floors.

2. DESCRIPTION OF FLOOR AND FORKLIFT TESTING

A number of dynamic tests were performed on three adjacent spans of a prestressed concrete floor in a hospital building under construction. Figure 1 shows a plan view of the test floor. The concrete slab is 350 mm thick, post tensioned, formed on metal tray formwork; and spanning 8.5 m between band beams which are 2400 mm wide and 600 mm deep. The main aim of these vibration tests is to determine basic dynamic properties of the floor and evaluate the floor acceptability for safely housing sensitive equipment when the floor is subjected to human excitations such as walking. Although the floor is not to be designed for forklift activities, the authors took this opportunity to include some forklift-related tests in order to gain a better understanding of forklift-floor interaction.

Experimental modal analysis (EMA) using Swept Sine Wave (SSW) forcing from a shaker was performed on the floor for evaluating its natural frequencies, modal damping and corresponding mode shapes. The grid points for performing acceleration response measurement were set out as shown in Figure 1. Accelerometers were relocated in 10 setups to cover 61 measurement points, with a reference accelerometer located near the centre of the leftmost test span. The floor appeared to be a high-frequency floor with the measured fundamental frequency of 14.2 Hz and corresponding damping ratio of about 1.9%. Having high natural frequencies, the floor is unlikely to experience resonant responses when subjected to normal walking.

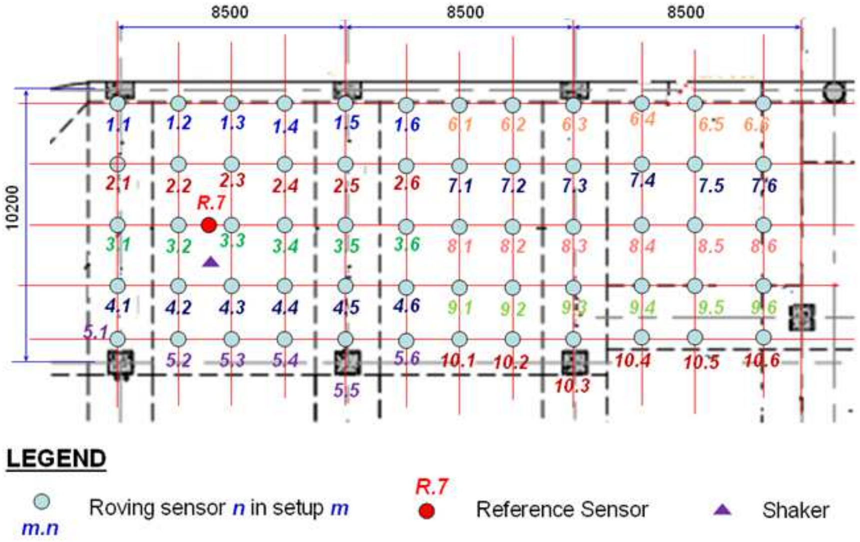


Figure 1: EMA test, location of shaker and test points

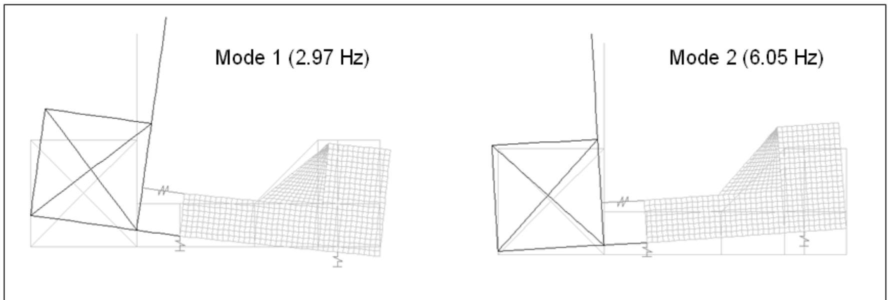
This paper focuses mainly on the dynamic load and floor response induced by a Toyota forklift truck with 1.5 tonne capacity (Figure 2). A sequence of experiments with the forks moving upwards, then downwards, at maximum speed then suddenly stopping, were performed for two different mass payloads of 1060 and 530 kg, and designated as full and half payload cases respectively. Two accelerometers were positioned on the test forklift with one being on the top of the payload and the other on the back of the forklift truck. The forklift was operated on the leftmost test span where accelerometers were also installed for measurement of the floor response at the same time.

Figure 2: Fork-lift up/down test (accelerometer on back of forklift is invisible)

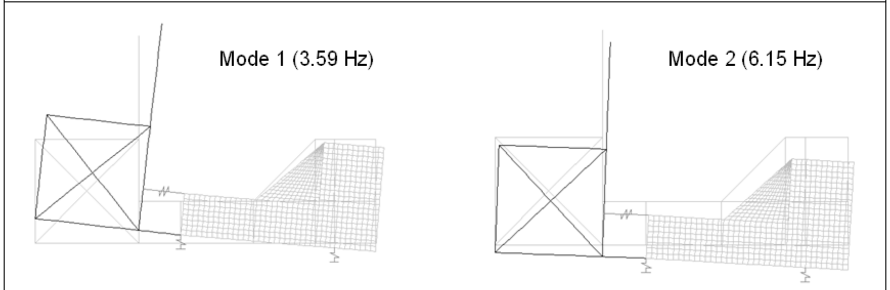
3. DETERMINATION OF FORKLIFT'S MODAL CHARACTERISTICS

3.1. FE modelling of forklift

A simplified FE model, as shown in Figure 3, was proposed to predict the modal properties of the Toyota forklift truck. The truck body and mast were represented by shell and frame elements whilst vertical springs were used to model the front and rear wheels and a horizontal spring was for the stiffness of the actuator governing the rotation of the mast. Typical ranges for the spring stiffness can be obtained from literature such as Ehland et al. (2010) . In this FE investigation, stiffness values of 2,200 kN/m and 20,000 kN/m were assumed for the vertical and horizontal springs respectively. In order to approximate the self-mass distribution of the forklift in a bare condition without payload, a few modelling adjustments in the geometry of the truck body were required until the calculated spring reactions at the axles closely met the axle loads given in the manufacturer's catalogue. FE modal analysis performed on the proposed model revealed the natural frequencies and associated mode shapes of the pitch (first) and bounce (second) modes for the Toyota forklift under consideration, as depicted in Figure 3. The pitch mode was predicted to have a frequency of 2.97 Hz with full payload, increasing to 3.59 Hz with half payload.



(a) Forklift with full payload



(b) Forklift with half payload

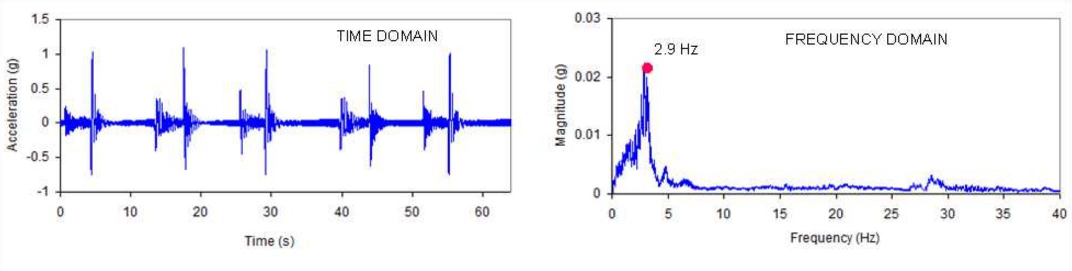
Figure 3: FE-predicted mode shapes of test forklift

3.2. Forklift testing

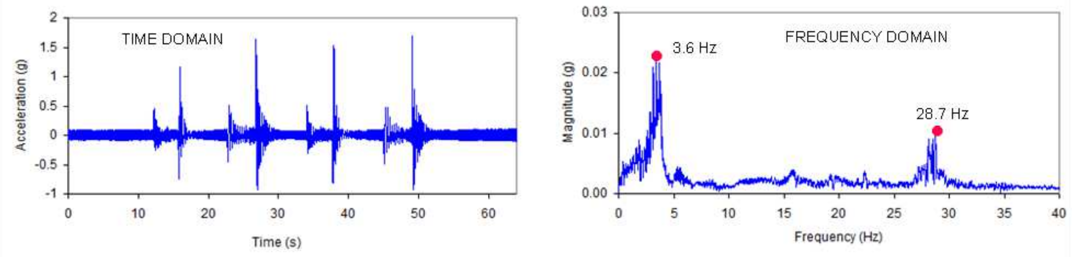
Figure 4 depicts the time histories and corresponding Fourier transform to the frequency domain of the acceleration measured at the payload location during the forklift up/down test with full and half payload. Each acceleration-time trace portion following a fork stopping event was found to have the form of a decay curve somewhat similar to that representing damped harmonic oscillation of typical SDOF systems. The sharp peaks observed at 2.9 and 3.6 Hz in the frequency spectrum may correspond to the pitch mode for the two payload cases. A lower peak observed at a much higher frequency of 28.7 Hz in Figure 4(b) may be associated with a local rotation mode of the mast-payload assembly. This local rotation mode would, however, not be critical to the floor response because its frequency is considerably higher than the floor fundamental frequency (14.2 Hz).

In order to obtain the mode shapes of the forklift, the measurement data from both the front and rear accelerometers on the forklift were analysed using the ARTeMIS experimental modal analysis software (SVS 2008). For the full payload case, a pitch mode with a frequency of 2.95 Hz and modal damping of 7.2% was found as shown in Figure 5(a). (ARTeMIS was unable to detect a heave-like mode from the measurements for the full-load case.) For the half payload case, both pitch mode (3.48 Hz) and bounce mode (6.99 Hz) were detected, as can be seen in Figure 5(b). Moreover, lower damping values were observed in the half payload case, being 5.5% and 0.4% for the first and second modes respectively.

In general, the modal frequencies and mode shapes of the forklift predicted by the proposed FE model compares well with the experimental findings.

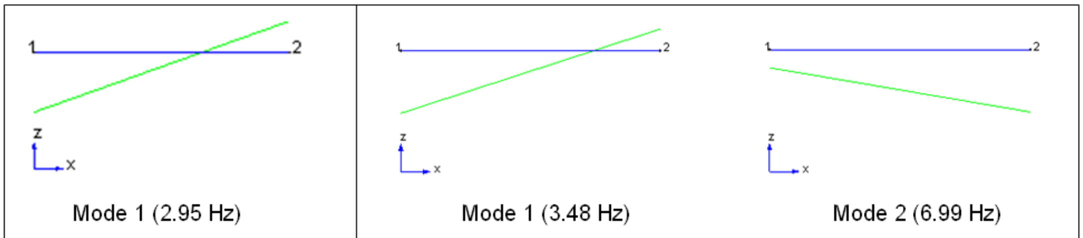


(a) Up/down with full payload



(b) Up/down with half payload

Figure 4: Observed acceleration traces at payload location



(a) Forklift with full payload

(b) Forklift with half payload

Figure 5: Measured mode shapes of test fork-lift

4. SIMPLIFIED MODEL FOR FLOOR LOADING INDUCED BY FORKLIFT

This section discusses a simplified procedure to determine the vertical forces transmitted to the floor system due to forklift up-down motion with payload. The process of suddenly stopping the travel of the forks on a forklift when these forks are moving upwards or downwards at the maximum speed V allowed by the controls, will result in damped oscillations with a circular frequency ω_n and damping value, ζ, associated with the pitch mode of vibration of the forklift, and an initial amplitude associated with the maximum speed of movement up-down of the forks with the payload in place.

Haritos et al. (2013) proposed a simplified expression for the dynamic forcing function at the payload centroid, as follows:

$$F(t) = mg\left(1 + e^{-\zeta\omega_n t}(DLF - 1)\sin(\omega_n t)\right) \tag{1}$$

where m is the mass of the payload and DLF is the dynamic load factor expressed as:

$$DLF = \sqrt{1+\left(\frac{\omega_n V}{g}\right)^2} \tag{2}$$

Consider a typical forklift truck shown in Figure 6(a). Once the force $F(t)$ at the payload centroid has been determined, a quasi static analysis can be performed to obtain the front and rear axle forcing, $F_f(t)$ and $F_r(t)$ respectively, depending upon the geometry of the forklift wheels relative to the payload.

For the Toyota forklift with full payload, Equation (1) estimated the loading function at the payload centroid as shown in Figure 6(b); using the pitch mode frequency and damping obtained from Section 3, a design maximum fork velocity of 0.68 m/s, and a DLF of 1.57 given by Equation (2). The dynamic loads transmitted to the floor at the front and rear wheels can then be determined as shown in Figure 7.

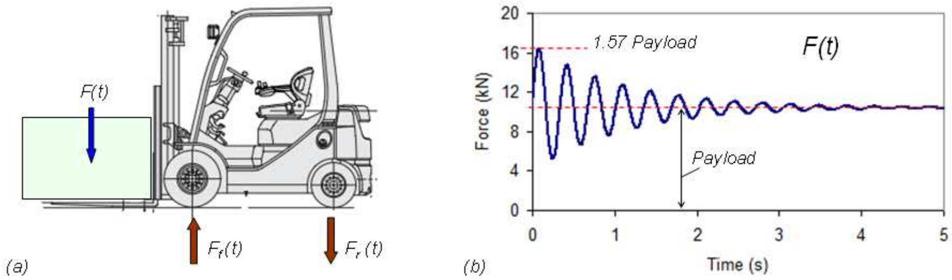


Figure 6: Simplified load model for fork-lift up/down

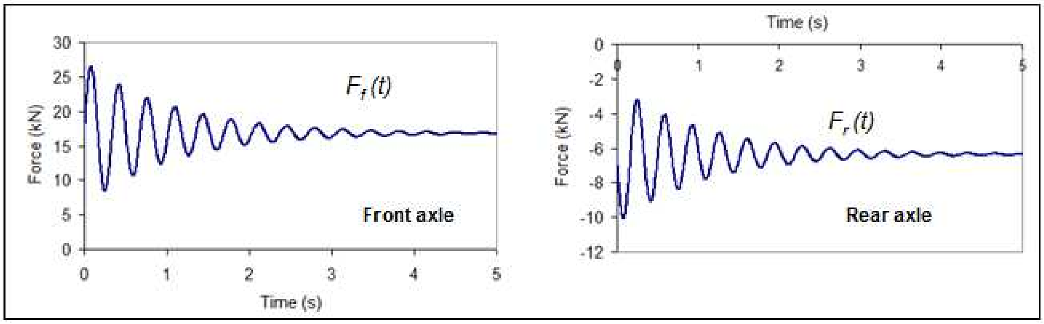


Figure 7: Forces transmitted to floor (full payload)

5. FLOOR RESPONSE TO FORKLIFT OPERATION

Figure 8(a) shows part of an FE model for the floor containing the test area, created with shell elements representing the slab, band beams and shear walls, and frame elements for the columns. The span marked as "A" is where the forklift force was applied and the floor response was considered. Figure 8(b) shows the floor response obtained from time history analysis of the floor model subjected to the simplified forklift-induced force of Figure 7. The calculated response history reveals a peak floor acceleration of 1.86% g and an Root Mean Square (RMS) floor acceleration for the first 1-second interval of about 0.47% g.

To facilitate comparison between analytical and experimental findings, two measured 64-second records of the floor response were placed consecutively, creating a 128-second acceleration record shown in Figure 9. A rolling RMS acceleration curve was also generated to represent the RMS acceleration values computed for successive one-second time intervals. Each peak in the observed acceleration trace would relate to an event of suddenly stopping the travel of the forks when these forks are moving upwards or downwards.

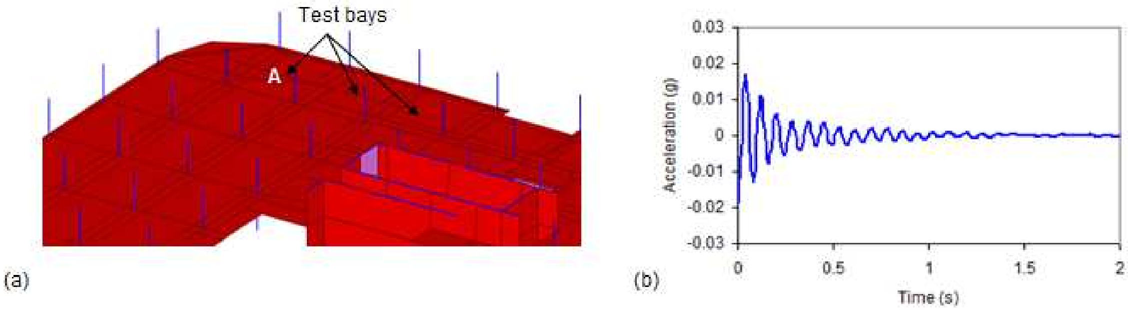


Figure 8: FE model of floor, (b) Floor response predicted using simplified load model

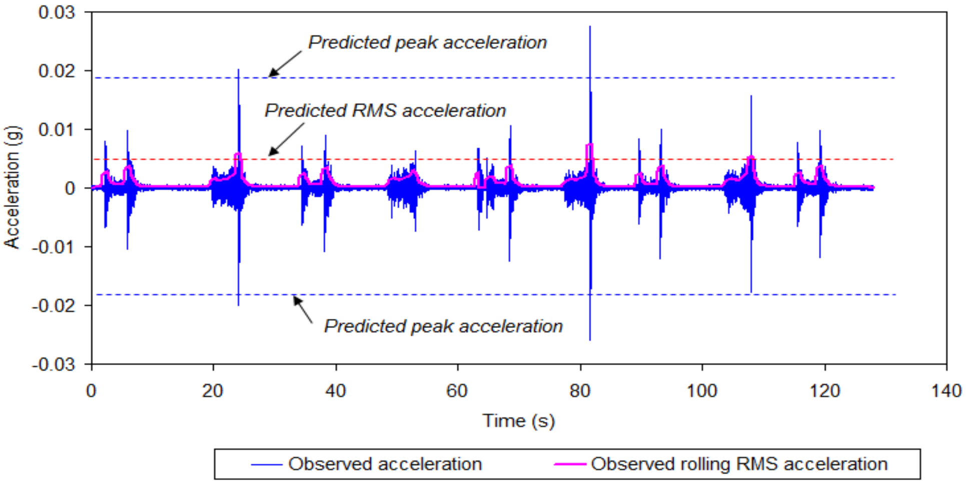


Figure 9: Floor response to fork-lift moving payload up/down

As clearly shown in Figure 9, most of the measured peak and RMS acceleration values are lower than the corresponding FE-predicted values. The average values of the measured peak and RMS acceleration were found to be 1.1% g and 0.36% g respectively. However, the maximum values of the observed peak and RMS acceleration can, correspondingly, be as high as 2.7% g and 0.74% g. Statistically speaking, the proposed simplified forklift load model appears to provide reasonably conservative estimates of floor vibration levels.

6. CONCLUDING REMARKS

Dynamic testing of a concrete floor subjected to forklift operation was conducted with vibration responses of both the floor and forklift being captured. The presented experimental findings have partially verified simplified analytical models proposed for vibration design of floors under forklift excitation from the up/down motion of the mast with payload.

The FE modelling approach used here for determining modal frequencies and mode shapes of the 15-kN Toyota forklift tested would equally be applicable to other forklift truck models and brands. The proposed semi-analytical model for the dynamic forcing function at the centroid of the payload proved to perform quite well resulting in a reasonably conservative prediction of vibration levels of the test floor. The mass of the payload was found to significantly affect both the frequencies and damping of the forklift. When experimental data is lacking, a 5% damping level for the pitch mode of the forklift-payload assembly is suggested. Moreover, as the parameters used in the load model of this paper can be numerically determined, the proposed dynamic load model would serve design engineers well even when no experimental forklift data are available, which is often the case.

REFERENCES

Brownjohn, J., Middleton, C., Pan, T.-C. and Tan, S.-C. (2014). "Vibration Serviceability Assessment of Floors in a Multi-Use, Multi-Storey Industrial Complex", *Structures Congress 2014*, ASCE, pp. 2595-2604.

Crispino, M. and D'apuzzo, M. (2001). Measurement and prediction of traffic-induced vibrations in a heritage building, *Journal of Sound and Vibration*, Vol. 246, No. 2, pp. 319-335.

Douglas, I., Donato, A. and Haritos, N. (2014) "Experimental observation of forklift-induced vibrations on a PSC floor", *ibid*.

Ehland, A., Williams, M. and Blakeborough, A. (2010). Dynamic load model for fork-lift trucks, *Engineering structures*, Vol. 32, No. 9, pp. 2693-2701.

EN 2002, *Eurocode 1991-1-1:2002. Action on structures. General actions. Densities, self-weight, imposed loads for buildings.*, viewed

European Commission (2006). *Generalisation of criteria for floor vibrations for industrial, office, residential and public building and gymnastic halls, RFCS Report EUR 21972 EN*, Luxembourg.

Hao, H., Ang, T. and Shen, J. (2001). Building vibration to traffic-induced ground motion, *Building and Environment*, Vol. 36, No. 3, pp. 321-336.

Haritos, N., Nguyen, T., Gad, E. and Wilson, J. (2013). "Floor Vibrations Induced by Forklifts", *Proceedings of the 2013 Australian Earthquake Engineering Society AEES conference*, AEES, pp. 9p.

Nguyen, T. H., Gad, E. F., Wilson, J. L. and Haritos, N. (2012). Improving a current method for predicting walking-induced floor vibration, *Steel and Composite Structures*, Vol. 13, No. 2, pp. 139-155.

Pan, T.-C., Mita, A. and Li, J. (2001). Vehicle-induced floor vibrations in a multistory factory building, *Journal of Performance of Constructed Facilities*, Vol. 15, No. 2, pp. 54-61.

Pridham, B. 2009, in *Proc. IMAC-XXVII, Feb 9-12,* Orlando, Florida, USA, p. 11

Reynolds, P. and Pavic, A. (2006). Vibration performance of a large cantilever grandstand during an international football match, *Journal of Performance of Constructed Facilities*, Vol. 20, No. 3, pp. 202-212.

Sanayei, M., P., A. K., Moore, J. A. and Brett, C. R. (2014). Measurement and prediction of train-induced vibrations in a full-scale building, *Engineering Structures*, Vol. 77, No. 2014, pp. 119-128.

SVS 2008, *ARTeMIS software (Online help),* Structural Vibration Solutions, Aalborg East, Denmark.

Zivanovic, S., Pavic, A. and Reynolds, P. (2007). Probability-based prediction of multi-mode vibration response to walking excitation, *Engineering structures*, Vol. 29, No. 6, pp. 942-954.