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Structural Dynamics Education in the New Millennium

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ABSTRACT

Structural Dynamics is the study of the response of structures to dynamic or time varying loads. This topic has emerged to be of importance to all structural engineers due to three important issues with structural engineering in the new millennium. These are: (i) vibration problems in slender structures that have emerged due to new materials technology and aesthetic requirements, (ii) ageing structures such as bridges whose health needs to be monitored and appropriate retrofitting carried out to prevent failure and (iii) increased vulnerability of structures to random loads such as seismic, impact and blast loads. Knowledge of structural dynamics is necessary to address these issues and their consequences. During the past two decades, research in structural dynamics has generated considerable amount of new information to address these issues. This new knowledge is not readily made available to practicing engineers and very little or none of it enters the class rooms. There is no universal emphasis on including structural dynamics and the recently generated new knowledge into the civil/structural engineering curriculum. This paper argues for the need to include structural dynamics into the syllabus of all civil engineering courses especially those having a first or second major in structural engineering. This will enable our future structural engineers to design and maintain safe and efficient structures.

Keywords: *structural dynamics, issues in structural engineering, real world examples, practising engineers, structural engineering students, new knowledge.*

INTRODUCTION

There are three major issues with structural engineering in the new millennium. They are: (i)) vibration problems in very tall and/or slender structures which have emerged as a consequence of new materials technology and aesthetic requirements (Thambiratnam et al, 2012), (ii) increased vulnerability of structures to random loads such as impact, blast and seismic loads (Thambiratnam and Perera, 2012) and (iii) safety concerns of aging structures, which suffer deterioration and/or subjected to increased loading (Chan and Thambiratnam, 2011). Real world examples of the consequences of these three issues are illustrated in Figures 1, 2, 3 and 4. Figure 1 shows the slender and aesthetically pleasing Millennium footbridge bridge in London. This bridge was closed on the opening day as it exhibited high levels of (lateral) vibration which the design engineers did not expect. It has since then been retrofitted with dampers at a cost similar to the cost of original construction. Figures 2 and 3 show the building damage caused by an earthquake and the damage of a bridge column by vehicular impact respectively. Figure 4 shows the aging (almost 70 year old) Story bridge in Brisbane which needs continuous monitoring of its structural health as it is now subjected to increased and faster moving loads and in addition, might have suffered deterioration due to environmental effects.

Figure 1: Millennium Bridge (London)

Figure 2: Seismic damage of buildings

Figure 3: Impact damage of a bridge column

Figure 4: Story Bridge, Brisbane

Knowledge in the area of structural dynamics is necessary to address these issues and their consequences. During the past two decades, research in structural dynamics has generated considerable amount of new information to address these issues. However, there has not been universal emphasis on including structural dynamics into the civil/structural engineering curriculum. Some universities have included structural dynamics as a core subject for all civil engineering students majoring in structural engineering, while other have this as an elective subject. Some other universities have not realised this need as many structural design codes and practice guides continue to recommend static methods of analysis and design. As a consequence our structural engineers have been deprived of knowledge in this important area as well as new information from current research findings

It is fair to say that education in structural dynamics has not kept pace with the research developments in the area to enable structural engineers to utilise the new knowledge and the methods to analyse, design maintain and retrofit structures to perform safely and efficiently. In addition to teaching the principles of structural dynamics in class, some of the recent research findings relevant to the three issues highlighted above, must be brought into the class and illustrated through examples.

It has been the author's experience during the past 3 decades that practicing engineers, who had either not been taught fundamentals of structural dynamics or who found it too hard and hence did not bother to understand the subject, seek advice from university professors on matters pertaining to structural dynamics and vibration. This has been of some benefit to the academics as it brought in some consultancies and/or had led to research projects, often supported by the industry. On the adverse side, this situation will delay the engineers' routine work and ultimately increase the cost to the building owner and society. Many of the Australian Research Council Grants awarded to the author through the Linkage scheme had their beginnings with inquiries from engineers and/or requests for consultancy jobs. Such ongoing inquiries on matters pertaining to structural dynamics from practicing engineers provide evidence to the lack of adequate knowledge in this area among the practicing engineers. Senior consulting engineers who had employed our engineering graduates have come back to us on many occasions and stressed the need for including structural dynamics in the curriculum of all civil engineering students who intend to specialise in structural engineering.

CHALLENGES

The author has been teaching structural dynamics to final year civil engineering students majoring in structural engineering during the past two decades. He has also been carrying out a number of research projects in the area of structural dynamics during the same period. This dual role has been beneficial and as a result, teaching and learning in structural dynamics has been quite effective. This is evidenced by the results of the many student surveys on this subject and its teaching. There have however, been some challenges in the teaching of structural dynamics as listed below:

1. Inadequate background knowledge of the students, especially in mathematics and structural mechanics.
2. Lack of interest among students as they have been taught static methods during the first three years and are unable to see the need for and benefit(s) of learning structural dynamics.
3. Loss of interest early in this subject due to its relatively difficult nature.

4. Inadequate time available to the teaching of this subject, partly due to the demand placed by other subjects and partly due to the need to teach the pre-requisites (item 1 above) to enable efficient teaching and learning
5. Preconceived notion among the students that they can manage without structural dynamics as they had not had the opportunity to know about the three issues highlighted above

The measures taken by the author to handle these challenges are briefly described below.

1. Discuss the importance of teaching structural dynamics with the lecturers who teach mathematics and structural mechanics in the early years so that they can illustrate the relevant theoretical information with applications in practice. For example, the important dynamic energy balance equation can first be written down in words as shown below, before its mathematical form, and each term explained with simple examples.

   Dynamic energy imparted = energy absorbed + potential energy (to deform the structure) + kinetic energy (to vibrate/move the structure)

2. The subject is made interesting at every possible stage. There are ample illustrations in real life and these are brought to the class. If the subject is interesting, the students will invest the time and effort to learn it.

3. There are formulae which need to be taught. The available teaching time is maximised by presenting a formula and explain its application and the contribution /meaning of each term in a qualitative manner. The theory can then be very briefly explained and the students can be asked to read the relevant text to study the details, if they wish to. This has worked very well for the author.

4. Illustrations of the problems associated with the three issues (mentioned above) and the possible solutions are presented to convince the students of the need to learn this subject.

5. New information from current research findings are presented to make the subject relevant and interesting. This aspect was introduced by the author's doctoral students whose research projects are in the area of structural dynamics.

NEW RESEARCH FINDINGS

Research in structural dynamics has kept pace with the issues mentioned above and the need to address them. This has been made feasible by the availability of sophisticated instrumentation and advanced computer simulation techniques. The new information generated from this research and its applications to the analysis and design of structures must be brought into the class room and be made available to the new generation of structural engineers. Motivated by the need to address some aspects of these issues and the knowledge gaps therein, a number of research projects have been undertaken at the Queensland University of Technology (QUT) using dynamic computer simulation techniques supported by experimental testing. The research focused on three areas: (i) vibration in slender structures, (ii) disaster mitigation of structures under seismic, impact and blast loads and (iii) structural health monitoring of aging structures, with applications in bridge and building structures. This paper will briefly describe the findings of some of these research projects.

Vibration in Slender Structures

New materials technology and aesthetics have resulted in floor plates, bridges and cantilever grandstands with high slenderness ratios that exhibit multi-modal and coupled vibration. Design codes and best practice guides either do not cover such phenomena adequately or they provide simplified techniques that cannot address the complex vibration in these structures. Historically there have been instances of alarming dynamic excitation of slender structures when subjected to human interaction. The most noteworthy example is the Millennium Footbridge in London (Figure 1) which experienced alarming levels of adverse vibration on the opening day and had to be closed for retrofitting. In Australia, steel deck composite floors used in buildings, airports and shopping centers have been prone to human induced vibration causing some concern to occupants. This paper treats the vibration characteristics of a steel concrete composite floor and a cable tensioned footbridge.

Composite floor structure

Steel-deck composite floor systems have one way spans and use high strength materials to achieve longer spans. Figure 5 shows common steel-deck composite floor systems that are in use in Australia. These types of floors have experienced vibration problems under human induced loads. Dynamics of the dovetailed composite floor system shown on the right hand side of Figure 5 with four equal panels and a total area of 16mx15.6m was treated using finite element (FE) techniques. Structural and material properties of the floor system and its modeling details can be found in (De Silva & Thambiratnam, 2009). Four load functions (PL1 – PL4) representing human activity were applied with load intensity, foot contact ratio and frequency as variable parameters.

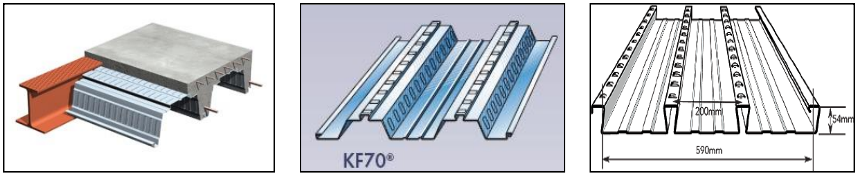

Figure 5: Corus Slimdek®, KingFlor Deck Unit® and Lysaght Bondek Dovetail Deck Unit®

Different values of foot contact ratios to simulate high impact jumping, normal jumping, high-impact aerobics and low impact aerobics were used with two different load densities. Different damping levels and activity frequencies in the normal range for pedestrian walking, running and jumping (1.5Hz to 3.5 Hz) were also considered. Pattern loads PL1 acting on a single panel and PL2, PL3 and PL4 acting on 2 adjacent panels parallel and perpendicular to the span, and on diagonal spans respectively were applied one at a time, to capture the dynamic response (De Silva & Thambiratnam, 2009). Figure 6 shows the shapes of the first 4 modes of vibration and it is evident that the pattern loads could excite all these modes.

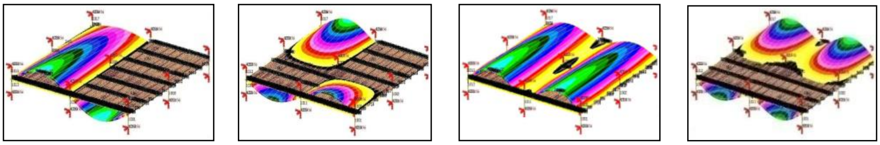

Figure 6: First four mode shapes with frequncies 4.0, 5.4, 5.9 and 6.9 Hz, L to R

Depending on the load case, maximum acceleration responses occurred at activity frequencies of 2.0, 2.7 and 2.95 Hz. Acceleration response spectrums of the floor under PL1 for high impact jumping at low damping are shown in Figure 7. The left hand Figure shows two distinct peaks at frequencies of 4.0 and 6.0 Hz corresponding to the excitation of the 1st and 3rd modes of the floor system by the 2nd and 3rd harmonics of the activity frequency of 2Hz. The right hand Figure depicts a single peak at 5.9 Hz corresponding to the the excitation of the 3rd mode by the 2nd harmonic of the forcing frequency of 2.95Hz. The other load cases also displayed analogous results on the excitation of higher vibration modes in this slender composite floor structure. Further details can be found in (De Silva and Thambiratnam, 2009). From the above results it is evident that in addition to the fundamental mode, higher modes of vibration can be excited in steel-deck composite floors by higher harmonics of the forcing dynamic activity. Current simplified methods of assessing floor vibration are primarily based on the fundamental natural frequency and are not adequate for all operating conditions.

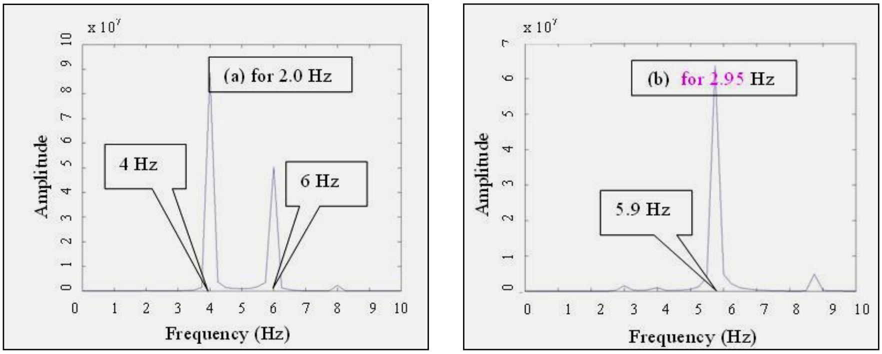

Figure 7: Response spectra under PL1 loading at activity frequncies of 2 Hz and 2.95 Hz

Cable Supported Footbridge

A cable supported bridge with top, bottom and side cables, as shown in Figure 8 is considered for FE analysis. The top cables support the gravity loads and the internal forces induced by the bottom pre-tensioned cables which have reverse profiles and introduce extra internal vertical forces to transverse bridge frames and the top cables. The side cables are a pair of bi-concave cables in the horizontal plane and provide extra horizontal stiffness. Structural, material and modeling details are given in (Huang et al, 2005 & 2007). Results from free vibration analysis showed that in this slender footbridge the lateral and torsional modes are often coupled with the amount of coupling depending on the cable properties, while the vertical modes remain mostly un-coupled (Huang et al, 2005).

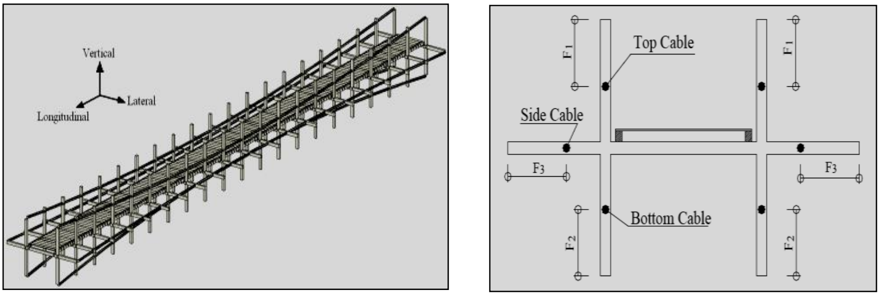

Figure 8: Cable supported footbridge model: isometric view (left) and cross-section (right)

Synchronous excitation can be caused by the combination of high density of pedestrians and low natural frequencies of bridges within the range of pacing rate (Huang et al, 2007). When synchronization occurs, footbridges resonate and a part of the pedestrians change their footfalls to match the vibration. To simulate different load patterns, walking dynamic load was modeled as a uniformly distributed or eccentrically placed load along one side of the bridge, with different pacing rates (frequencies) to cover slow walk, normal walk, brisk walk and fast walk. The bridge experienced resonant vibration when the pacing rate of synchronized pedestrians coincided with a natural frequency of the bridge. The first coupled lateral-torsional mode and the first vertical modes were easier to be excited when the entire deck was full of pedestrians, while the first coupled torsional-lateral mode and the torsional mode were excited by eccentrically distributed walking dynamic loads (Huang et al, 2007). These research findings provide new knowledge on the dynamics of slender footbridges.

Investigations of human activity induced floor and bridge deck vibrations based on existing codes and practice guides are limited to either the first mode of vibration or a few uncoupled modes in the vertical direction of a single panel directly exposed to the activity. The present research showed that in slender multi-panel floor structures and bridge decks multi-modal and coupled vibrations under patterned load effects are significant. In addition, higher modes have an impact on adjacent panels not exposed to direct activity. The new generation of structural engineers need to be aware of this and need a knowledge of structural dynamics for proper evaluation of such slender floor structures to enable safe designs.

New information that can be included in the structural dynamics syllabus:
Vibration in composite floor and cable supported footbridge structures can be complex under human induced loads and this can compromise safety. Comprehensive dynamic evaluation of these structures is necessary by considering their multi-modal and coupled vibration under pattern loads.

Seismic Mitigation of Building Structures

There is a need to control the response of structures when they are subjected to random loads such as seismic, impact and blast loads to protect them from failure. Considerable amount of new information has been genearted in this area during the past two decades. This paper summarises a part of QUT reserach on the use of pasive dampers for seismic mitigation of building structuress.

An 18 storey frame-shear wall structure with passive dampers embedded in cut-outs of the shear wall as shown in Figure 9 is considered. The use of two different damper types (i) viscoelastic (VE) and (ii) friction dampers are investigated. Finite element models of the structural-damper systems are analysed under different earthquake records, all scaled to a common peak ground acceleration (PGA) for meaningful comparison of results. Details of modelling, structural and material details are given in (Marko et, 2006). The response parameters are tip deflections and accelerations of the frame shear wall structure, but only results for the former are given in this paper.

The natural frequency of the undamped structure was 0.614 Hz and in the range 0.570 - 0.650 Hz when fitted with dampers. These values are within the range of dominant frequencies of all the seismic records chosen in this investigation (varying from 0.58 Hz to 1.07 Hz) and hence this study treated the structural response under a range of seismic excitations including a resonant range. Different damper configurations and placements were considered.

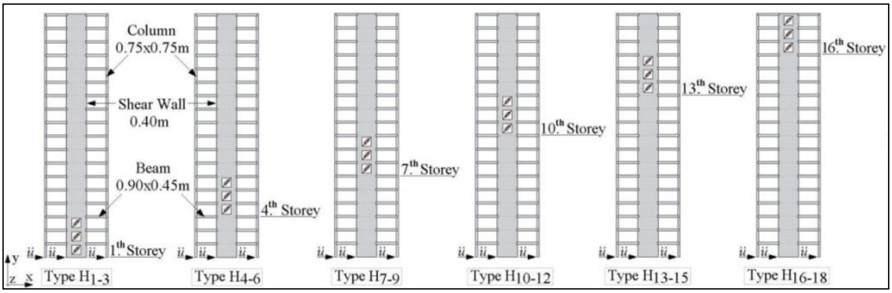

Figure 9: Damper placements in 18-storey frame-shear wall structure

The structure was analysed under five seismic records, with different frequency contents and durations of strong motion, all scaled to a peak acceleration of 0.15 g and applied for the first 20s. Evaluation of tip deflection is a reasonable measure of the overall effect of the earthquake and hence any reduction in tip deflection represents a worthwhile reduction in overall seismic design force. Figure 10a illustrates the deflection time histories of the un-damped structure and the structure fitted with diagonal VE dampers in the lowest three storeys under the El Centro seismic record. From these graphs as well as from numerous other results it was evident that embedded dampers were able to effectively provide seismic mitigation. Results for the tip deflection reductions showed that reasonable seismic mitigation was possible with all damper types and in general best results for the VE dampers occurred when they were placed in the lower storeys while the best results with the friction dampers were obtained when they were placed at locations with highest inter-story drifts (generally in the 14- 18 storeys for this structure).

Based on the above findings, the effect of a combined damping system consisting of a diagonal friction damper in the 16th storey and a diagonal VE damper in the 1st storey (called diag. CO) was investigated. Figure 10b compares the average tip deflection reductions of this system with those of the diagonal friction and VE dampers under all five seismic records. It is evident that the combined damping system can provide significant mitigation under all seismic recodes, even though it consisted of only two dampers.

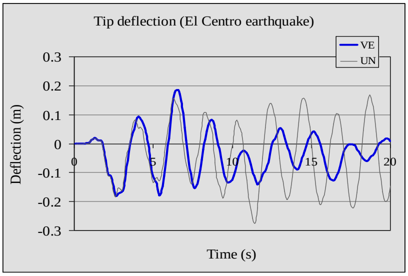

Figure 10a: Tip deflection time histories

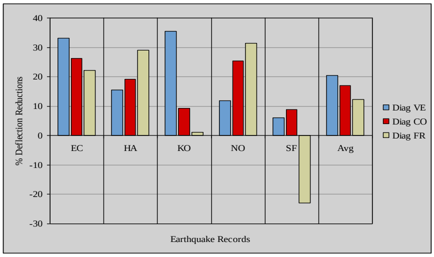

Figure 10b: Deflection mitigation

New information

Structural control and seismic mitigation of building structures are possible with carefully designed passive damper systems. Knowledge of structural dynamics is imperative to understand and implement this in practice.

Monitoring the Health of Aging Structures - Structural Health Monitoring

Structures such as buildings and bridges are designed to have long life spans, but changes in their loading and environmental conditions can cause damage to these structures. Vibration based Structural Health Monitoring (SHM) is the technique in which the condition of a structure is monitored through the changes in its vibration characteristics which can then be used to evaluate damage indices that can detect damage. Early detection of damage and appropriate retrofitting will prevent structural failure. Damage in a structure results in a change in its vibration characteristics and this is the basis of vibration-based SHM techniques which are extensively used today (Shih et al, 2009 and 2012). There has been extensive research at QUT in this area, of which damage detection in the main load bearing elements of bridges and buildings, was an important part. Figure11 illustrates the detection of damage at the mid span in a beam, using damage indices based on the variations in vibration characteristics of the beam. Further information on this can be found in Shih et al (2009).

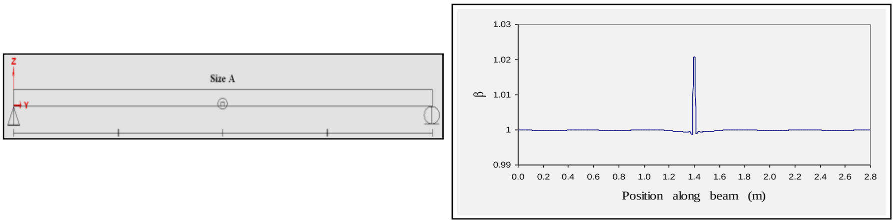

Figure 11: (a) beam with mid span damage and (b) damage detection using vibration based method

New information

Vibration based structural health monitoring techniques can be used to detect damage in aging bridge and building to enable timely retrofitting and prevention of collapse of the structure. In order to implement this important and life- saving strategy, knowledge of structural dynamics is indispensable.

CONCLUSIONS

Structural engineering has important issues in the new millennium and principles of structural dynamics are required to address these. This paper had argued the case for including structural dynamics in the syllabus of all structural engineering courses. Real life experiences of the author over two decades as well as new information from his research in structural dynamics are used to support this proposition. Some of the important information from this research area are: (i) higher modes and coupled modes of vibration can be excited in slender floor and bridge structures under human induced loads, (ii) seismic mitigation in frame shear wall structures can be realised through strategically placed passive dampers and (iii) vibration based parameters can be effective in assessing damage in bridge girders. The new generation of structural engineers must be made aware of these findings so that they can be used for the benefit of the community. This can only be achieved if these engineers are equipped with an adequate knowledge of structural dynamics. It is hoped that the proposition made herein will be acceptable to the decision makers so that the emerging structural engineers have the capability to design and construct our structures to function safely and efficiently.

This paper treated a particular topic in engineering education. The ingredients required for achieving a successful outcome in this topic however may be stated in a generic manner as follows: (i) identifying and addressing the current issues in the topic (ii) using real world examples to illustrating the topic, (iii) coordinating with practising engineers to determine the current issues in the topic and (iv) presenting the new knowledge generated through research to the engineering students. These will enable and empower our engineering students to address the current engineering issues facing the community and provide value to their engineering education.

REFERENCES

Chan, THT and Thambiratnam, DP (2011), *Structural Health Monitoring in Australia*, Nova Science Publishers, New York.

De Silva, S, & Thambiratnam, DP (2009). Dynamic characteristics of steel deck composite floors under human- induced loads. *Computers & Structures*, *87*, 1067-1076.

Huang, MH, Thambiratnam, DP & Perera, NJ. (2005).Vibration characteristicsof shallow suspension bridge with pre-tensioned cables. *Engineering Structures, 27*, 1220-1223.

Huang, MH., Thambiratnam, DP, & Perera, NJ. (2007). Dynamic performance of slender suspension footbridges under eccentric walking dynamic loads. *Journal of Sound and Vibration*, *303*(1-2), 239-254.

Marko, J, Thambiratnam, DP, & Perera NJ (2004), Influence of Damping Systems on Building Structures Subject to Seismic Effects. *Journal of Engineering Structures, 26/13*, 1939-1956.

Shih, H, Thambiratnam, DP, & Chan, THT. (2012). Damage detection in slab on girder bridges using vibration characteristics. *Journal of Structural Control and Health monitoring, article first published online 20th November, doi:0.1002/stc.1535.*

Shih, HW, Thambiratnam, DP, & Chan, THT. (2009). Vibration based damage detection in flexural members using multi-criteria approach. *Journal of Sound & Vibration, 323*, 645-661.

Thambiratnam, DP and Perera, NJ. (2012). Protection of structural systems and mechanisms from catastrophic and life-threatening failure caused by unforeseeable events. *Australian Journal of Structural Engineering, 13 (1)*, 81-96.

Thambiratnam, DP, Perera, NJ, Abeysinghe, CM, Huang, MH and De Silva, SS. (2012). Human activity-induced vibration in slender structural systems. *Structural Engineering International, 22(2)*, 238-245.