The floor vibration terminology health and social care essay

This chapter presents the background of the study, aim and scope, the research methodology, definitions and terms, significance of study and the layout of the project.

1. 1Background

Floor vibration is a natural phenomenon of a floor system in response to dynamic forces. It is predominantly induced by human activity, such as walking, dancing, jumping, or in other cases by mechanical equipment, such as air-conditioning systems, heating, ventilation, washing and drying machines. Occupants, depending on their living conditions, can be either very well aware about or they can be totally unfamiliar with this phenomenon. Modern floor systems combine the use of lightweight concrete and high-strength materials that are used to fabricate flexible, long-span floors. As a result, this becomes a serviceability issue due to a decrease in the natural frequency at which buildings vibrate. To further add to this point, all floor systems, regardless of the type of construction, are flexible, and as such they respond by vibrating when impacted. The problem arises when the vibration is of an intensity that annoys the occupants. A lightweight long span floor needs extraordinary measures in order to become acceptable for its occupants. Floors with low damping increase vibration and this is more difficult to predict because the damping properties are not only dependent on the structure, but is mostly associated with non-structural components. Thus partitions, suspended ceiling, and furniture such as cabinets and bookshelves affect the damping properties significantly. The current trend towards longer spans and lighter floor systems has resulted in a significant increase in the number of floor vibration complaints by building owners and

occupants, generating the second most frequent source of complaints; second only to roofs. According to Ellingwood (1996), floor performance which is sufficiently poor to cause users to complain may incur loss of confidence, costly remedial measures and/or litigation. Therefore, building developers and concrete floor designers should be concerned about anything that may undermine the performance of floors. Remedies for annoying floor vibration are often expensive and difficult to implement furthermore causing inconvenience to the occupant, therefore it is better to design the floor properly the first time, rather than retrofit the structure once a problem develops. Accurate prediction of the vibration problem is not available due to every person having his or her own idea of personal comfort. Current methods of predicting vibration in floor systems range from hand calculations of a simplified model to complex finite element models. However, shall be noted that each prediction method would yield different results due to different simplifying assumptions in each methods. Generally speaking, human induced footfall loading has proved to be the major source of floor vibration disturbance as it happens frequently and, in practice, cannot be isolated (Murray, 1975; Ohlsson, 1988; Hanagan & Murray, 1997). Therefore, excessive floor vibrations due to human induced loading have been characterised as " probably the most persistent floor serviceability problem encountered by designers" (Murray, 1988).

1. 2Aim and scope of study

The goal of this project is to determine the fundamental frequency and acceleration response of floor structure subjected to human-induced loads, i. e. walking and jumping. Additional aims are: To model and analyse floor

structure using Finite Element Analysis. Provide the natural frequency of the floor as well as the dynamic response of the floor using FEA. Compare data of FEA model to measured data from experiment.

1. 3Research methodology

In order to achieve the research aims, a wooden floor system was selected for the experimental and analytical investigation. This research was carried out using dynamic simulations based on FE techniques. The experimental investigation consisted of two types of excitations: Walking excitation – walking across floor panels to the direction of beams and then perpendicular to the direction of beams, each time passing near the accelerometer. Bouncing excitation – bouncing in place at a slowly increasing frequency until harmonic resonance with the lowest frequency is achieved. Finite element models were analysed using LUSAS. The FE model was calibrated against the experimental results.

1. 4 Floor vibration terminology

To better understand the terms used throughout this project, a brief overview is presented of some of the terms used in the area of structural engineering. Vibration – is form of dynamic motion in which the structure oscillates about an equilibrium position (Meirovitch, 1986). Transient and Steady-state Floor Vibration. Floor vibration can be classified as either transient or steady state, depending upon the type of excitation and its duration. Transient vibrations are caused by an impact force, such as walking, which dissipate with time. Steady-state vibrations are continuous over time and are typically caused by people jumping to the beat of music or rotating machinery. Amplitude. The maximum extent of a floor vibration,

when subjected to an excitation, either an exterior or impulse force, measured from the position of equilibrium. It is apparent that a low-amplitude vibration is less annoying to humans than a high-amplitude one. Frequency. Based on the stiffness, mass, and damping of a floor, a floor system vibrates at certain frequencies. Period (T) is the time it takes for one cycle to complete, reported in seconds. For floor vibrations, it is convenient to not describe the number of seconds in a cycle, but the number of cycles in a second(s). Frequency (f) is the number of oscillation a point undergoes within a second, which is 1/s or Hertz (Hz). Frequency is inversely related to period as shown in Equation 1. 1. The lowest natural frequency of a floor system is the fundamental frequency of the system. $f = 1/T$ (Hz)(1. 1)Damping. Damping is simply the rate of decay of the amplitude i. e. the exponential decrease in the amplitude of an oscillation as a result of energy losses. It occurs due to the presence of frictional forces. If damping is completely absent in an ideal system, the floor once excited will oscillate indefinitely with constant amplitude at its natural frequency. In contrast, critical damping is defined as that amount of damping due to which a freely excited system does not oscillate but returns to its original position in the shortest possible time. Dynamic Loading. Dynamic loading is defined as an external force applied to a system that varies with time, or loads applied over a finite period of time, as opposed to static loads. There are four different types: harmonic, repetitive, transient, or impulse. Harmonic dynamic loading is usually caused by an unbalanced rotating machine that can repeat the same force at a consistent time interval. Repetitive dynamic loadings are impulse loads applied frequently to a system, such as human walking, running, dancing, etc. Transient dynamic loading is a force applied

at random to a system. They are usually associated with wind loads but can also be associated with the movement of people. An impulse load is a single dynamic load or force that is applied in a relatively short period of time. Resonance. Resonance is when a dynamic load applied to a floor system causes the system to vibrate at or near the same frequency as the fundamental frequency.

1. 5 Significance of Study

1. 6 Layout of Project I

The information reported in this project is organised in to five chapters. Their content is as follows: Chapter 1: An introduction and background to the research topic, aims and scope, outlining the method of investigation used in this research. Chapter 2: This chapter highlights a review of previous literature published on the dynamic performance of floor structure system under human-induced loading. It describes the current design methods and previous experimental and numerical investigations and identifies the gaps in the knowledge. Chapter 3: The experimental methodology and the testing procedure for a wooden floor are described here. Chapter 4: The results are used to determine the dynamic characteristics of the investigated floor system as well as the validation of FE model. Chapter 5: The dynamic responses (acceleration responses) under human-induced dynamic activities are discussed in this chapter.

Chapter 2 - Literature Review

The purpose of this section is to present an overview of relevant past research work which has been performed by numerous researchers in the

area of floor vibration to gain an insight and an awareness of different arguments, theories and approaches. The review of literature reported in this section will be focused on vibration serviceability of long-span floors accommodating relatively ' quiet' occupancies such as offices. For these occupancies, the dynamic loading induced by walking has proved to be the most critical, as vibrations caused by normal walking are frequent and may become annoying to other floor users (Ohlsson, 1988; Wyatt, 1989; Eriksson, 1994).

2. 1Overview of Vibration Codes

2. 1. 1 General Design Codes

The guidance provided in the Australian Standards AS3600 (2009), AS4100 (2007), AS2327. 1 (2003), AS5100. 2 (2007), British Standards BS8110-1(1997), BS5950 (1994) and the Structural Euro Codes EN 1992, EN 1993 and EN1994 (Structural Euro Codes, 1992; 1993; 1994) covering concrete, steel, composite and bridge structures is generic and limited to isolating the vibration source, increasing the damping and limiting frequencies to control the effects of floor vibration induced by human activity.

2. 1. 2British Standards

There are currently two relevant British Standards. BS 6841(British Standards, 1987) provides general requirements for the measurements and evaluation of human exposure to whole-body vibration and repeated shocks. BS 6472-1 (British Standards, 2008) gives guidance on the evaluation of human exposure to building vibrations (1 – 80 Hz range). It refers to existing methods to calculate vibration response of simple structures such as

rectangular plates under harmonic or impulsive loads. It suggests the use of finite element techniques for other floor structures. Excitation functions for human activities are provided in this standard which also highlights the use of realistic damping based on previous experience with similar floor structures. This standard requires the acceleration to be frequency-weighted using the charts provided.

2. 1. 3Australian Standard

The Australian Standard that relates directly to vibration is AS2670 (2001). It provides guidance on the evaluation of human exposure to whole-body vibration: Part 1 gives general requirements, while Part 2 treats continuous and shock induced vibration in buildings and presents base curves for acceleration limits.

2. 1. 4Canadian Standards

2. 1. 5ISO Codes

International Standardisation Organisation (ISO) Codes provides guidelines for occupancy comfort and operating criteria for structures subjected to vibration. There are currently three ISO publications:(i) ISO 2631-1 (1997) provides general requirements for the evaluation of human exposure to whole-body vibrations. This code suggests the use of frequency-weighting functions to evaluate vibration for human perception/discomfort in both the vertical and horizontal directions. It describes the frequency weighting method and the method of determining the RMS acceleration.(ii) ISO 2631-2 (2003) includes the evaluation of human exposure to vibrations in building in the range 1 -80 Hz. This code has extended requirements compared to ISO

2631 (REF). However, it does not provide any guidance on vibration assessment based on acceptable limits.(iii) ISO 10137 (2007) is the latest edition and contains the bases for the serviceability design of building structures and walkways subjected to vibration. It provides base curves with acceptable RMS acceleration limits for vibration assessment. This ISO code also provides damping ratios for different types of floor structures and walkways. It suggests the use of the simplified methods in the practice guides (discussed below) or numerical techniques such as the finite element and boundary element methods for determining the vibration response and acceleration of structures.

2. 1. 6Practice Guides

There are two guides commonly used in North America; the American Institute of Steel Construction (AISC) Design Guide 11 (1997) and the Commentary D of the National Building Code of Canada (2005). Both guides use the peak unweighted accelerations as the acceptability criteria for vibration control in building floors for different occupancy types. These limits are based on the recommendations made by Allen and Murray (1993) in a previous publication, and do not consider the influence of vibration duration and frequency on the acceptable limits. AISC Design Guide 11 (1997) provides a method to determine the peak acceleration and the fundamental frequency of concrete/steel framed floor structures which are then used to check compliance. A more recent practice guide is the Design of Floors for Vibration: A New Approach by the Steel Construction (SCI) of the U. K (Smith et al, 2007), which can be used, as the title indicates, in the design of floor structures for vibration. It provides methods of analysis, design and

assessment of vibrations in steel framed concrete composite floors and floors using C and Z shaped steel joists with screw-fixed floor boarding. Finite element modelling is suggested for other types of structures. Acceleration response must be frequency weighted and used to calculate the RMS acceleration. The response factor, which is the ratio of the RMS acceleration to the base value given in BS 6472-1 (2008), is then calculated and used as an assessment criterion.

2. 1. 7Summary

The codes and practice guides outlined provide simplified methods to determine vibration response, but these are limited to certain types of structures. Both the codes and practice guides suggest the use of Finite Element (FE) techniques to determine the vibration response of structures, but they do not provide adequate guidance on the appropriate FE techniques for different types of floors. The simplified procedures for the design of building floors for human induced vibration in the 2009 JCR (2009) are not applicable to structures which exhibit complex vibration.

2. 2 Early Research

The first known stiffness criterion for floors was proposed by Thomas Tredgold (1828), a famous carpenter and one of the fifty founders of the UK Institution of Civil Engineers (ICE). Allen and Rainer (1975) and Sabins (1979) quoted the following statement made by Tredgold (1828): " Girders should always, for long bearings, be made as deep as they can be got; an inch or two taken from the height of a room is of little consequences compared with a ceiling disfigured with cracks, besides the inconvenience of not being able to move on the floor without shaking everything in the room". In the year

1929, Hyde and Lintern reported that the growing transportation systems had raised considerable concern about the damage to roads and buildings due to external vibrations. According to them, the problem was not new as H. R. A. Mallock had experimentally investigated in 1901 vibrations caused by the Central London Railway. Upon numerous complaints, Mallock investigated the effects of vibration from passing trains on houses near Hyde Park. This work is one of the earliest pieces of evidence of research on human sensitivity to vibrations in buildings (Steffens, 1965). Mallock considered floor (presumably peak) accelerations of 5% g to be a nuisance whereas five times lesser accelerations could be considered as " noticeable" to the floor users. He also maintained that different people will have different personal sensitivity to the same floor vibrations. This was one of the first attempts to understand the variability in subjective annoyance to vibrations (Dupius & Zerlett, 1986). Reiher and Meister (1931) conducted one of the first laboratory studies into human vibration. In 1931 they published a paper entitled " The Sensitiveness of the Human Body to Vibration" in which a group of people were subjected to steady-state vibrations and were asked to rate the experience. The aim of their study was to determine exactly what combinations of frequency and amplitude affect humans. The frequencies varied from 5 to 70 Hz and the amplitude ranged from 0. 001 to 0. 04 in. Classifications of " slightly perceptible", " distinctly perceptible", " strongly perceptible", " disturbing", and " very disturbing" were used to describe the vibration conditions. From this data, a chart was created, called the Reiher-Meister Scale (Fig. 1). General, designs that approach or exceed the upper portion of the " distinctly perceptible" range should be avoided. Various researchers have verified that the modified Reiher-Meister scale is accurate

for predicting perceptibility to vibrations for concrete slab (including concrete fill on metal deck) floor systems framed with steel joists or steel beams, as depicted in Fig. 1. However, in 1966, Lenzen discovered that humans are much less sensitive to transient vibrations than they are to steady-state vibrations and proposed that the Reiher-Meister's 1931 criteria should be multiplied by a factor of 10 to take into account the transient nature of floor vibrations. Lenzen based this modification on conclusions that acceptable damping found in floors will limit the magnitude of vibrations caused by transient loads. Fig. 1. Modified Reiher-Meister scale relates perception of vibrations to amplitude and frequency (REF).

2. 3Walking Excitation

Harper, in the year 1962, published one of the first papers on the forces caused by human walking. The research conducted was not based on the vibration of floors but the abrasion and slipperiness of floor structures. Nevertheless, Harper characterised walking footprint time signatures as " broadly similar for all subjects" indicating that some sort of generalisation of the walking forcing function could be possible for the whole human population (Harper, 1962). Wiss and Parmelee, in 1974, studied the effect of transient vertical vibrations on a group of test subjects, using frequency displacement and damping as parameters (Wiss and Parmelee, 1974). In 1976, a design criterion was introduced by Allen and Rainer on a number of walking tests performed on long span floors. This criterion was included in the Canadian Standards Association Standard, CSA S16. 1 (CSA, 1989). In 1985, Wyatt introduced a design criterion for walking similar to the current American Institute of Steel Construction (AISC) Design Guide procedure

(Murray, et al., 1997). Wyatt (1989) stated that due to rising and falling while walking, a human body can experience accelerations as high as 3 m/s2 (30%g). This is perfectly acceptable even though it is several hundred times greater than the vibration perception threshold. This is because the nervous system of humans is capable of associating such high accelerations with walking in progress and simply disregards them (Wyatt, 1989). As a consequence, very small vibrations of the structure, across which the walking is performed, pass unnoticed by walkers as their vibration perception thresholds are automatically adjusted to a much higher level. This is the reason why equal contour criteria applicable to stationary people are not applicable to those who are moving. In 1989, the International Organization for Standardization (ISO) presented the scale shown in Fig 1. This scale, which shows the recommended 10 limits of peak acceleration, due to walking, for human tolerance, later became a core portion of the AISC Design Guide procedure.

Fig. 1. Recommended Peak Accelerations (Allen and Murray, 1993).

In the publication Design Criterion for Vibrations Due to Walking, Allen and Murray (1993) recommended peak accelerations, as shown in Figure 1, for offices, residences, malls, and footbridges. In addition, Allen and Murray developed design techniques and approaches for estimating required floor properties based on walking excitation. Many of the same procedures used in the AISC Steel Design Guide Series 11 Floor Vibration Due to Human Activity is based on the work performed by Allen and Murray.

2. 4 Control and Minimisation Floor Vibration Problems

Several methods are found in the literature to control and minimise floor vibrations and a summary of some of the most interesting as well as some of the most commonly reported are given below. Floor systems with poor serviceability due to excessive vibrations have several solutions. Tuned Mass Dampers (TMD) is known to reduce vibrations. Rottmann (1996) performed research in this area. It was concluded that TMD can be used to control floor vibrations if there is initially a low relative damping in the system. She states, that there are difficulties in using TMDs to control multiple modes of vibration with high damping and closely spread frequencies. Rottmann also noted that the true effectiveness of TMDs is dependent on the perceptivity of occupants in a structure. Active control is another solution to overcome annoying excessive floor vibrations. Active control uses an actively controlled mass to dampen vibration (Hanagan, 1994). Hanagan stated that this method is very effective and provides much less disruption in the building than undertaking other methods of repair. According to Hanagan, high initial and maintenance costs are regarded as serious disadvantages to using this system. In a paper written by Allen & Pernica (1998) it was stated that a simple floor deflection criterion (deflection of less than span/360 under distributed live load) has been used to control ' excessive shaking' for more than 100 years. Floor vibration generally makes people uneasy and creates fear of structural collapse, although such fear is usually unnecessary because of the small displacements and stresses that are actually produced. Nonetheless, perceptible vibration is usually considered to be undesirable and can significantly impact how a person perceives the quality of a building and even affect a worker's efficiency. The following are ways which can be

evaluated to minimise floor vibrations: Changing the frequency of floor – by changing bay sizes, increasing the depth of the floor system. Adding weight to the floor – by thickening a slab, using normal weight instead of light weight concrete. Increasing the weight of the floor increases the amount of force necessary to excite floor vibrations. Damping the floor – damping a floor decreases the magnitude of vibrations that have been introduced. Isolating the affected area from the rest of the structure – provide separate framing for the area of extreme vibration, such as aerobic studios, dance halls, running tracks, so that it is completely isolated from the rest of the structure. Floor vibration is a more significant concern today than it ever was. Open floor plans need larger bays and wider column spacing, which are more susceptible to vibration problems. However, due to more efficient structural designs and stronger construction materials the weight and the size of the floor framing have been reduced. For today's buildings it is important that a structural engineer uses the most current analysis techniques. If floor vibrations are encountered after a floor is constructed, the options for addressing floor vibrations are limited and may be expensive or impractical. If the floor has additional load capacity, weight can be added, columns can be added to decrease span lengths, and damping systems can be used to minimise floor vibrations.

2. 5 Prediction and Assessment of Vibration Serviceability

People are generally very sensitive to unexpected vibrations. Very small levels of building floor movements due to activities such as walking can become annoying to occupants. Accurate prediction, evaluation, and assessment of vibrations can greatly assist engineers and architects to

design cost-effective building structures without such problems. Following the ISO 10137 procedure, the first step towards the assessment of vibration serviceability of floors is to identify and characterise the following three factors: The vibration source, The transmission path, andThe receiver.

Vibration Source

For floor vibration, the source is typically human induced vibration due to normal usage, such as walking or jumping. Lenzen (1966) stated that " a normal floor is not subjected to a steady-state vibration induced by machinery" because " the machinery can be easily isolated from the floor system and, thus, the vibrations eliminated". Therefore, most research concerning floor vibrations is focused on limiting the effect of transient and steady-state human-induced vibrations. Vibrations in buildings can have a wide variety of causes. It may vary both in time and in space. These can conveniently be broken down into two groups: (1) ' external', and (2) ' internal' vibration sources. External Vibration SourceAccording to Wyatt & Dier (1989), problems with vibrations caused by external sources are generally best treated by isolating the building as a whole. ISO 10137 gives the following examples: Construction activity (pile driving, compaction, excavation, etc.); Construction, mining or quarry blasting; Road and rail traffic; Fluid flow (wind or water); Punching presses or other machinery in nearby buildings. Internal Vibration SourceInternal vibration sources, originating in the building, consist of ventilation systems, elevators, lift trucks, cranes, objects falling on the floor, human excitation, such as walking, running, jumping and stomping and various construction activities within the building. ISO 10137 states the following as examples for internal

vibration sources: Human excitation; Moving machinery (trolleys, overhead cranes, conveyors, elevators, etc.); Impact machinery (punches, presses, etc.); Rotating machinery;

2. 5. 2The Transmission Path

The transmission path is defined as the path through which vibration energy is transferred from the vibration source to the receiver. In this case, the building structure is the path. The receivers of the transmitted vibrations are other humans occupying the same floor system as source. Structural components transmitting vibrations could be column, walls, foundations and floors, whereas non-structural paths may be access floors, removable partitions, cladding, etc. For vibrations in buildings, the transmission path is most frequently assumed to comprise the building structure itself. However, ISO 10137 (ISO, 1992) gives the following examples of transmission path: Ground, air, or water; Structural components (foundations, floors, columns, walls, etc.); Non-structural components (pipes, partitions, etc.).

2. 5. 3The Receiver

The receiver is defined in ISO 10137 (ISO, 1992) as the " person, structure or equipment subjected to vibrations". The person is the occupants of the building whereas the objects can be either vibrating or non-structural elements (walls, beams, slab, etc.) or contents of the building such as instruments or machinery. Vibration serviceability is best considered in the early stages of design development. Owners and architects must be made aware of the implications of their decisions. Engineers should not take responsibility for conditions they cannot control. The more complex a

structure becomes, the more difficult it is to accurately predict and effectively minimize the impact of vibration.

2. 6 Vibration Testing of Floors

Generally in vibration test of floors, initial tests are conducted using the impact method of loading, such as the instrumented impact hammer or heeldrop loading. The results from the impact tests are used to identify a perceived critical area for further detailed forced vibration tests. In the case of an instrumented hammer, the force is measured by a load cell installed at the tip of the hammer. Whereas, the heel-drop test is a simple standard impact test in which a person of average weight rises to the balls of his feet and suddenly drops onto his heels, thus impacting the floor. The resulting response of the structure can be measured, from which the natural frequencies of the floor can be derived. To determine the fundamental natural frequency and frequencies for higher modes of a floor system, the method of experimental testing and finite element modelling can be undertaken. Experimental testing is done using an accelerometer and a data collector. The accelerometer is placed in an area of interest and the floor system is subjected to a dynamic load. The standard heel-drop function is applied to a system by having a 170-lb person rocking up on the balls of his feet with his heels about 2. 5 in. off the floor, and then relaxing and allowing his heels to impact the floor (Murray, 1981). Other methods of loading the system include walking in various directions or doing a bounce test. A bounce test is where a person will try to bounce at a multiple of the natural frequency of the floor system in an attempt to excite the system at its natural frequency. For all tests, dynamic response is measured.

2. 7 Modal Testing of Floors

Several researchers have reported studies which include modal tests of building floors. Modal testing, as described by Ewins (1995), is " the processes involved in testing components or structures with the objective of obtaining a mathematical description of their dynamic or vibration behaviour". This mathematical description normally consists of the natural frequencies, mode shapes and modal damping ratios. There are two types of modal test; a) the excitation force creating the response is not measured and b) where the excitation creating the response is measured. A modal test consists of an acquisition and an analysis phase. The complete process is often referred to as a Modal Analysis or Experimental Modal Analysis. It has traditionally been used by mechanical engineers to design relatively small structures and components through prototyping. It has recently been used as validating Finite Element models of such structures, hence reducing the number of prototypes required. According to Pavic (1999) the sheer size of civil engineering structures, combined with technical problems such as very low responses to be measured in the presence of a great deal of environmental noise, means that sensitive instrumentation and complex signal processing techniques are required. These have not been available until the last few years. Lenzen and Murray (1969) used the impact excitation and amplitude decay method to measure damping on 20 full-scale steel-concrete floors. The estimated damping ratios varied between 3. 8% and 15. 9%, the average value being 7. 9%. The other damping values obtained were dismissed later as unreliable by Ohlsson (1988) and Eriksson (1994), due to an inappropriate measurement techniques. Similar problems with damping measurements were seen in the papers by Lenzen et al.

(1971), Lenzen (1972) and Murray (1975). Caetano and Cunha (1993) described a modal testing facility which they set up for the testing of various sizes of civil engineering structures. The exciters were an instrumental hammer, an electrodynamics shaker and a rotating eccentric mass shaker. They also presented a case study of the modal testing applied to a 6. 6 m × 6. 6 m reinforced concrete roof plate for which they managed to determine its natural frequencies, mode shapes and modal damping ratios. Eriksson (1994), in his doctoral thesis, considered the problem of the vibration of low frequency floors. He used experimental modal analysis as a tool to determine the modal properties of the structures that he was examining (concrete and composite steel-concrete floors with natural frequencies lower than 9 Hz). Excitation was applied using an impactor, the floor response was measured using accelerometers and both the excitation and response signals were processed by a dual channel spectrum analyser. Although some success was achieved, the relative crudity of the test equipment and data processing techniques limited the reliability of the experimental data. Pavic (1999) performed one of the most comprehensive applications of modal testing technology applied to civil engineering structures, in terms of testing and analysis procedures. He successfully tested a number of structures, applied complex modal parameter estimation techniques and performed quite complex model correlation and manual model updating to FE models of the same structures. However, the only exciter used in this work was an instrumented impact hammer, due to financial constraints. Using more improved methods and procedures of excitation such as an electrodynamics shaker, it would be possible to obtain more accurate and consistent modal test results.

2. 8 Laboratory and in-situ Floor Testing

The results obtained of vibration of floors in laboratories are different to that in real life situations. A great advantage when undertaking test in laboratories is that full control of the setup can be achieved. The boundary conditions can be controlled, which combined with the floor properties, would determine the accuracy of the dynamic measurement of a floor. To minimise the effects of the surroundings the floor should be unaffected by its supporting walls which in practice means that the floor is put on rigid concrete supports or any other support with higher stiffness than the floor so that the boundary condition is as exact as possible. For in-situ measurements, the exact boundary condition is usually not known. This is because of the complicated interactions, for example external and interior walls. For that particular setup the results should be treated as valid and not as result of the specific floor construction solely. The results from the experimental measurements in laboratories and in-situ measurement inside real buildings have significant differences between them. The natural frequency varies due to stiffness vibration of the boundary conditions, mass loading from partitions etc. For the in-situ floor, damping is significantly higher. A lightweight floor in laboratory has a damping ratio of 1-2% and in-situ can increase to 10%. Shope and Murray (1994) recorded accelerations on a laboratory test floor and an in-situ long span (52 feet) steel joist composite floor identified from occupant complaints of excessive levels of vibrations. The authors presented unreferenced acceleration time histories of both structures from heel drop and walking excitations, and the study included the successful implementation of tuned-mass dampers to reduce the acceleration response. Kitterman (1994) investigated several vibration

characteristics of steel member supported floors, particularly the effective width of one-way steel joist and steel beam-concrete slab floors and the effective moments of inertia of steel joist and joist-girder members. The author created finite element models of numerous theoretical floors and performed a dynamic response analyses to synthesized heel drop impacts. The only experimental work conducted was on an atypical steel joist and joist-girder laboratory floor, investigating the ability of joist seats to transfer shear from the supporting girder to the overlying slab. The experimental work included finite element modelling and frequency measurements. Finite element modelling techniques recommended by Kitterman were incorporated in the presented research. Pavic et al. (1997) performed impact hammer modal testing of a large concrete parking garage floor and performed finite element modelling. Although his investigation involved a concrete structure and not a steel composite structure, Pavic concluded that using significantly higher values for modulus of elasticity of concrete was needed to bring computed results into agreement with measured frequencies. This agreed with the DG11 recommendation of using 1. 35 times the computed modulus of elasticity for concrete (Murray et al. 1997). Warmoth (2002) investigated the effect of joist seats on effective girder moment of inertia and girder frequency of steel joist composite systems. The frequency spectra of several laboratory test floors were measured. He proposed a method for calculating the effective moment of inertia based on the type of joist seats used in the composite construction, which is insightful for use of the presented research techniques for FE modelling of the stiffness of steel joist floor systems. Ritchey (2003) investigated the use of specialized tuned-mass dampers to reduce floor vibrations. His research included

experimental modal testing of a one-way steel composite laboratory test floor both with and without the device installed. The experimental testing he accomplished was conducted with the same test equipment as the presented research.

2. 9 What is an Operating Deflection Shape (ODS) Analysis?

An operating deflection shape (ODS) is defined as any forced motion of two or more points on a structure. Specifying the motion of two or more points defines a shape. A shape, stated differently, is the motion of one point relative to all others. Motion is a vector quantity, which means that it has both a location and a direction associated with it. Motion at a point in a direction is also called a Degree Of Freedom, or DOF. Experimental modal parameters are obtained by artificially exciting a machine or structure, measuring its operating deflection shapes, and post-processing the vibration data. Olsen (1984) classified structural dynamic excitation techniques into five general types: operating, steady-state, periodic, transient and random. Operating excitation represents the dynamic loading applied to a structure in its operating condition and is normally not measured. Since a requirement of EMA is a measurable form of excitation (Ewins, 1995), operating excitation is not suitable. The first attempts at experimental modal analysis of civil engineering structures were performed by measuring only the response of the structure due to unmeasured excitation. Since the excitation is not measured in this technique, ' it is not theoretically possible to completely decouple multiple modes of vibration and the ' mode shapes' measured are in fact ' operating deflection shapes' which contain contributions from all modes of vibration' (Spectral Dynamics, 1994). However, near a resonant

frequency, for a system with well separated modes of vibration, an operating deflection shape is a close approximation to a mode shape. This form of testing was applied to floor structures by Rainer and Swallow (1986) and by Pernica (1987). A reasonable degree of success was achieved and the testing enabled a fairly accurate assessment of the natural frequencies and mode shapes.

2. 5 Finite Element Modelling of Floors

Floor vibration can be calculated using Finite Element Analysis (FEA) based on building structural elements, such as floor thickness, beam, etc. FEA is a powerful tool using differential and integral equations that shows all the details of the vibration. Nevertheless, several considerations are required for the finite element modelling of floors. Some of the most recent research which used complex finite element models was performed by Sladki (1999). For the lowest natural frequency of floor systems, it was concluded in the research that finite element methods gave better prediction than the Design Guide criteria. However, for peak acceleration the analytical methods did not compare well with the actual test results (Sladki, 1999).

Boundary Conditions of floors

Theoretically, a simply supported end condition provides no moment resistance, while a fixed end condition provides infinite capacity to carry moment. The true boundary conditions in real floor structures cannot be absolutely known from visual inspection of the floor or floor plans. However, laboratory floor systems can provide an opportunity to investigate how the floor response under a forcing function is affected by different end conditions, from nearly free to the condition that approximates a " real

world" floor. In this study, floors were tested at five different end conditions. First, each floor was supported by two steel pipes at the ends to approximate a simply supported boundary condition. This was necessary because the proposed analytical model needs to be validated with experimental data under an ideal boundary condition before it can be applied. Then, each floor was tested while the ends were supported with aluminium bars (simulation of hard supports), decayed jack pine boards (simulation of soft supports), and decayed jack pine boards with a layer of neoprene material on top of the boards (simulation of super-soft supports). These conditions were examined because they are often encountered in some floor structures where one end of the joists rests on a wooden or steel girder in used to mimic floor joist ends resting on decayed wooden sill plates. Finally, the floors were tested with the ends of joists embedded in prefabricated masonry pockets, which simulates the end conditions of typical floor structures in existing buildings.

2. 5 The Effects of Access Floors

Access floors are types of floor that provide an elevated structural floor above a concrete slab to create a hidden void for the passage of electrical and mechanical services. They are widely used in modern office buildings, computer rooms where the route for wiring is needed. There are only a handful of papers in the literature which described the possibly beneficial effects of access floors with respect to floor vibrations. Osborne & Ellis (1990) presented the results from vibration tests on a composite steel-concrete floor prior and post the addition of an access floor. They did not detect any changes in the modal properties of the floor after addition of the access floor, but they reported that the perception of floor vibrations due to

footfall loading was considerably reduced. Williams and Waldron (1994) presented the results of tests carried out on 14 structures, 4 of which contained access floors. They concluded that floors with access floors were quite heavily damped in comparison with floors without access floors. However, on further examination it was known that these damping values were estimated using inappropriate method, and it is possible that these larger damping values were caused by the likely presence of modes of vibration of the floors close to the fundamental. Rainer & Pernica (1981) presented data which demonstrated an increase in the damping of a composite floor sample following the addition of a suspended ceiling. This was due to the friction between the ceiling panels and the supporting T-sections. It is expected that access floors may exhibit this damping mechanism than suspended ceiling due to the fact that access floors are significantly heavier than suspended ceilings. A paper by William & Falati (1999) described a series of test undertaken on a small slab trip constructed at the University of Oxford. The authors concluded that the access floors may be designed and utilised in such a way as to increase the damping of floor systems and hence improve their vibration serviceability performance. However, as with other work, this also has its limitations. Firstly, the methods used (half-power bandwidth and logarithmic decrement methods) to determine the modal damping ratios have been shown to typically overestimate damping. An important limitation is that the slab on which the access floors were tested was very small compared to what might be expected in practice, while the access floors were the same size as would be used in practice. This may be responsible for the overestimation of the effects of the access floors to a degree which is not possible to quantify. So,

while these tests clearly indicate the benefits of using access floors, the magnitude of the benefits remain uncertain.

2. 6 Probabilistic Methods

Brownjohn et al. (2004) developed a frequency domain modelling approach for long flexible structures which account for walking imperfection of individuals and crowds. They indicate that the leaking of energy into adjacent frequencies accounts for the reduced measured response compared to finite element predictions. One case study is presented, indicating that for normal walking, the degree of correlation of vertical walking forces among pedestrians approaches zero. One useful conclusion for the current research is that a very large number of normal walkers is required to produce an acceleration larger than that produced by a single resonant walker. Zivanovic et al. (2007) extended the work of Brownjohn et al. (2004) by introducing the concept of sub-harmonics of walking forces which occur in the frequency domain halfway between main walking harmonics of the walking force. These occur due to the inevitable difference between left and right footsteps. They developed loading models in the frequency and time domains and a response simulation procedure using 2000 generated force histories.

2. 6 NEED FOR RESEARCH

There are many areas for future research in the topic of floor vibration. The wide variety of scales and prediction techniques available to engineers is an indication of the complex nature of this topic. Furthermore, not all methods of prediction are equally applicable to all solutions due to different simplifying assumptions in each method and because of the general complex

nature of the floor vibration. It is due to these considerations that several aspects of floor vibration and modelling assumptions should be studied in greater detail. If the accuracy of testing of floors is increased there will be fewer problems occurring in complete structures. A probabilistic procedure has been developed by Zivanovic et al. (2007). This procedure results in predicted probabilities of vibrations exceeding specific levels. However, the procedure is only available through the use of proprietary software owned by the University of Sheffield. Very limited verification of the accuracy of the procedure has been presented by Zivanovic et al. (2007) using measured modal properties in the predictions. The accuracy of any response prediction, regardless of the elaborateness of the loading function, depends on the accuracy of modal property prediction. Therefore, it is useful to develop alternative response prediction methods, based on finite element modelling and backed up by modal tests. These will be generally applicable, as easy as possible to learn and use, and available for immediate use by design engineers using readily available structural analysis software. Instead of assuming rigid supports for the retrofit posts, they could have been modelled as springs with appropriate stiffness's. This closer investigation would provide more accurate results in predicting the effectiveness of retrofits in floor systems. Further research in the area of floor vibrations is needed where the AISC Design Guide does not provide methods to analyse certain floors by simple hand calculations. Such floors cannot use these hand calculations due to inherent complexities. A lot of research is needed in the computer modelling aspect of floor vibrations.