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The effects of partitions on the vibration
serviceability of concrete floors

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Thesis submitted to the Faculty of Engineering and The Built Environment of the University of Cape Town in partial fulfilment of the requirements for the Degree of Master of Science in Civil Engineering.

July 2012

DECLARATION

This dissertation is submitted to the Faculty of Engineering and the Built Environment of the University of Cape Town in partial fulfilment of the requirements for the Degree of Master of Science in Civil Engineering.

I know the meaning of plagiarism and declare that all the work in the document, save for that which is properly acknowledged, is my own.

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July 2012

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Summary

The growing demand to construct long, slender floors with minimum supports for aesthetic and economic reasons especially in modern building developments has resulted in increased floor slenderness leading to vibration problems. As a result, vibration serviceability has become the governing design criterion for many of these new civil engineering structures. It is known that long span, slender floors possess lower natural frequencies and reduced damping leading to vibration serviceability problems. As vibration serviceability becomes a major concern in the design of concrete floors, investigations of the beneficial effects of non-structural elements to the vibration serviceability of floors are becoming increasingly important. The vibration serviceability of long span, slender concrete floors may be improved through the installation of non-structural elements such as partition walls and raised access floors.

Little research exists into the quantification of the effects of various types of partitions on the vibration serviceability of concrete floors that support them. There are no guidelines available to designers which take into account the effects of partitions in the design of concrete floors for vibration serviceability besides the different damping ratios that are recommended in different codes for bare floors as well as floors with half- or full-height partitions. Therefore a research project was initiated with the objectives of investigating the effects of non-structural partitions on the vibration serviceability of concrete floors as well as proposing guidelines on how to account for partitions in the design of concrete floors for vibration serviceability.

The research project consisted of modal testing on a prestressed pre-tensioned concrete floor slab. The excitation of the floor was generated by an electrodynamic shaker and instrumented impulse hammer. The electrodynamic shaker excitation was used mainly to extract the natural frequencies and mode shapes of the test floor. The instrumented impulse hammer excitation was used mainly for damping studies. Force-balanced QA 700 accelerometers with a sensitivity of 8 V/g mounted to base plates were used to measure the responses of the test floor. The Data Physics Signal Calc Mobilyser was used to acquire the data from the accelerometers. A personal computer was used to store, analyse and present the data. The curve fitting method in Vibrant Technologies ME'Scope was used to estimate the natural frequencies and mode shapes of the test floor. Modal 1.20 by Brownjohn (2009) was used to estimate the damping ratios of the test floor. Modal 1.20 uses the logarithmic decrement method to estimate damping. The tests investigated the effects of partitions on the vibration serviceability of concrete floors.

Plywood with a thickness of 21 mm was used to simulate half-height as well as full-height timber partitioning. A brick wall was constructed to simulate half-height as well as full-height brick partitioning. The difference between half-height and full-height was based on the fixity at the top of the partitions. The half-height partitions were not fixed horizontally at the top, therefore they were free to rotate. The half-height timber partitions were fixed to the concrete floor by four steel brackets spaced at 600 mm centres. Full-height brick and full-height timber partitions were fixed horizontally at the top. A steel frame was built to provide restriction at the top of the plywood and brick wall in order to simulate full-height partitioning. Four layouts were used to simulate half-height timber partitioning. One layout was used to simulate full-height timber, half- and full-height brick partitioning. The brick and timber partitions had a height of 1.20 m.

It was found that half-height brick and timber partitions decrease the natural frequencies of the floor supporting them. This is caused by the increase in mass being more significant than any increase in stiffness following the installation of half-height partitions. Half-height brick and timber partitions were also found to increase the damping of the floor supporting them. It was further found that half-height timber partitions do not change the mode shapes of the floor supporting them regardless of

their orientations. It was also found that the half-height brick partition at midspan does not change the mode shapes of the floor supporting it. It was found that full-height brick and timber partitions increase the natural frequencies of the floor supporting them. This is caused by the increase in stiffness being more significant than any increase in mass following the installation of full-height partitions. Full-height brick and timber partitions were also found to increase the damping of the floor supporting them. It was further found that full-height brick and timber partitions do not change the mode shapes of the floor supporting them. The response factor of the test floor did not change following the installation of the various configurations of partitions. This was because it depended on the geometry and material properties of the test floor and not on the modal parameters, therefore it was not influenced by the installation of partitions.

It was concluded that the modal parameter of interest when dealing with full-height partitions is the natural frequency since full-height partitions were found to increase the stiffness of the floor supporting them. The modal parameter of interest when dealing with half-height partitions is the damping ratio since half-height partitions were found to increase the damping of the floor supporting them.

Some damping ratios obtained in this research project are similar to those recommended by SCI P076 (1989), SCI P331 (2004) and AISC (1997). The damping ratios recommended by CSA (1989) are double those recommended by the other codes of practice as well as those obtained from this research project. Therefore the damping ratios recommended by SCI P076 (1989), SCI P331 (2004) and AISC (1997) can be considered reasonable and used in design of floors for vibration serviceability to account for the presence of half-height partitions. The damping ratios recommended by CSA (1989) are an overestimation. These values are double those recommended by the other codes of practice as well as those obtained in this research project and should not be used as a guideline to estimate damping ratios for concrete floors.

The proposed model by Fatali (1999) to account for the effects of full-height partitions on the vibration serviceability of simply supported beams can be used to quantify the effects of full-height partitions on the vibration serviceability of simply supported concrete floors because the latter usually behave as simply supported beams and the results obtained in this research project are similar to those obtained by Fatali (1999).

The lack of damping is the main cause of the resonant vibration of floors. Therefore by increasing damping, the vibration serviceability of floors will improve significantly since it was found by Lenzen (1966) that occupants of a building using a given floor could tolerate higher initial response if the damping was increased.

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NOTATION

a = Length of the plate

(a) = Distance of the partition from the nearest support

a_p = Peak acceleration in units of gravity

$a(t)$ = Frequency – weighted acceleration

$a_w(t)$ = Weighted time history

AISC = American Institute of Steel Construction

b = Width of the beam

C = Viscous damping coefficient

C_{cr} = Critical damping coefficient

CCAA = Cement Concrete & Aggregates Australia

CCIP = Cement and Concrete industry publication

CSA = Canadian Standards Association

E = Modulus of elasticity of the material

f_1 = First natural frequency of the floor in Hz

f_n = Natural frequency

f_o = Beam frequency before addition of the partition

f_{oc} = Frequency after the partition has been installed

FE = Finite element

FRF = Frequency response function

g = Acceleration due to gravity (9.81 m/s^2)

h = Thickness of the beam

HFF = High frequency floor

I = Second moment of area

K = Stiffness of the system

K_p = Stiffness of the partition material

L = Effective length

LFF = Low frequency floor

m = Mass of the system

M_n = Modal mass

P_o = The constant force based on a person weight and assumed as 746 N

RMS = Root mean square

S = Effective width

SCI = Steel Construction Institute

t = Total duration of the vibration exposure in seconds

T = Period of interest

VDV = Vibration dose value

W = Effective weight of the floor

δ = Total static deflection

ϕ = Mode shape value

γ = Mass per unit area

λ = Value depending on the ratio between the length and width of the plate

ν = Poisson's ratio of the material

ρ = Density of the material

τ = Representative sample of duration

ζ = Damping ratio

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1 INTRODUCTION

1.1 Background

The growing demand to construct long, slender floors with minimum supports for aesthetic and economic reasons especially in modern building developments has resulted in increased floor slenderness leading to vibration problems. As a result, vibration serviceability has become the governing design criterion for many of these new civil engineering structures. It is known that long span, slender floors possess lower natural frequencies and reduced damping leading to vibration serviceability problems (Pavic, 1999; Reynolds, 2000).

Concrete floors were traditionally designed to an ultimate limit state (ULS) where the primary focus was on strength and safety. This strength and safety criterion governed the dimensions of floors as well as their components. The serviceability limit state (SLS) design philosophy was used to control maximum deflections. The limit in SLS was not set to avoid damage of structural components but to avoid cracking of finishes (Middleton and Brownjohn, 2010). Because of vibration problems that occur in long span, slender concrete floors; vibration serviceability has become a major concern in their design (Pavic, 1999; Reynolds, 2003).

As vibration serviceability becomes a major concern in the design of concrete floors, investigations of the beneficial effects of non-structural elements to the vibration serviceability of floors are becoming increasingly important (Reynolds, 2000). The vibration serviceability of long span, slender concrete floors may be improved through the installation of non-structural elements such as partition walls and raised access floors (Fatali, 1999; Reynolds, 2003).

1.2 Need for research

It is known that non-structural elements have beneficial effects on the vibration serviceability of concrete floors (Fatali, 1999; Pavic, 1999; Reynolds, 2000; Middleton and Brownjohn, 2010). There has been very little study into quantifying the beneficial

effects of non-structural elements on the vibration serviceability of concrete floors. Fatali (1999) studied the effects of gypsum plasterboard partitions on the vibration serviceability of concrete floors. Reynolds (2000) also studied the effects of non-structural elements on the vibration serviceability of concrete floors but focussing on false floors. It has been suggested that the installation of partitions may improve the vibration serviceability of the floors that support them (Chen, 1999; Fatali, 1999; Middleton and Brownjohn, 2010).

Design guidelines assign different values of damping ratios to bare floors, floors with half- or full-height partitions. The assigned damping ratios are based either on measurements or past experiences with similar floors. This practice is incorrect and introduces errors in the estimation of damping ratios because it has been shown that the modal parameters (natural frequencies, damping ratios and mode shapes) of even nominally identical floors could significantly differ because of different arrangements of non-structural elements such as partition walls, false floors and suspended ceilings (Miskovic et al., 2009). Most design guidelines give empirical values of damping ratios for bare floors and floors with half- or full-height partitions. The damping ratios that are proposed in design guidelines do not take into account either the type or layout of the partitions. A value of damping ratio is given for bare floors and another for floors with half- or full-height partitions as shown in Table 1.1.

Table 1.1 shows the recommended damping ratios for bare floors, floors with half-height as well as full-height partitions as they appear in the Steel Construction Institute publications SCI P076 (1989) and SCI P331 (2004). Table 1.1 also includes the recommended damping ratios for bare floors, floors with half-height and full-height partitions as they appear in the American Institute of Steel Construction (AISC) as well as Canadian code (CSA).

Little research exists into the quantification of the effects of various types of partitions on the vibration serviceability of concrete floors that support them. There are no guidelines available to designers which take into account the effects of partitions in the design of concrete floors for vibration serviceability besides the different damping ratios that are recommended in different codes for bare floors as well as for floors with half- or full-height partitions. Therefore there is a need for further study into the effects of

partitions other than gypsum plasterboard partitions on the vibration serviceability of concrete floors. These effects will have to be quantified in order to develop design guidelines.

Table 1.1: Damping guidelines from different codes of practice (Middleton and Brownjohn, 2010)

	Bare floors or very few non-structural components (%)	Non-structural elements, i.e. furniture, fixtures and fittings and half-height partitions (%)	Heavily partitioned floor with full-height partitions (%)
SCI P076	1.5	3	4.5
SCI P331	1.1	3	4.5
AISC	2	3	5
CSA	3	6	12

1.3 Research objectives

This research project was undertaken with the following objectives:

- To investigate the effects of non-structural partitions on the vibration serviceability of concrete floors.
- To propose guidelines on how to account for partitions in the design of concrete floors for vibration serviceability. These guidelines are presented in Chapter 8.

1.4 Scope of research

The research project was restricted to linear, elastic dynamic behaviours of concrete floors. Therefore it is assumed that nonlinear behaviours did not occur at any stage of the project. The research work and results are presented in eight chapters as described below.

The next chapter is a review of the background knowledge necessary for this research project. It includes important dynamic characteristics of floors, different types of concrete floors and partitions.

Chapter 3 is a review of the current state of the art on vibration serviceability of concrete floors.

Chapter 4 is a review of the early research into the effects of non-structural elements on the vibration serviceability of concrete floors.

Chapter 5 describes the methodology adopted to achieve the objectives of the research project.

Chapter 6 presents and discusses the laboratory work results.

Chapter 7 presents and discusses the field work results.

Chapter 8 concludes the research project, describes the results and gives recommendations for future work.

1.5 Summary

This chapter has presented the background to the vibration serviceability problem of concrete floors. The need and objectives of the research project were outlined. The layout of the dissertation was presented in this chapter. The next chapter will review the knowledge required for the research project including important dynamic characteristics of floors, different types of concrete floors and partitions.

2 BACKGROUND KNOWLEDGE

2.1 Introduction

Vibration is the oscillation of a system about its equilibrium position following some disturbance (Alvis, 2001). There are two types of vibrations namely forced vibration and free vibration (Alvis, 2001). Forced vibration exists when the equilibrium in a system is disturbed by an applied dynamic force such as a moving lift within a building. Free vibration takes place when the equilibrium in a system is disturbed in the absence of an applied dynamic force such as the continuous vibration within a building when the lift that generated the initial excitation is stationary.

The vibration behaviour of a structure can be described by its modal parameters. The modal parameters are the natural frequencies, damping ratios, modal masses and mode shapes. This chapter will discuss important dynamic characteristics of floors, different types of concrete floors and partitions.

2.2 Important dynamic characteristics of floors

The natural frequency is the frequency of the vibration that a system experiences (Ljunggren, 2006). The first natural frequency is also referred to as the fundamental frequency. The fundamental frequency is the lowest natural frequency of the actual system. The natural frequency is dependent on the stiffness and mass of the given system. The natural frequency in Hertz (Hz) can be calculated using:

$$f_n = \frac{1}{2\pi} \sqrt{\frac{K}{m}} \quad (2.1)$$

where K is the stiffness of the system, m is the mass of the system and f_n is the natural frequency in Hz.

The fundamental frequency of a floor can also be calculated by assuming it to behave either as a beam or plate. When a floor is assumed to behave as a beam, its fundamental frequency can be estimated using:

$$f_o = \frac{K}{2\pi} \sqrt{\frac{EI}{mL^4}} \quad (2.2)$$

where f_o is the fundamental frequency in Hz, E is the modulus of elasticity of the material, I is the second moment of area, L is the span of the beam, m is the mass per metre width and K is the constant which depends on the fixity of the beam and the mode of vibration.

When a floor is assumed to behave as an isotropic, simply supported plate; its fundamental frequency can be estimated using:

$$f_o = \frac{\lambda^2}{2\pi a^2} \sqrt{\frac{Eh^3}{12\gamma(1-\nu^2)}} \quad (2.3)$$

where f_o is the fundamental frequency of the floor, h is the thickness of the plate, ν is the Poisson's ratio of the material, a is the length of the plate, γ is the mass per unit area and λ is the value depending on the ratio between the length and width of the plate.

The fundamental frequency of a floor can also be estimated by the deflection method using:

$$f_o = \frac{1}{2\pi} \sqrt{\frac{g}{\delta}} \quad (2.4)$$

where f_o is the fundamental frequency, δ is the total static deflection and g is the acceleration due to gravity.

Another method of estimating the fundamental frequency of a floor is the Dunkerley's method. This method estimates the natural frequency of a floor by first estimating the natural frequencies of its individual components such as the composite slab, the primary

and secondary beams (Middleton and Brownjohn, 2010). The Dunkerley's formula is as follows:

$$\frac{1}{f_o^2} = \frac{1}{f_1^2} + \frac{1}{f_2^2} + \dots + \frac{1}{f_n^2} \quad (2.5)$$

where f_o is the fundamental frequency of the floor and f_n are the fundamental frequencies of the component parts of the floor system.

The damping ratio (ζ) is the ratio of the damping constant to the critical damping coefficient (Chopra, 2001). The damping ratio is calculated using:

$$\zeta = \frac{C}{C_{cr}}, \quad (2.6)$$

where C is the viscous damping coefficient and C_{cr} is the critical damping coefficient obtained using:

$$C_{cr} = 2\sqrt{Km} \quad (2.7)$$

where K and m are the stiffness and mass of the system respectively.

The critical damping coefficient is the smallest value of the damping coefficient that makes a system to return to its equilibrium position without oscillation (Johansson, 2009). Other authors such as Clough and Penzien (1975) simply define the critical damping as the smallest amount of damping required for no oscillation to occur in the free response.

Damping is a property of energy dissipation within a system (Alvis, 2001). A system with a high damping will develop a quick decay of amplitude in free vibration. A system with a low damping will retain its energy for a longer time (Alvis, 2001). It is an inherent property of all materials since they all have their own specific internal damping. The damping of a system is more complicated than the damping of its materials and components. This is because all joints, couplings, different connections within a system contribute to its overall damping (Ljunggren, 2006).

The damping values of a structural system cannot be estimated either from its dimensions or material properties but can only be measured or estimated from existing similar structures (Fatali, 1999 ; Johansson, 2009). The damping ratio is usually in the range of 2 to 10 % for real structures (Salzmann, 2002). If damping is not present in a given structure, it implies that the vibrations will never die out but will continue on forever. But in reality, all structures have some amount of damping as it is an inherent property of every material (Salzmann, 2002 ; Johansson, 2009).

The modal mass is the mass that participates in each displacement or mode of vibration (Middleton and Brownjohn, 2010). The modal masses of structures with regular geometries can be estimated from their total masses. The modal mass is half of the total mass for a simply supported beam and a quarter of the total mass for a simply supported floor bay (CCIP-016, 2006). For a simply supported beam, the modal mass is estimated using:

$$M = \frac{mL}{2} \quad (2.8)$$

where M is the modal mass in Kg, m is the total mass per unit length and L is the beam's length.

For a simply supported floor bay, the modal mass is calculated using:

$$M = \frac{mLW}{4} \quad (2.9)$$

where M is the modal mass in Kg, m is the total mass per unit area, L is the floor's length and W is the floor's width.

The mode shape is a specific deformed shape of a system (Chopra, 2001). It contains information on how a system undergoes displacement. Mode shapes are also referred to as modes of vibration. Each natural frequency corresponds to a specific mode shape. The mode shape corresponding to the lowest natural frequency is of great importance and it is called the fundamental mode of vibration (Salzmann, 2002). This mode shape is important because it is where the amplitudes of vibration are the largest (Salzmann, 2002).

2.3 Types of concrete floors

2.3.1 Introduction

A floor is an essential part of practically every modern industrial, commercial or residential building (Pavic et al., 2001). There are generally two types of concrete floors namely suspended floors and ground floors (Pavic and Reynolds, 2002a). Suspended floors are supported by structural members such as beams, columns or walls. Ground floors are supported directly by the ground. The Cement Concrete & Aggregates Australia (CCAA) in its technical report 36 (2003) assigns two groups to suspended concrete floor systems namely in-situ concrete floor systems and precast and composite floor systems.

2.3.2 In-situ concrete floors

In-situ concrete floor systems consist of elements made entirely of concrete poured onto formwork on site together with the supporting building frame to form a monolithic system (CCAA, 2003). They are further subdivided into 6 different categories: flat slab, beam and slab, ribbed (waffle) slab, band beam and slab, flat plate; and slab and joist.

A flat slab floor system (Figure 2.1) is a one-way or two-way spanning system with thickenings in the slab at the columns and drop panels (CCAA, 2003). Drop panels are loadbearing walls that increase the shear capacity and stiffness of the floor system under vertical loads (CCAA, 2003). The maximum span length for this floor system is 9.5 m when reinforced and 12 m when prestressed (CCAA, 2003). Flat slab floor systems are characterised by minimum structural depth and medium spans.

A beam and slab floor system (Figure 2.2) is one that consists of beams framing into columns and supporting slabs spanning between the beams. The beams provide stiffness to the floor therefore making it longer in span and resistant to lateral loads (CCAA, 2003). This floor system is characterised by thick slabs and long spans.

A ribbed (waffle) slab floor system (Figure 2.3) that consists of equally spaced ribs is usually supported directly by columns. This floor system is either one-way spanning known as ribbed slab or two-way spanning known as waffle slab (CCAA, 2003).

This floor system is known for its high stiffness and long spans. The maximum span length for this floor system is 15 m when reinforced and longer when prestressed (CCAA, 2003).

A band beam and slab floor system (Figure 2.4) consists of a series of parallel, wide, shallow beams with the floor slab spanning transversely between the beams. The parallel, wide and shallow beams are known as band beams or thickened slab bands. The floor slab is designed as a continuous slab with the shallow band beams carrying all the loads from the slab (CCAA, 2003). This floor system is known for its minimum structural depth and long spans. The minimum economical span with this floor system is 8 m (CCAA, 2003).



Figure 2.1: Flat slab (CCAA, 2003)



Figure 2.2: Beam and slab floor system (CCAA, 2003)

A flat plate floor system (Figure 2.5) is a one or two-way spanning system usually supported directly on columns or loadbearing walls. The main feature of this floor system is the uniform or near-uniform thickness with a flat soffit which requires only simple formwork (CCAA, 2003). This floor system is characterised by minimum structural depth and medium spans. The maximum span length for this floor system is 8 m when reinforced and 12 m when prestressed.



Figure 2.3: Ribbed (waffle) floor system



Figure 2.4: Band beam and slab floor system



Figure 2.5: Flat plate floor system (CCAA, 2003)

A slab and joist floor system (Figure 2.6) is one that consists of a slab spanning between beams. The beams in turn span between the columns (CCAA, 2003). This floor system is characterised by minimum structural depth and long spans.



Figure 2.6: Slab and joist floor system

The band beam and slab, flat plate; and slab and joist floor systems have minimum structural depths and long spans making them slender. Because of their slenderness and long spans, these floor systems possess lower natural frequencies and reduced damping leading to vibration serviceability problems. The flat slab, ribbed (waffle) slab; and beam and slab floor systems are thick, heavy and stiff. Because of their high stiffness, thickness and heaviness; these floor systems possess higher natural frequencies and damping. Therefore they do not experience vibration serviceability problems and are preferred for sensitive occupancies such as hospitals, laboratories or factories equipped with highly sophisticated and extremely sensitive machinery.

2.3.3 Precast and composite floor systems

Precast and composite floor systems consist of precast floor elements spanning one way onto suitable supports that can either be in-situ or precast beams (CCAA, 2003). They are further subdivided into 5 different categories: hollowcore, permanent formwork or soffit slabs, composite floors: beam and infill, solid slabs; and single and double T-beams.

A hollowcore floor system (Figure 2.7) is a floor system consisting of hollowcore floor planks that are precast, prestressed units produced on long line casting beds using slide forming or extrusion methods (CCAA, 2003). This floor system is characterised by minimum structural depth and long spans. The maximum achievable span with this type of floor system is 18.5 m with a slab depth of 400 mm (CCAA, 2003).



Figure 2.7: Hollowcore floor system (CCAA, 2003)

A permanent formwork or soffit slab floor system (Figure 2.8) is a floor system that incorporates precast concrete slabs, usually 55 mm thick with embedded reinforcement and trusses (CCAA, 2003). This floor system is characterised by minimum structural depth and medium spans. The maximum achievable span with this type of floor system is 9 m with a slab thickness of 270 mm (CCAA, 2003).



Figure 2.8: Permanent formwork or soffit slab floor system (CCAA, 2003)

A composite floor: beam and infill floor system (Figure 2.9) is a floor system that consists of precast, prestressed concrete inverted T-beams spaced apart with an infill material spanning between the flanges of the beams (CCAA, 2003). This floor system is characterised by minimum structural depth and long spans. The maximum achievable span with this type of floor system is 12 m with a thickness of 250 mm.



Figure 2.9: Composite floor: beam and infill (CCAA, 2003)

A solid slab floor system (Figure 2.10) is a floor system that consists of floor slabs that are typically wet-cast on long-line beds in unit moulds or by hollowcore equipment using slipform or extrusion methods (CCAA, 2003). The maximum achievable span with this type of floor system is 12 m with a thickness of 250 mm (CCAA, 2003). The slenderness ratio of this floor system can go to 45. But for applications that are

sensitive to vibrations such as hospitals or laboratories, the slenderness ratio can be limited to 35 in order to avoid vibration serviceability problems resulting from lower natural frequencies and reduced damping.



Figure 2.10: Solid slab floor system (CCAA, 2003)

A single and double T-beam floor system (Figure 2.11) is a floor system that covers the span range beyond slab-type members such as hollowcore planks (CCAA, 2003). This floor system is characterised by thick slabs and long spans. The maximum achievable span with this type of floor system is 30 m for single T-beam and 24 m for double T-beam.



Figure 2.11: Single and double T-beam floor system (CCAA, 2003)

The hollowcore, permanent formwork or soffit slabs; and composite floor: beam and infill floor systems have minimum structural depths and long spans making them slender. Because of their slenderness and long spans, these floor systems possess lower natural frequencies and reduced damping leading to vibration serviceability problems. The solid slab and single and double T-beams floor systems are heavy and stiff. Because of their heaviness and stiffness, these floor systems possess higher natural frequencies and damping. Therefore they do not experience vibration serviceability problems and are preferred for sensitive occupancies such as hospitals and laboratories.

2.4 Types of partitions

2.4.1 Introduction

Partitions are non-load bearing internal walls including any finish (NHS, 2005). Their primary function is to physically separate adjacent spaces (NHS, 2005). Partitions come in different forms namely composite partitions, glass partitions, aluminium partitions, drywall partitions, timber partitions, steel partitions, brick partitions and concrete partitions.

2.4.2 Materials and connections

Composite partitions consist of aluminium framed systems that are constructed from panels manufactured with outer layers (Newbury Interiors, 2007). These outer layers are normally lightweight plasterboards. The aluminium framed systems are fixed to the concrete floors with nail anchors. No work has been done to study the effects of composite partitions on the vibration serviceability of concrete floors.

Glass partitions (Figure 2.12) are erected mainly of glass. The glass is held in place with mastic. The glass used to erect glass partitions is either made from sheet glass or hollow glass bricks (The constructor, 2010). The sheet glasses or hollow glass bricks are then fixed in a framework of wooden or steel members (Newbury Interiors, 2007). The framework in turn rests on the floor. The framework is fixed to the floor with nail plugs where permission is granted to drill through the concrete slab. And where permission is not granted, double sided tapes are used to fix the framework to the floor. No work has

been done to study the effects of glass partitions on the vibration serviceability of concrete floors.



Figure 2.12: Glass partition (Newbury Interiors, 2007)

Aluminium partitions (Figure 2.13) are made with single or double layers of normal plasterboard that is fixed on each side of the aluminium frame for the purpose of fixing it in position (Newbury Interiors, 2007). The frame is then fixed to the floor with nail anchors. No work has been done to study the effects of aluminium partitions on the vibration serviceability of concrete floors.



Figure 2.13: Aluminium partition (Newbury Interiors, 2007)

Drywall partitions can be used in all types of buildings from private housing to commercial as well as industrial buildings (Newbury Interiors, 2007). Galvanised steel frames are used to support the gypsum plasterboards. The frames are fixed to the floor with nail plugs where permission to drill through the concrete slab is granted. Where

permission is not granted, double sided tapes are used. The galvanised steel frame is usually made of 0.5 mm thick steel U-channel. Fatali (1999) studied the effects of gypsum plasterboard partitions on the vibration serviceability of concrete floors.

Timber partitions consist of a wooden framework that is supported either on the floor below or by side walls (Newbury Interiors, 2007). The wooden framework is made up of a rigid arrangement of timber members (Newbury Interiors, 2007). The wooden framework is fixed to the floor with nail anchors or nail plugs. No work has been done to study the effects of timber partitions on the vibration serviceability of concrete floors.

Steel partitions can be single or double skinned, of solid or mesh construction (Newbury Interiors, 2007). The steel frame is fixed to the floor either with nail plugs or double sided tapes where permission to drill through the concrete slab is not granted. Research is yet to be done to investigate the effects of steel partitions on the vibration serviceability of concrete floors.

Brick partitions (Figure 2.14) can be made with plain bricks, reinforced bricks or bricks nogged. Plain brick partitions are constructed by laying bricks as stretchers in cement mortar (The constructor, 2010). Reinforced brick partitions are similar to plain brick partitions except that at every third or fourth course, the bricks are reinforced with reinforcement bars as used in conventional reinforced concrete (The constructor, 2010). Brick nogged partitions consist of brickwork built within a framework of wooden members (The constructor, 2010). Research is yet to be done to investigate the effects of brick partitions on the vibration serviceability of concrete floors.



Figure 2.14: Brick partition

Concrete partitions can be made with plain (Figure 2.15) or reinforced concrete. The partition walls are either cast on site or made from precast blocks. When the partition walls are cast on site, they are cast monolithically with the intermediate columns (The constructor, 2010). Research is yet to be done to investigate the effects of concrete partitions on the vibration serviceability of concrete floors.



Figure 2.15: Plain concrete partition

2.5 Summary

The important dynamic characteristics of floors were discussed in the chapter and they are natural frequencies, damping ratios, modal masses and mode shapes. The different types of floor systems were also discussed in the chapter and their issues with vibration serviceability were highlighted. The band beam and slab, flat plate, slab and joist, hollowcore; and permanent formwork or soffit slabs floor systems are known to have vibration serviceability problems because of their slenderness and long spans leading to lower natural frequencies and reduced damping. On the other hand, the flat slab, ribbed (waffle) slab, beam and slab, solid slab; and single and double T-beams floor systems do not develop vibration serviceability problems because of their high stiffness and heaviness leading to higher natural frequencies and damping. Therefore these floor systems are used for sensitive occupancies such as hospitals, laboratories or factories equipped with highly sophisticated and extremely sensitive machinery. It is known that partitions may improve the vibration serviceability of the floors that support them. Therefore different types of partitions were discussed in the chapter. The gypsum plasterboard partition has been investigated for its effects on the vibration serviceability

of concrete floors. However the other types of partitions (i.e. composite, glass, aluminium, timber, steel, brick and concrete partitions) are yet to be investigated for their effects on the vibration serviceability of concrete floors. The next chapter will review the current state of the art on vibration serviceability of concrete floors.

University of Cape Town

3 VIBRATION SERVICEABILITY OF CONCRETE FLOORS

3.1 Introduction

Concrete floors were traditionally designed to an ULS where the focus was on strength and safety. The SLS philosophy was used to control maximum deflections and cracking. Vibration serviceability has now become a major part of the design of concrete floors because of the vibration problems that occur in long span, slender concrete floors. Five parameters are used to quantify floor vibrations. They are root mean square (RMS) acceleration, RMS velocity, vibration dose value (VDV), peak acceleration response and response factor. This chapter will discuss the current state of the art on vibration serviceability of floors.

3.2 Classification of floors for vibration serviceability

In structural dynamics, floors are divided into two categories based on the value of their fundamental frequency as low frequency floors (LFFs) and high frequency floors (HFFs) (Middleton and Brownjohn, 2010). Eriksson (1994) defines LFFs as floors having their first natural frequency below 8 Hz and HFFs as those having their first natural frequency above 8 Hz. Talja and Toratti (2006) on the other hand, define LFFs as floors having their first natural frequency below 10 Hz and HFFs as those having their first natural frequency above 10 Hz.

HFFs are generally constructed for sensitive occupancies such as hospitals, laboratories or factories equipped with highly sophisticated and extremely sensitive machinery. These HFFs are subjected to stringent vibration control depending on the sensitivities within them (Middleton and Brownjohn, 2010).

3.3 Assessment of vibration serviceability of floors

The assessment of vibration serviceability of floors consists of identifying as well as characterising the following three factors: vibration source, transmission path and receiver (ISO, 1992).

3.3.1 Vibration source

The vibration source can either be internal or external (ISO, 1992). The internal vibration source can be human excitation due to walking, running, jumping; machinery such as lifts, ventilation fans or air conditioning systems. The external vibration source can be ground motion, rail traffic, road traffic, wind and construction activities especially when piling is involved. This happens when the building is in close approximation to construction sites, highways or railway lines.

The most important source of annoying vibrations in residential and office buildings is human walking (Johansson, 2009). According to Pavic and Reynolds (2002a), footfall forces generated by human walking are a major source of floor vibration disturbance. This is because they happen frequently and are difficult to isolate (Pavic and Reynolds, 2002a). Walking is a periodic excitation. A number of researchers including Pavic and Reynolds (2002a), suggest that walking takes place at frequencies between 1.5 Hz and 2.5 Hz for normal walking. The step frequencies for different human activities are shown in Table 3.1.

A floor system is subjected to both vertical and horizontal footfall force components but the horizontal footfall force components are not important when dealing with floor vibration (Eriksson, 1994). Therefore the horizontal components of a footfall force can be ignored when dealing with floor vibration.

3.3.2 Transmission path

The transmission path is a medium which transfers the vibration from the source to the receiver (Pavic and Reynolds, 2002a). The transmission path in a given building could be the foundations, floors, columns, walls, false floors as well as partitions.

Table 3.1: Step frequencies for different human activities (Johansson, 2009)

Activity	Hz (step per second)
Walking	1.7 – 2.3
Running	2.0 – 3.5
Jumping	1.8 – 3.0
Sports activity	2.0 – 3.0
Dancing	1.9 – 3.3

3.3.3 Receiver

The receiver is the person or object for which the vibration serviceability of a given structure is assessed (ISO, 1992). The persons are the human occupants of the given building or structure. The objects can either be the non-structural components of the building such as windows, walls or the contents of the building such as sensitive machinery. The amount of vibration transmitted from the source to the receiver is assessed according to existing criteria.

3.4 Quantifying vibration

There are five parameters available to quantify floor vibration. They are RMS acceleration, RMS velocity, VDV, peak acceleration response and response factor.

3.4.1 RMS acceleration

The RMS acceleration is a measure of the total vibration that causes distress and discomfort to the human body (Pavic and Reynolds, 2002a). Therefore higher RMS accelerations will correspond to higher vibration magnitudes. It is measured in m/s^2 .

The RMS acceleration is calculated using:

$$\text{RMS} = \left[\frac{\int_{t_1}^{t_2} a_w^2(t) dt}{t_2 - t_1} \right]^{\frac{1}{2}} \quad (3.1)$$

where $a_w(t)$ is the weighted time history.

ISO 10137 (1992) uses the RMS acceleration to assess the acceptability of floor vibration. The calculated RMS acceleration for vertical vibration has to be smaller than the curve shown in Figure 3.1.

The Cement and Concrete industry publication CCIP-016 (2006) and Steel Construction Institute publication SCI P354 (2007) also use the RMS acceleration to assess the acceptability of floor vibration.

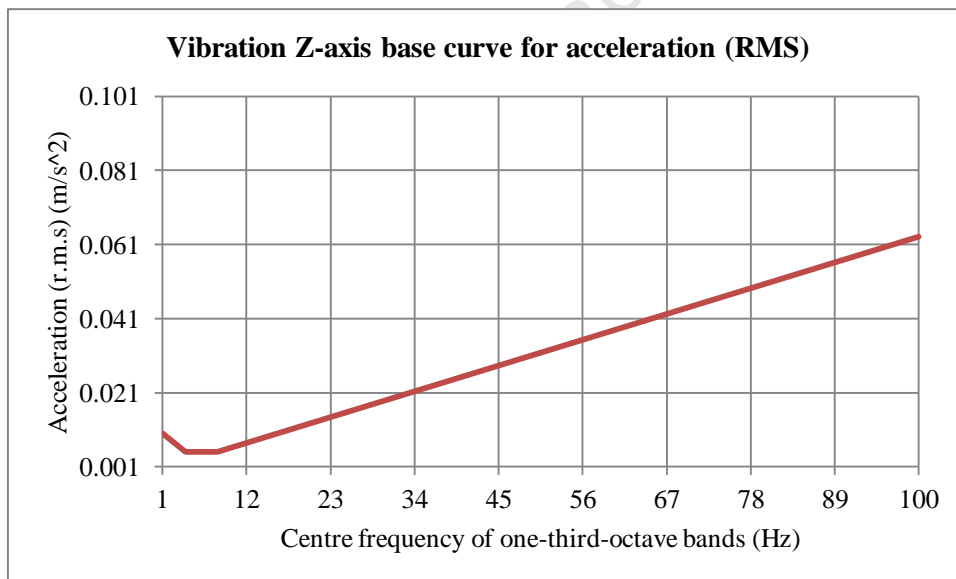


Figure 3.1: Vibration z-axis base curve for acceleration (ISO 10137, 1992)

3.4.2 RMS velocity

The RMS velocity is a measure of the average vibration amplitude. Therefore higher RMS velocities will correspond to higher vibration amplitudes. It is measured in mm/s.

The RMS velocity is calculated using:

$$X_{RMS} = \sqrt{\frac{1}{T} \int_t^{t+T} x^2 dt} \quad (3.2)$$

where X_{rms} is the RMS velocity in mm/s, x is the velocity at every instant and T is the averaging period.

The CCIP-016 (2006) uses the RMS velocity to assess the acceptability of floor vibration for sensitive occupancies such as hospitals, laboratories or factories equipped with highly sophisticated and extremely sensitive machinery. The calculated RMS velocities have to be smaller than the limits provided in Table 3.3.

3.4.3 Vibration dose value (VDV)

The VDV is defined as the cumulative measure of the amount of vibration transmitted to a human receiver during a certain period of interest (Pavic and Reynolds, 2002a). It is measured in $m/s^{1.75}$.

The VDV is calculated using:

$$VDV = \left[\int_{t_1}^{t_2} a_w^4(t) dt \right]^{\frac{1}{4}} \quad (3.3)$$

where $a_w(t)$ is the weighted time history.

BS 6472-1 (2008) uses the VDV to assess the acceptability of floor vibrations. In this code, the calculated VDV has to be smaller than the limits provided in Table 3.2. Multiplying factors of 2 and 4 for offices and workshops respectively should be applied to the VDV ranges for a 16 hours day (BS 6472:1, 2008).

The SCI P354 (2007) also uses the VDV to assess the acceptability of floor vibration.

Table 3.2: VDV ranges which might result in various probabilities of adverse comment within residential buildings (BS 6472-1, 2008)

Place and time	Low probability of adverse comment (m/s ^{1.75})	Adverse comment possible (m/s ^{1.75})	Adverse comment probable (m/s ^{1.75})
Residential buildings 16 hours day	0.2 – 0.4	0.4 – 0.8	0.8 – 1.6
Residential buildings 8 hours day	0.1 – 0.2	0.2 – 0.4	0.4 – 0.8

3.4.4 Peak acceleration response

The American Institute of Steel Construction Design Guide 11 (1997) uses the peak acceleration response in units of gravity to assess the acceptability of floor vibrations. It is calculated using:

$$\frac{a_p}{g} = \frac{P_o \text{Exp}(-0.35 f_1)}{\zeta_1 W} \quad (3.4)$$

where f_1 is the first natural frequency of the floor in Hz, P_o is the constant force based on a person weight and assumed as 746 N, ζ_1 is the damping ratio and W is the effective weight of the floor. The calculated peak acceleration should be smaller than the curves shown in Figure 3.2.

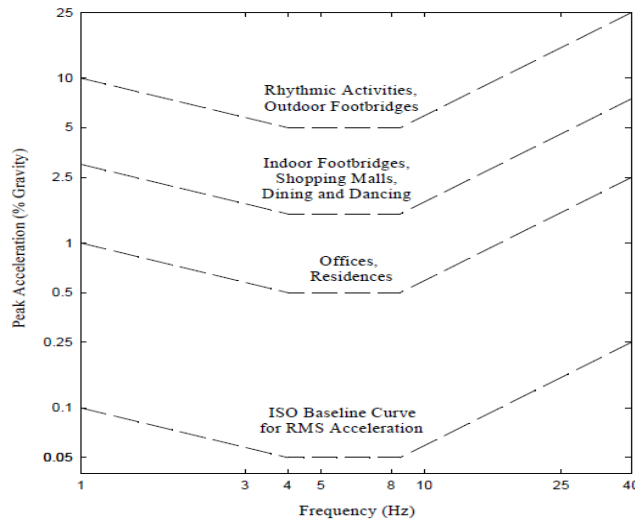


Figure 3.2: Acceptance criteria for floor vibrations (AISC/CISC Design Guide 11) (Alvis, 2001)

3.4.5 Response factor

The response factor (R) is a multiplier on the level of vibration at the average threshold of human perception (CCIP-016, 2006). A response factor of 1 represents the magnitude of vibration that is just perceptible by a human being (CCIP-016, 2006). It is required in vibration serviceability design to find all modes of vibration below 15 Hz for LFFs in order to determine their resonant response. And to determine the impulse response of HFFs, all modes with a frequency less than twice the fundamental frequency are needed (CCIP-016, 2006).

The CCIP-016 (2006) and SCI P354 (2007) use the response factor to assess the acceptability of floor vibration. The calculated response factors have to be smaller than the limits provided in Table 3.3.

Proper modal parameters are not easily extracted by walking tests. Proper instrumentation such as electrodynamic shaker or instrumented impulse hammer is necessary to fully excite a structure and thereby extracting reliable modal parameters. The RMS acceleration, RMS velocity, VDV and peak acceleration response rely on the walking tests in order to quantify vibration. The response factor is the only parameter that can be easily estimated from modal parameters (i.e. natural frequencies, damping

ratios, modal masses and mode shapes). The interest in this research project is on modal parameters and vibration quantification. With the instrumentation available for this research project (i.e. electrodynamic shaker and instrumented impulse hammer), the response factor is the most suitable parameter among the five available to quantify floor vibration. Therefore the focus in this research project is on the response factor seeing its practicality with the available instrumentation.

3.5 Design procedure for the response factors of floors

The response of a floor to the application of a footfall force depends on many factors. The most important factors are the stiffness and mass of the floor, damping of the floor and the ratio between the natural frequency of the floor and the walking frequency (CCIP-016, 2006). Footfall rates usually vary between 1.5 Hz and 2.5 Hz. Therefore any floor with natural frequencies between 1.5 Hz and 10.5 Hz is potentially susceptible to the higher responses associated with resonance (CCIP-016, 2006). Resonance is a state where a structural system is excited at one of its natural frequencies. LFFs are usually designed for resonant response and HFFs are designed for impulsive response.

3.5.1 Acceptance criteria

The maximum representative vibration level that is likely to occur is calculated and compared to acceptance criteria when assessing the dynamic performance of floors. BS 6472 (2008) sets out criteria for continuous vibration at which the probability of adverse comment is low. The vibration criteria for floors with sensitive equipment are more stringent than those of floors for ordinary, everyday usage. These criteria are shown in Table 3.3.

The achievement of the vibration levels shown in Table 3.3 should result in a low probability of adverse comment. But if they are doubled, adverse comment may result. The adverse comment may increase significantly if the response factors are quadrupled (CCIP-016, 2006).

Table 3.3: Acceptance criteria of vibration for floors with sensitive equipment (CCIP-016, 2006)

Criterion curve	Max RMS velocity (microns/s)	Detail size (microns)	Description of use
Workshop R = 8, ASHRAE J	800	N/A	Distinctly perceptible vibration
Office R = 4, ASHRAE I	400	N/A	Perceptible vibration
Residential day R = 2, ASHRAE H	200	75	Barely perceptible vibration
Operating theatre R = 1, ASHRAE F	100	25	Threshold of perception
VC-A (BBN-A or ASHRAE E) R = 0.5	50	8	Adequate for optical microscopes to 100x, microbalances, optical balances, proximity and projection aligners, etc.
VC-B (BBN-B or ASHRAE D) R = 0.25	25	3	Adequate for optical microscopes to 1000x, inspection and lithography equipment (including steppers) to 3micron line widths.
VC-C (BBN-C or ASHRAE C) R = 0.125	12.5	1	Adequate for most lithography and inspection equipment to 1-micron detail size.
VC-D (BBN-D or ASHRAE B) R = 0.0625	6	0.3	Adequate for the most demanding equipment including electron microscopes and E-beam systems, operating to the limits of their capability.
VC-E (BBN-E or ASHRAE A) R = 0.03125	3	0.1	Adequate for the most demanding of sensitive systems including long path, laser-based, small target systems and other systems requiring extraordinary dynamic stability.

The detail size refers to the line widths for microelectronics fabrication, the particle size for medical and pharmaceutical research (CCIP-016, 2006).

3.5.2 Loading model

A single person walking at the most critical footfall rate is considered as the loading case for the design of floors for vibration serviceability. Footfall induced vibration is

sensitive to the speed of walking. Therefore for design purposes, the maximum footfall rates to be used are those given in Table 3.4.

Table 3.4: Maximum footfall rates for floors (CCIP-016, 2006)

Environment	Footfall rate (Hz)
Corridor and circulation zones in any building	2.5
Within office bays and residential rooms (i.e. not corridor zones)	2.0
Within laboratories, operating theatres, and the like	1.8

3.5.3 Design methods

3.5.3.1 Limitations

The design methods to be discussed are limited to certain rectangular floor bays of uniform properties. These rectangular floor bays are easily approximated to simply supported plates having equal or different stiffnesses in the two orthogonal directions (CCIP-016, 2006). These methods can be easily applied to bays composed of flat slabs, ribbed slabs, waffle slabs and composite slabs.

These design methods are based on the modal parameters of a single mode of vibration and response multipliers. The latter are used to account for the response of higher modes as well as the participation of adjacent bays. The response multipliers are given in Figure 3.3 and Figure 3.4. These design methods only apply to bare floors (i.e. floors with non-structural elements such as partitions). If a floor supports partitions, these design methods become unreliable because they cannot take account of the effects of the partitions on the response factor of the floor.

3.5.3.2 Modal parameters

The first step in the design of floors for vibration serviceability is to find the fundamental modal parameters (i.e. natural frequency and modal mass). After finding the fundamental frequency, a resonant or impulsive response is then calculated. The influence of higher modes and adjacent spans is incorporated at a later stage.

The fundamental frequency of the floor can be calculated using the equations given in Section 2.2 or using:

$$f_0 = \frac{\pi}{2} \sqrt{\frac{D_y}{mL^4}} \quad (3.5)$$

where f_0 is the fundamental frequency in Hz, D_y is the flexural stiffness per metre width in the main span direction, m is the mass per unit area and L is the span length.

For flat slabs of thickness t , the flexural stiffness per metre width in the main span direction (D_y) is calculated using:

$$D_y = \frac{Et^3}{12(1-\nu^2)} \quad (3.6)$$

where E is the modulus of elasticity of the material, t is the thickness of the floor and ν is the Poisson's ratio of the material.

And for ribbed slabs or steel composite floors with equidistantly spaced ribs or beams, the flexural stiffness per metre width in the main span direction is calculated using:

$$D_y = \frac{EI_y}{S_y} \quad (3.7)$$

where E is the modulus of elasticity of the material, I_y is the second moment of area of the beam and slab units spanning in the main direction and S_y is the spacing between the ribs or beams.

The natural frequency of higher modes is calculated using:

$$f_1 = K_f f_0 \quad (3.8)$$

where f_1 is the natural frequency of higher modes in Hz, f_o is the fundamental frequency in Hz and K_f is a multiplier on the natural frequency of the elements spanning in the main direction to account for two-way spanning. It is a function of the width/span ratio of the floor and the ratio of the floor stiffnesses in the two orthogonal directions.

The modal mass of the fundamental mode is calculated using:

$$M = \frac{mLW}{4} \quad (3.9)$$

where M is the modal mass in Kg, m is the total mass per unit area in Kg/m^2 , L is the length of the floor and W is the width of the floor.

3.5.3.3 Simplified calculation of resonant response

The first step in the design for the resonant response of floors is to calculate the peak resonant acceleration of the first mode for the most critical walking speed using:

$$a_1 = \frac{\rho F_h}{2\zeta M} \quad (3.10)$$

where a_1 is the peak resonant acceleration in the first mode for the most critical walking speed, F_h is the harmonic force amplitude appropriate to the floor's natural frequency, ζ is the floor's damping ratio, M is the modal mass and ρ is the resonant correction factor calculated using:

$$\rho_{h,m} = 1 - e^{-2\pi\zeta_m N}, \quad (3.11)$$

$$N = 0.55h \frac{L}{I} \quad (3.12)$$

where h is the harmonic number, m is the mode number, L is the floor's span, I is the stride length.

The resonant correction factor can be taken as unity for floors since it is only significant for bridges (CCIP-016, 2006).

The harmonic force amplitude F_h for different harmonic numbers is given in Table 3.5.

Table 3.5: Harmonic force amplitude F_h for different harmonic numbers

Harmonic number h	Harmonic forcing frequency F_h (Hz)
1	1 – 2.8
2	2 – 5.6
3	3 – 8.4
4	4 – 11.2
$h > 4$	$F_h > 11.2$

The second step in the design for the resonant response of floors is to determine the resonant response multiplier K_{rm} . The latter is a factor by which the resonant response in the first mode must be increased to account for the contribution of all the other modes. It is a function of the width/span ratio of the floor and the ratio of the floor stiffnesses in the two orthogonal directions (CCIP-016, 2006). Figure 3.3 can be used to approximate K_{rm} for different scenarios.

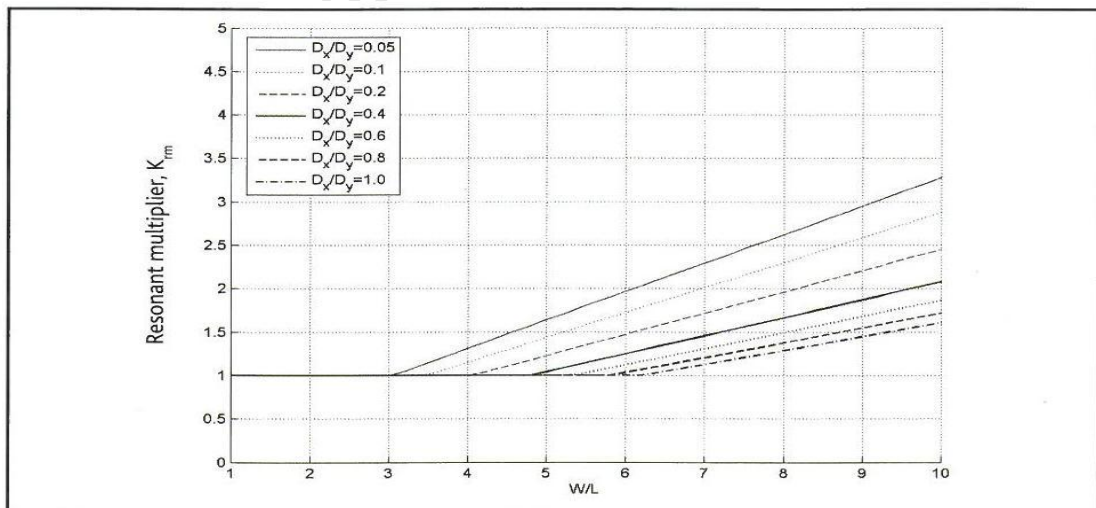


Figure 3.3: Resonant response multipliers for concrete floors (CCIP-016, 2006)

After determining the resonant response multiplier K_{rm} , the next step is to calculate the total peak acceleration response using:

$$a_t = K_{rm} a_1 \quad (3.13)$$

where a_t is the total peak acceleration response, K_{rm} is the resonant response multiplier and a_1 is the peak resonant acceleration of the first mode.

After calculating the total peak acceleration response, the final step in the design for the resonant response of floors is to calculate the response factor R using:

$$R = \frac{a_t}{0.0071} \quad (3.14)$$

The calculated response factor is then compared to the acceptance criteria given in Table 3.3 for different floor usage in order to determine whether or not the floor meets the specified vibration requirements.

3.5.3.4 Simplified calculation of impulsive response

The first step in the design for the impulsive response of floors is to calculate the impulsive peak velocity response in the first mode using:

$$V_1 = \frac{I_{eff}}{M} \quad (3.15)$$

where V_1 is the impulsive peak velocity response in the first mode, I_{eff} is the effective impulse appropriate to the floor's natural frequency and M is the modal mass.

The effective impulse I_{eff} is calculated using:

$$I_{eff} = \frac{54 f_w^{1.43}}{f_n^{1.30}} \quad (3.16)$$

where f_w is the walking frequency in Hz and f_n is the floor's natural frequency for the given mode of vibration.

The second step in the design for the impulsive response of floors is to determine the impulsive response multiplier K_{im} . The latter is a function of the width/span ratio of the

floor and the ratio of the floor stiffnesses in the two orthogonal directions. Figure 3.4 can be used to approximate K_{im} for different scenarios.

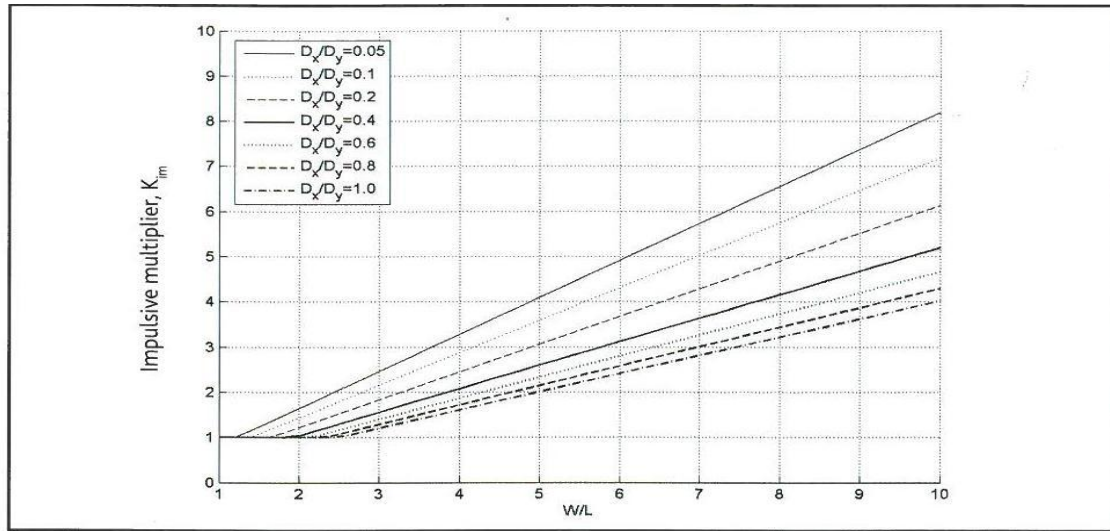


Figure 3.4: Impulsive response multipliers for concrete floors (CCIP-016, 2006)

After determining the impulsive response multiplier K_{im} , the next step is to calculate the total impulsive peak velocity response V using:

$$V = K_{im} V_1 \quad (3.17)$$

After calculating the total impulsive peak velocity response, the next step is to calculate the RMS velocity V_{RMS} . The latter is calculated using:

$$V_{RMS} = 0.3V \quad \text{for } K_{im} > 2.0. \quad (3.18)$$

$$V_{RMS} = 0.3 + 0.12(2 - K_{im}) \quad \text{for } 1.0 < K_{im} < 2.0. \quad (3.19)$$

After calculating the RMS velocity V_{RMS} , the response factor is then calculated using:

$$R = \frac{V_{RMS}}{V_{R=1}} \quad (3.20)$$

where V_{RMS} is the RMS velocity and $V_{R=1}$ is the baseline RMS velocity for $R = 1$ at the fundamental frequency f_1 .

The baseline RMS velocity for $R = 1$ at the fundamental frequency f_1 is calculated using:

$$V_{R=1} = \frac{0.005}{2\pi f_1} \text{ m/s} \quad \text{if } f_1 < 8 \text{ Hz.} \quad (3.21)$$

$$V_{R=1} = 1.0 \times 10^{-4} \text{ m/s} \quad \text{if } f_1 > 8 \text{ Hz.} \quad (3.22)$$

The calculated response factor is then compared to the acceptance criteria given in Table 3.3 for different floor usage in order to determine whether or not the floor meets the specified vibration requirements.

3.5.3.5 Partitions

The design procedures discussed above for response factors apply only to bare floors. These design procedures do not take account of partitions. If the floor being assessed supports partitions, the latter will not be included in the calculation of the response factors. It is known that the installation of partitions may improve the vibration serviceability of the floors that support them (Chen, 1999; Fatali, 1999; Middleton and Brownjohn, 2010). It has also been shown that the modal parameters of even nominally identical floors could significantly differ because of different arrangements of partition walls (Miskovic et al., 2009). The presence of full-height partitions significantly changes the dynamic properties of the floors supporting them leading to less vibration serviceability problems (CCIP-016, 2006). The presence of partitions is essential to the usage of floors especially in residential and hospital buildings. Therefore it is necessary to include the partitions in the proposed floor's layout before assessing it for vibration serviceability.

3.6 Summary

It is known that partitions can change the dynamic properties of the floors supporting them. When designing floors for vibration serviceability using design procedures such as those discussed above, partitions are not included. This is because the design procedures were developed for bare floors only. The installation of partitions whether

full-height or half-height can change either the stiffness or mass of the floor therefore changing its natural frequencies and modal masses. Partitions can also change the damping of the floors supporting them. The influence of partitions cannot be easily included in the estimation of damping at design stage using hand calculations. This is because damping cannot be estimated from the dimensions or material properties of the floor but can only be measured or estimated from similar existing structures. The five parameters used to quantify floor vibrations were also discussed in this chapter. They are RMS acceleration, RMS velocity, VDV, peak acceleration response and response factor. The next chapter will review the early research into the effects of non-structural elements on the vibration serviceability of concrete floors.

University of Cape Town

4 EARLY RESEARCH

4.1 Introduction

Little research exists into the quantification of the effects of various types of partitions on the vibration serviceability of the concrete floors that support them. There are no guidelines available to designers which take into account the effects of partitions on vibration serviceability of concrete floors besides the different damping ratios that are recommended in different codes for bare floors as well as for floors with half- or full-height partitions. This chapter will review the early research into the effects of non-structural elements on the vibration serviceability of concrete floors.

4.2 Early research into the effects of non-structural elements on vibration serviceability of concrete floors

Lenzen (1966) studied the vibration serviceability of slab and joist floor systems. It was found that damping was key in the prevention of existing floor vibration and it improved floor vibration serviceability. It was then concluded that occupants of a building using a given floor will tolerate higher initial response if the damping is increased.

Reynolds et al. (1998) carried out modal testing on a 150 tonne concrete slab incorporating a false floor system. It was found that the presence of the non-structural false floor altered the vibration performance of the floor slab by increasing both the stiffness and modal damping ratios. It was concluded that by examining the manner in which the additional stiffness and damping have developed in the false floor, it may be possible to design a false floor system which could be used to improve the vibration performance of a floor structure either at design stage or as a remedial measure for already constructed floors.

Reynolds et al. (1999) did a modal testing, finite element (FE) analysis and FE model correlation of a 600 tonne post-tensioned concrete floor. The floor structure was tested

on three separate occasions during the course of its construction with the following configurations:

1. Bare post-tensioned concrete floor only (December 1995)
2. Post-tensioned concrete floor with services installed (June 1996)
3. Post-tensioned concrete floor with services and false floor installed (July 1996).

The first test was performed using impulse excitation provided by a 5.4 Kg instrumented impulse hammer. The second and third tests were performed using excitation provided by an electrodynamic shaker. For all modal tests, roving excitation was utilised and the excitation and response signals were stored using a 16 channel analogue tape recorder. The excitation and response channels were fed into a dual-channel portable spectrum analyser for immediate calculation and inspection of frequency response functions (FRFs). This exercise was done to ensure that high quality data were collected. Therefore any poor quality FRFs were disregarded. The acquired data were processed using the multi-degree-of-freedom parameter estimation algorithms implemented in the commercially available ICATS suite of software. After the study, it was concluded that the common practice of idealising columns and edge beams as pin supports significantly underestimates the stiffness of floors. It was also suggested that a value around or even slightly higher than 40 GPa was more appropriate for the elastic modulus of post-tensioned concrete floors than the values of 30 – 35 GPa commonly assumed.

Pavic (1999) carried out modal testing, FE analysis and FE model correlation and updating of a number of long-span reinforced and prestressed floors. Throughout the research, parameters were identified which affect significantly the vibration behaviour of long-span reinforced and prestressed floors. And these parameters are not currently considered enough in normal civil engineering practice. The most important observation made was that in-situ cast columns which are rigidly connected to a floor that they are supporting, significantly increase the bending stiffness of that floor. This observation is contrary to normal design practice in which columns are commonly considered as pin supports.

Fatali (1999) investigated the contribution of non-structural components to the overall dynamic behaviour of concrete floor slabs. Results showed that a significant effect on

the floor dynamic properties was gained by the addition of full-height partitions. And when these partitions were rigidly attached between two floors, they acted as a line support resulting in an increase in floor stiffness. It was also found that half-height partitions were most effective when placed perpendicular to the floor span and at a point where the fundamental mode of the floor had a high slope. It was further found that when the half-height partitions were connected to each other, a transfer of energy took place from those with higher response to those with lower response causing an increase in the overall energy absorption of the whole partition system. It was concluded that partitions can add stiffness and damping to a floor structure and the level of addition depends on the layouts of the partitions with respect to the mode shapes. It was proposed that the effects of full-height partitions on simply supported beams could be modelled using:

$$f_{oc}^2 = f_o^2 + \frac{K_p}{2\pi^2 \rho b h L} \sin^2\left(\frac{\pi a}{L}\right) \quad (4.1)$$

where f_{oc} is the frequency after the partition has been installed, f_o is the beam frequency before addition of the partition, K_p is the stiffness of the partition material, a is the distance of the partition from the nearest support, L is the span length, ρ is the density of the material, b is the width of the beam and h is the thickness of the beam. The partition type used in this study was gypsum plasterboard.

Reynolds (2000) carried out experimental and analytical modal testing of three full-scale floor structures. These tests were done before and after the installation of various configurations of raised access floors. It was found that raised access floors had only minor effects on the modal properties of the three long-span concrete floors. The reduction in natural frequencies due to the increased mass was offset to some degree by the slight increase in stiffness following the installation of the access floors. It was further found that the modal damping ratios increased for some modes of vibration, but these changes were rather unpredictable and therefore unreliable to be used in design. It was also found that the reduction appeared to be greater for relatively deep access floors (500 – 600 mm) than for relatively shallow access floors (150 – 200 mm). Therefore it was concluded that the effects of access floors may be included in vibration serviceability analyses by applying a reduction factor to the predicted responses

calculated by assuming a bare floor. The proposed reduction factors are 0.9 for access floors where the finished floor height is less than 500 mm and 0.8 for access floors where the finished floor height is 500 mm or greater.

Pavic et al. (2001) combined experimental and analytical investigation into the as built vibration properties of a long-span post-tensioned concrete floor conducted using advanced modal testing and FE model correlation and updating technologies. The aim of the test was to measure the floor modal parameters: natural frequencies, mode shapes and modal damping ratios. The floor was impacted manually with an instrumented impulse hammer by an operator remaining as still as possible during data capture after the impact. The modal testing of the floor was performed twice. The first test took place immediately after the floor was cast, when it was completely bare and in the unclad building without partitions. The second test took place 6 months after the first test when services were attached to the soffit of the floor and the building was clad but no internal partitions were installed. The ANSYS FE code was used to develop the FE model in the pretest analysis. It was found that the bending of in-situ cast concrete columns supporting the in-situ cast concrete floor slab contributed significantly to the floor bending stiffness and therefore should not be modelled as pin-supports. It was also found that the bending stiffness of the columns contributed to the floor's overall bending stiffness. Therefore it was concluded that modelling the columns as vertical pin-supports allowing free rotation was a major source of error in simplistic mathematical models of floor structures as adopted in many design guidelines. It was also concluded that the width of wide and shallow band beams which are common in ribbed post-tensioned floor design, contributes considerably to the lateral bending stiffness of the floor.

Reynolds and Pavic (2003) did a comprehensive and systematic study into the effects of false floors on the vibration serviceability of long span concrete floors. The aim of the study was to measure the floor modal parameters before and after the installation of false floors in order to assess the change in the modal parameters of the floor. It was found that false floors had the capacity to change the modal parameters significantly and particularly the modal damping ratios. Therefore it was concluded that the installation of false floors tends to reduce the measured vibration response of the floor under controlled pedestrian excitation.

Ljunggren (2006) investigated the vibration of lightweight steel framed floors. The aim of the study was to measure the modal parameters of steel framed floors in order to understand the effects of different supports, top layers, ceiling joists and simulated partitions on their dynamic properties. It was found that the change of the natural frequency of an existing floor was not sufficient since it required two major modifications in order to be justifiable. Therefore it was concluded that increasing damping is more practical and applicable to the vibration serviceability of floors since the lack of damping is mostly the main cause of resonant vibration.

Miskovic et al. (2009) did a combined experimental and numerical investigation of the modal properties of two full-scale and nominally identical steel-concrete composite floors. The floors were one above the other in the same fully operational multi-storey building. Both floors accommodated open-plan as well as partitioned offices. The aim of the study was to measure the floor modal parameters: natural frequencies, mode shapes and modal damping ratios. It was found that the natural frequencies of the floors as well as the character of their mode shapes could significantly differ for even nominally identical floors because of different arrangements of non-structural elements such as partition walls.

Middleton and Brownjohn (2010) did a literature review on the response of HFFs to dynamic loading. Following the review, it was found that:

1. Bare structures do not provide a great deal of damping, generally less than 3 % with most of the damping provided by non-structural elements.
2. False floors will only contribute to damping if they are not rigidly connected to the structure. If rigidly connected, they will not increase stiffness or damping.
3. Full-height partitions act as spring supports and add damping to the structure.
4. Screed can add damping.
5. The damping added by partitions that are not full-height depends on their directions.
6. This dissipative mechanism is due to rotation of the partitions relative to the floor. Therefore for maximum effect, the partitions should be perpendicular to the mode of interest.

7. To increase damping further, a partition parallel to the mode shape of interest should be connected to another partition perpendicular to the same mode shape of interest.

Therefore it was concluded that the stresses involved in dynamic analyses are much lower than those involved in static analyses. This conclusion has two consequences, firstly the dynamic elastic modulus of concrete will be higher than that used for static analyses and secondly pinned connections may act as if they were fully fixed.

4.3 Summary

Little research exists into the quantification of the effects of various types of partitions on the vibration serviceability of concrete floors that support them. Looking at the early research into the effects of partitions on the vibration serviceability of concrete floors, not much has been done. The effects of gypsum plasterboard partitions on the vibration serviceability of concrete floors have been investigated. However the effects of partitions such as aluminium, brick, concrete, glass and timber on the vibration serviceability of concrete floors are yet to be investigated. Therefore this research project will investigate the effects of brick and timber partitions on the vibration serviceability of concrete floors. The next chapter will present the methodology adopted to achieve the objectives of the research project.

5 METHODOLOGY

5.1 Introduction

The installation of partitions may lead to the improvement of the vibration serviceability of the floors that support them (Chen, 1999; Fatali, 1999; Middleton and Brownjohn, 2010). Fatali (1999) investigated the effects of gypsum plasterboard partitions on the vibration serviceability of concrete floors. However the effects of partitions such as brick and timber on the vibration serviceability of concrete floors are yet to be investigated. There are no guidelines available to designers to account for the effects of partitions in the design of concrete floors for vibration serviceability. The effects of partitions on the vibration serviceability of concrete floors have to be quantified in order to develop guidelines that will take them into account at design stage. These guidelines will have to consider the type, layout as well as height of the partitions. The aim of this research was to investigate the effects of partitions on the vibration serviceability of concrete floors. This chapter will present the methodology adopted for the investigation of the effects of partitions on the vibration serviceability of concrete floors.

5.2 Laboratory work (Modal testing)

5.2.1 Introduction

Modal testing is an experimental technique used in deriving the modal model of a linear time-invariant system subjected to vibration (He and Fu, 2001). The objective of modal testing was to assess the change in the modal parameters of a prestressed concrete floor slab before and after the installation of various configurations of partitions. The modal parameters investigated include: natural frequencies, modal damping ratios, modal masses and mode shapes.

5.2.2 Experimental work

5.2.2.1 Dimensions of experimental floor slab

The space available in the University laboratory was the most important factor in determining the size of the experimental floor slab. The floor slab was 5 m long by 2 m wide and 125 mm thick. SANS 0100-1 (2000) recommends a minimum thickness of 125 mm for concrete floor slabs where shear reinforcement is not provided. Where shear reinforcement is provided, a minimum thickness of 150 mm is recommended for concrete floor slabs. The experimental floor slab was prestressed pre-tensioned and no shear reinforcement was required, therefore 125 mm was the minimum recommended thickness. Prestressing was used in order to achieve a slender concrete member and to eliminate cracking of concrete.

The experimental concrete floor slab was prestressed pre-tensioned with a design concrete strength of 40 MPa using ordinary portland cement. Concrete cubes were made at casting and the 28-day concrete strength was 47 MPa. SANS 0100-1 (2000) recommends a minimum design concrete strength for prestressed pre-tensioned concrete of 40 MPa. For such strength, SANS 0100-1 (2000) recommends a static elastic modulus of 31 GPa and a dynamic elastic modulus of 40 GPa. SANS 0100-1 (2000) also recommends a Poisson's ratio of 0.2 for concrete. The density of the concrete was taken as 2400 Kg/m³.

5.2.2.2 Static design of floor slab

The floor was designed as a class 1 concrete member with maximum tensile stress $f_t = 0$ MPa and maximum compressive stress $f_{cc} = 13$ MPa. The latter is 33 % of the characteristic strength of the concrete as recommended in SANS 0100-1 (2000). Each tendon was stressed to 45 KN which was 70 % of its ultimate breaking force as recommended in SANS 0100-1 (2000). The prestressing force generated an average compressive stress in the floor slab of 3.6 MPa, which was high but well below the allowable compressive stress. The average compressive stress was kept high in order to keep the deflections of the floor slab within the allowable.

The floor slab was designed as a class 1 member according to SANS 0100-1 (2000) to prevent cracking of concrete because cracking increases damping through the dissipation of energy and reduces natural frequencies due to the reduction in stiffness (Fatali, 1999). In order not to have any other effects such as cracks influencing the modal parameters of the floor slab except the partitions, a class 1 member was chosen. Class 1 prestressed concrete members are designed to develop no tensile stresses within themselves, therefore no structural cracking can develop.

The design dead load was 6 KN/m^2 and the live load was 1.25 KN/m^2 to allow for a person or two walking across the floor slab. The floor slab was simply supported 0.10 m from each edge by two IPE 100 I-section steel beams. The dimensions of the floor slab resulted in a span-depth ratio of 38, making the floor slab slender. The prestressing force was provided by twenty indented wires of 7 mm diameter and characteristic breaking load of 64.3 KN as well as characteristic strength of 1670 MPa. The design eccentricity was 20.5 mm. A steel mesh consisting of 12 mm diameter bars spaced at 200 mm centres was placed 30 mm from the top concrete surface.

A separate mechanism was erected to carry the prestressing force before it was transferred to the concrete. The transfer happened 7 days after casting to allow sufficient strength gain. The mechanism was designed to carry a total load of 900 KN resulting from the prestressing. The mechanism was made of four 200x200x16 mm steel angles welded in pairs in order to improve the properties of the angle sections. The properties of the steel angles needed improvement in order to prevent yielding. Additional stiffeners were added to the steel angles to prevent rotation of the flanges and excessive deflection of the webs. The welded steel angles were anchored to the concrete floor by M16 and M20 rawbolts. Figure 5.1 shows the welded stiffened steel angles bolted to the concrete floor of the laboratory.



Figure 5.1: Welded stiffened 200x200x16 mm steel angle

Figure 5.2 shows the formwork before concreting with the prestressing wires pulled to the design force. Figure 5.3 shows the concreting operation.



Figure 5.2: Formwork before concreting



Figure 5.3: Concreting process

5.2.2.3 Vibration serviceability design of floor slab

The experimental floor was also designed for vibration serviceability. Following its static design, the fundamental frequency of the floor was found to be 10.2 Hz. Its modal mass was found to be 720 Kg. Using the calculated values and making use of Figure 3.4, the total impulsive peak velocity response of the floor was found to be 10 mm/s. The response factor of the floor was found to be 4.2. This implies that its magnitude of vibration is highly perceptible by a human being since it is greater than unity. A response factor of 1 represents the magnitude of vibration that is just perceptible by a human being (CCIP-016, 2006). Figure 5.4 shows the test floor without any partition (bare floor).

5.2.2.4 Timber partitions

Plywood was used for half-height as well as full-height timber partitions. The plywood had a thickness of 21 mm. The difference between half-height and full-height was based on the fixity at the top of the partitions. Half-height partitions were not fixed horizontally at the top, therefore they were free to rotate. They were fixed to the concrete floor by four steel brackets spaced at 600 mm centres. The brackets were 75x125x8 mm thick unequal steel angles. Each steel bracket was fixed to the concrete floor by a single 5 mm diameter, 50 mm long self tapper screw. Figure 5.5 shows the steel bracket and the 5 mm diameter self tapper screw. Full-height partition was fixed horizontally at the top. A steel frame was built to provide restriction at the top of the plywood in order to simulate full-height partitioning. Four layouts were used to simulate half-height partitioning. The first layout consisted of a partition 1.20 m high fixed at midspan (Figure 5.6). The second layout consisted of three partitions 1.20 m high fixed perpendicular to the floor span at 1.20 m centres (Figure 5.7). In the third layout, two more partitions 1.20 m high were added to the existing partitions of Layout 2 (Figure 5.8). These two additional partitions were fixed parallel to the floor span at 1 m from the edges. The fourth layout consisted of a partition 1.20 m high fixed at midspan and two partitions 1.20 m high fixed at 1 m from the edges and parallel to the floor span (Figure 5.9). Layout 1 was used to simulate full-height partitioning as shown in Figure 5.10.



Figure 5.4: Bare floor



Figure 5.5: Steel bracket with 5 mm diameter self tapper screw



Figure 5.6: Layout 1 (Timber partition)



Figure 5.7: Layout 2 (Timber partitions)



Figure 5.8: Layout 3 (Timber partitions)



Figure 5.9: Layout 4 (Timber partitions)



Figure 5.10: Timber full-height partition

5.2.2.5 Brick partitions

A brick wall was constructed to simulate half-height as well as full-height brick partition. A steel frame was built to provide fixity at the top of the brick wall in order to simulate full-height partitioning. The half-height brick partition consisted of a brick wall 1.20 m high built at mid-span (Figure 5.11). The full-height brick partition consisted of a brick wall 1.20 m high built at mid-span and restricted to rotate at the top by the steel frame (Figure 5.12).



Figure 5.11: Half-height brick partition



Figure 5.12: Full-height brick partition

5.2.2.6 Dynamic testing equipment

The excitation was generated by a APS Dynamics Modal 400 Electro-Seis electrodynamic shaker (Figure 5.13) and a Dytran Model 5803A 5.4 Kg instrumented impulse hammer (Figure 5.14). The electrodynamic shaker was used to extract the natural frequencies and mode shapes of the test floor. The instrumented impulse hammer was used for damping studies. Force-balanced QA 700 accelerometers with a sensitivity of 8 V/g mounted to base plates (Figure 5.15) were used to measure the responses of the floor slab. The Data Physics Signal Calc Mobilyser (Figure 5.16) was used to acquire the data from the accelerometers. The drive power for the electrodynamic shaker was obtained from the power amplifier APS 145. A chirp excitation running from 5 Hz to 180 Hz was used to excite the floor with the electrodynamic shaker. The electrodynamic shaker was set to operate in the free armature mode. A personal computer was used to store, analyse and present the data. The curve fitting method in Vibrant Technologies ME' Scope was used to estimate the natural frequencies and mode shapes of the test floor. Modal 1.20 by Brownjohn (2009) was used to estimate the damping ratios of the test floor. Modal 1.20 uses the logarithmic decrement method to estimate damping.

The accelerometers were mounted to base plates. The latter kept the accelerometers from lifting off the test floor during excitation therefore making the measured data reliable. The responses of the test floor to the applied excitation were measured at forty points. These points were located on the test floor and equally spaced. These points

were kept constant throughout the research project for different test scenarios. Figure 5.17 shows the forty test points used during modal testing. The test floor was excited at a single position and the responses of the test floor to the applied excitation were measured at the forty test points shown in Figure 5.17. The test floor was excited at the centre of the red coloured surface quad shown in Figure 5.17. This position was used for both continuous and impulse excitations throughout the research project for the different test scenarios.

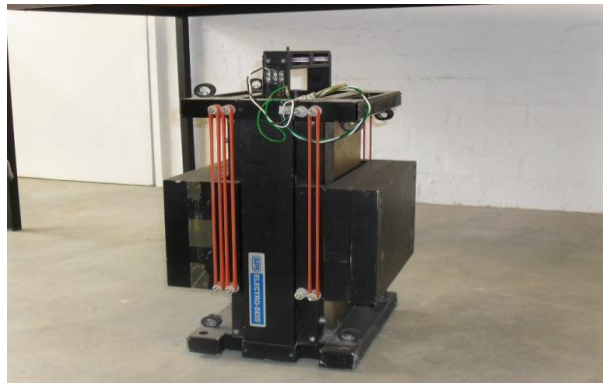


Figure 5.13: Electrodynamic shaker



Figure 5.14: Instrumented impulse hammer

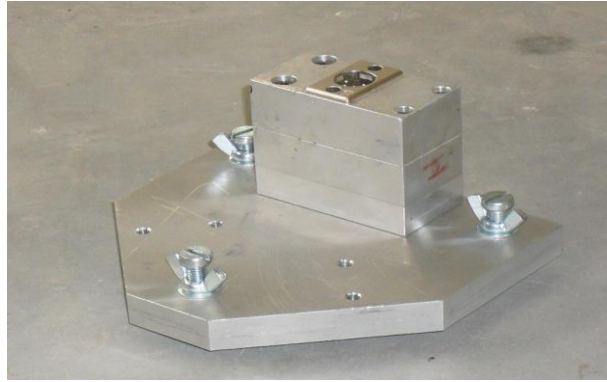


Figure 5.15: Force-balanced QA 700 accelerometer mounted on base plate



Figure 5.16: Data acquisition system

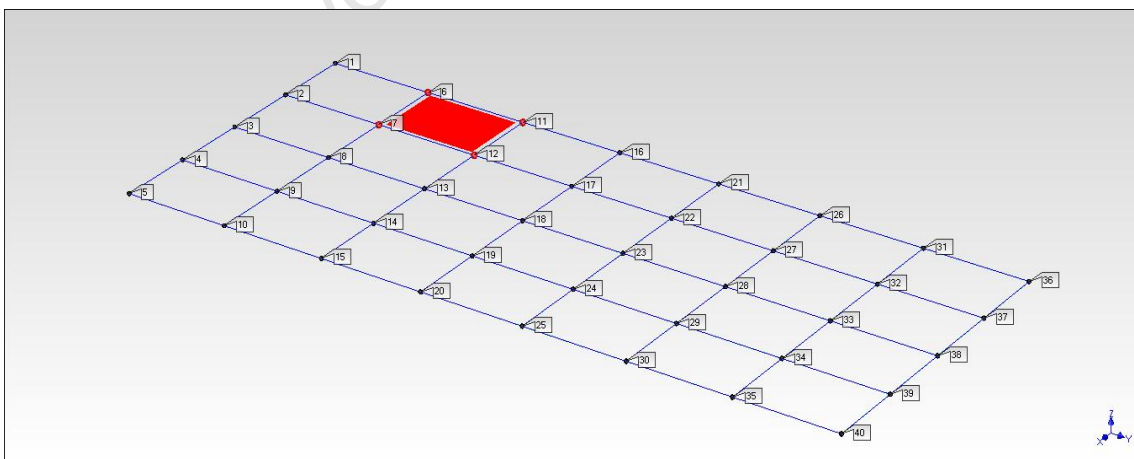


Figure 5.17: Test points used during modal testing

5.2.2.7 Measurement errors

Preliminary testing and calibration were done before the laboratory modal tests to make sure that the test equipment was functioning properly and to make sure that the test structure behaved linearly and not excessively excited by extraneous excitation. Different measurements were performed in order to determine the suitability of the concrete floor slab for modal testing and to determine the data acquisition parameters to be used during the tests. These measurements were excitation/response check, immediate repeatability check, homogeneity check, reciprocity check, coherence function check, FRF shape check and end of test repeatability check. These measurements also helped to determine whether the test equipment was operating satisfactorily, or the test structure behaved linearly and not excessively excited by extraneous excitation.

The different tests performed before the laboratory modal testing also had the objective to eliminate the occurrence of measurement errors. These tests were done before the actual modal tests in the laboratory in order to identify any error or fault in the instrumentation that could jeopardise the validity and accuracy of the measured data.

The measured data obtained in the laboratory during modal testing should be considered reliable and accurate since any possible error that could arise during modal testing was taken into account and dealt with appropriately in order for it not to occur during the actual laboratory test.

5.3 Field work

5.3.1 Test structure

The floor of the operating theatres of a newly built hospital building in Cape Town was tested before and after the installation of full-height brick partitions. The operating theatres were located on the first floor of the two storey building. Because of the large size of the first floor of the hospital, the focus was based only on the floor of the operating theatres. This floor consisted of a 250 mm thick conventionally reinforced solid concrete slab. The slab was supported by twelve rectangular reinforced concrete

columns and two reinforced concrete beams. The beams were 415x425 mm and 280x1105 mm in cross-section respectively. The floor had a length of 26.85 m and a width of 6.9 m. Figure 5.18 shows the configuration of the test floor structure.

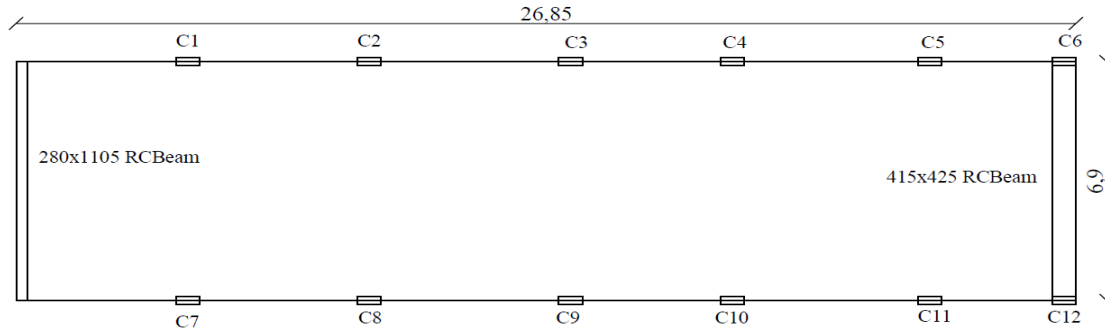


Figure 5.18: Test structure configuration

The test floor was made of conventionally reinforced concrete with a characteristic strength of 30 MPa using ordinary portland cement. For a concrete characteristic strength of 30 MPa, SANS 0100-1 (2000) recommends a mean static elastic modulus of 28 GPa and a mean dynamic elastic modulus of 38 GPa. SANS 0100-1 (2000) also recommends a Poisson's ratio of 0.2 for concrete. The concrete floor was further partitioned into four different rooms using full-height brick partitions (Figure 5.19). For the post-partition modal test, only Theatre 4 was tested because of time constraint.

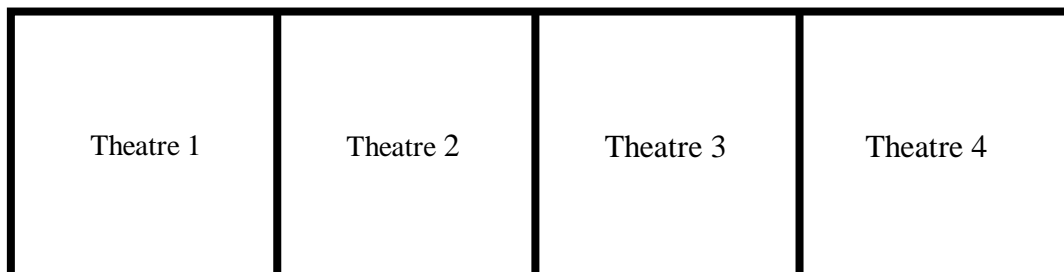


Figure 5.19: Test structure configuration with partitions

5.3.2 Modal testing procedures

The objective of modal testing was to measure the modal parameters of the test floor before and after the installation of full-height brick partitions. The excitation of the test floor prior partitioning was generated by a Dytran Model 5803A 5.4 Kg instrumented impulse hammer. The excitation of the floor post partitioning was done using the Multi Input Multi Output (MIMO) technique where two APS Dynamics Modal 400 Electro-Seis electrodynamic shakers were used because of the added mass of the partitions. Force-balanced QA 700 accelerometers with a sensitivity of 8 V/g mounted to base plates were used to measure the responses of the test floor. The excitation forces were measured using two Piezotronics/ICP accelerometers with a sensitivity of 1 V/g mounted to the two electrodynamic shakers. The accelerometers were placed in Theatre 4. The two electrodynamic shakers were placed in different rooms in order to fully excite the test floor. One electrodynamic shaker was placed in Theatre 4 together with the accelerometers and the other electrodynamic shaker was placed in Theatre 2. The drive power for the two electrodynamic shakers was obtained from two power amplifiers namely APS 125 and APS 145. The two electrodynamic shakers were set to operate in the free armature mode and a chirp excitation running from 5 Hz to 180 Hz was used to excite the test floor.

To determine the modal parameters of the test floor, FRFs were required. Therefore both the excitation and response signals were fed into the data acquisition system which in turn calculated the FRFs. A personal computer was used to store, analyse and present the data. The modal parameter estimation was done using the software called Vibrant Technologies ME'Scope. The curve fitting method in ME'Scope was used to estimate the modal parameters i.e. natural frequencies, damping ratios and mode shapes.

5.4 Summary

This chapter has presented how the effects of partitions on the vibration serviceability of concrete floors were investigated. This chapter has presented the methodology adopted for the modal tests performed on the experimental floor slab. The methodology adopted to perform modal testing in the field on a full-scale conventionally reinforced concrete

floor before and after the installation of full-height brick partitions was also presented in the chapter. The next chapter will present and discuss the results of modal testing on the experimental floor slab before and after the installation of various configurations of timber and brick partitions.

University of Cape Town

6 LABORATORY WORK

6.1 Introduction

The results from modal testing on the experimental floor slab are presented and discussed in this chapter. These results were obtained using the methodology presented in Chapter 5. The mode shapes with their associated natural frequencies and damping ratios for the bare floor and those with various configurations of partitions are presented in this chapter. The FRFs for each test configuration are also presented in the chapter.

6.2 Bare floor

The FRFs of the bare floor are displayed in Figure 6.2. Each peak in the FRFs represents at least one mode. Each mode is associated to a natural frequency and damping ratio. Figure 6.1 shows the layout of the test floor including its span and width.

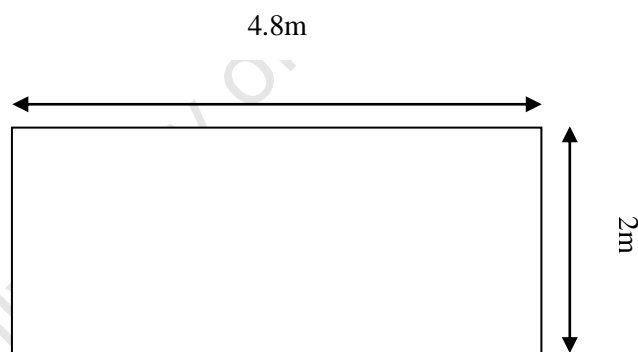


Figure 6.1: Layout of test floor (bare floor)

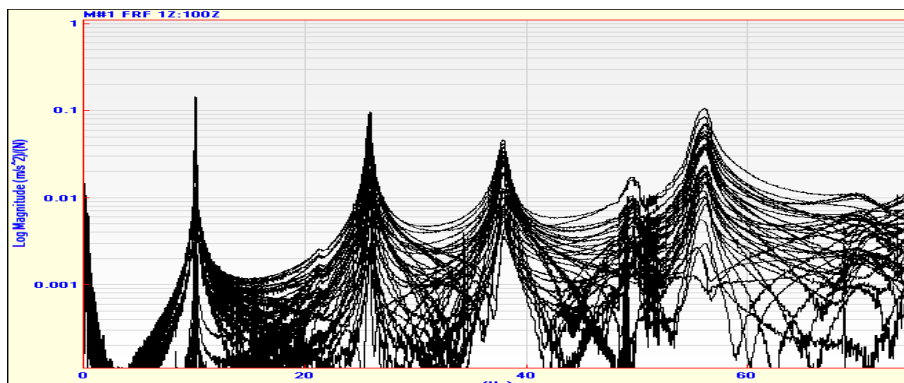


Figure 6.2: FRFs of bare floor

The signal processing option in ME'Scope was used to analyse the measured responses of the test floor. After the signal processing, FRFs were generated. The latter were generated from the measured responses of the test floor to the electrodynamic shaker excitation. The FRFs were used mainly to extract the natural frequencies and mode shapes of the test floor.

The measured responses of the test floor to the instrumented impulse hammer excitation were used to extract the damping ratios of the test floor. Figure 6.3 shows the response at a node of the bare floor to impulse excitation. Figure 6.4 shows the logarithmic decrement process in Modal 1.20 for the bare floor. Figure 6.5 shows the results of the damping studies at a node obtained from Modal 1.20.

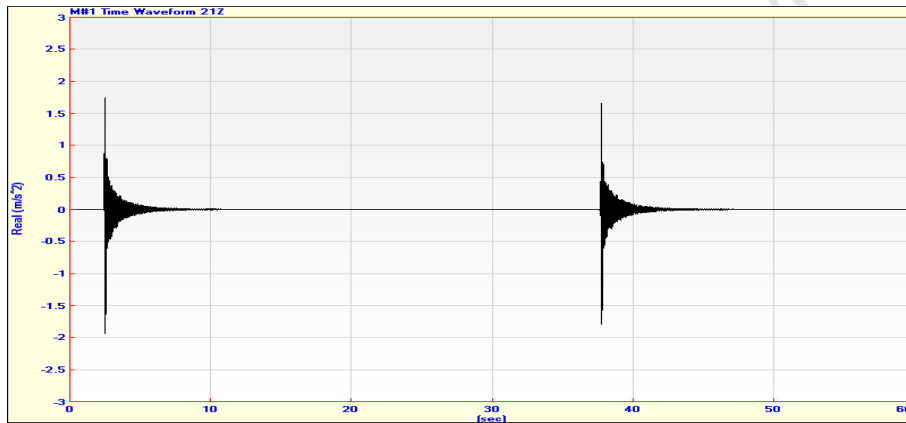


Figure 6.3: Impulse response at a node of bare floor

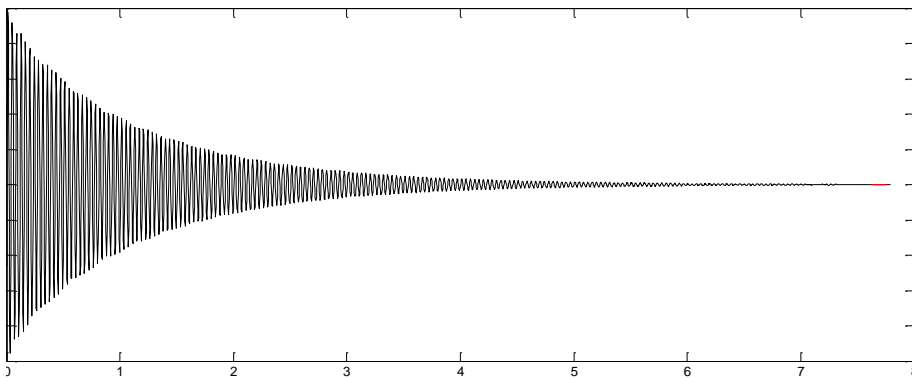


Figure 6.4: Logarithmic decrement in Modal 1.20 for bare floor

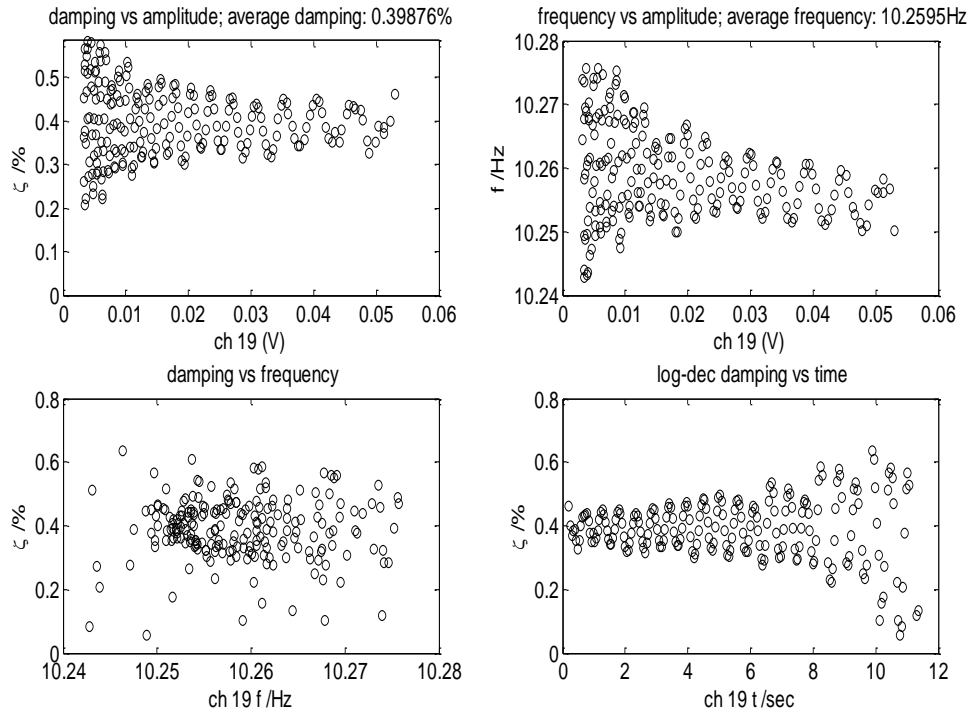
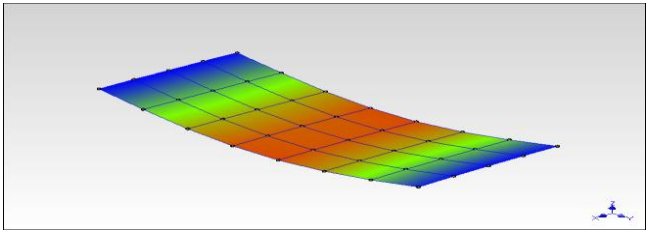
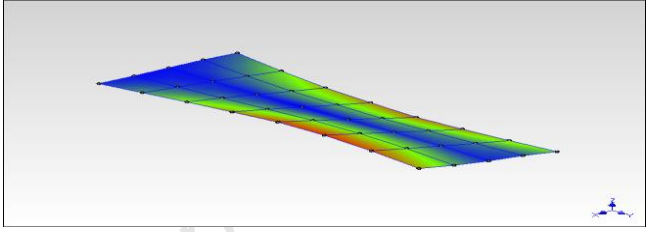
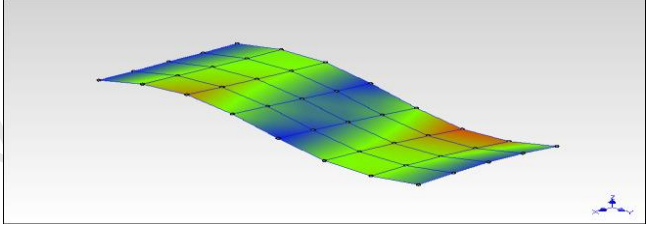
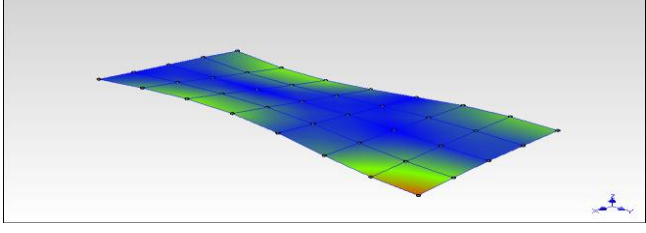


Figure 6.5: Damping studies for bare floor

The natural frequencies below 75 Hz of the bare floor with their associated mode shapes and damping ratios are given in Table 6.1.

Table 6.1: Measured modal parameters of bare floor

Mode description	Frequency (Hz)	Damping ratio (%)	Mode shape
1 st Bending	10.1	0.4	
1 st Torsion	25.7	0.5	
2 nd Bending	38.1	0.75	
2 nd Torsion	56.1	1.5	

6.3 Layout 1: Timber partition

Figure 6.6 is a sketch of the test floor as per Layout 1. The FRFs of the test floor with the timber half-height partition as per Layout 1 are displayed in Figure 6.7.

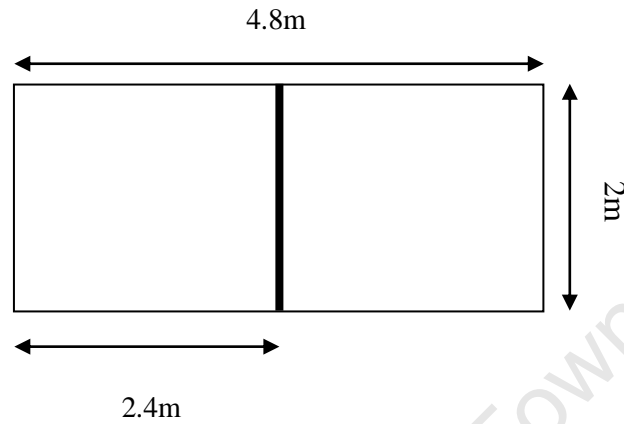


Figure 6.6: Layout 1 (Timber partition)

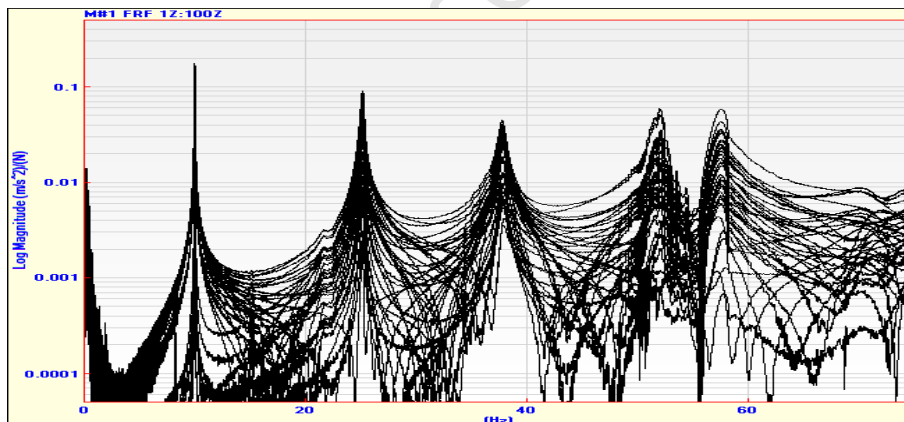
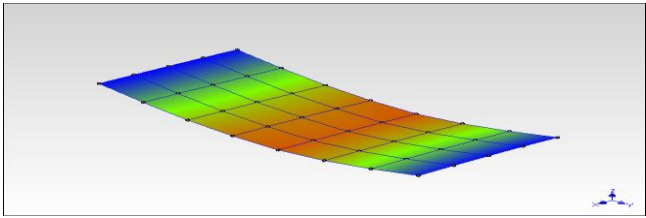
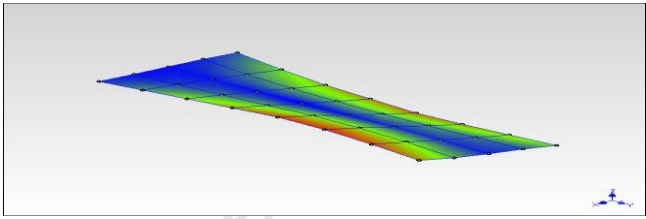
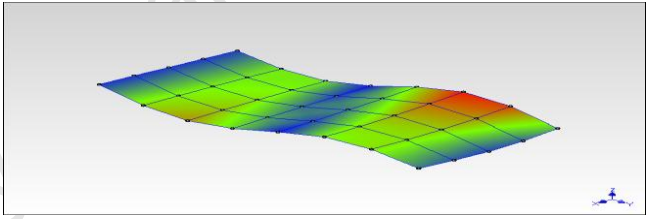
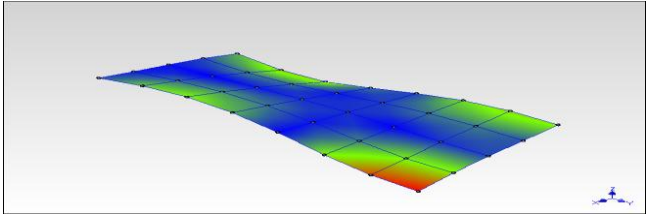
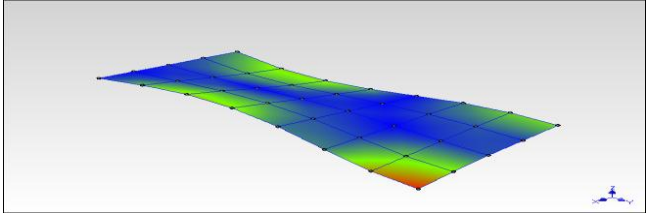


Figure 6.7: FRFs of test floor as per Layout 1

The natural frequencies below 75 Hz of the test floor as per Layout 1 with their associated mode shapes and damping ratios are given in Table 6.2.

Table 6.2: Measured modal parameters of test floor as per Layout 1

Mode description	Frequency (Hz)	Damping ratio (%)	Mode shape
1 st Bending	9.95	0.4	
1 st Torsion	24.7	0.7	
2 nd Bending	37.7	1.75	
2 nd Torsion	52.2	1.67	
2 nd Torsion	57.5	1.85	

6.4 Layout 2: Timber partitions

Figure 6.8 is a sketch of the test floor as per Layout 2. The FRFs of the test floor with the timber half-height partitions as per Layout 2 are displayed in Figure 6.9.

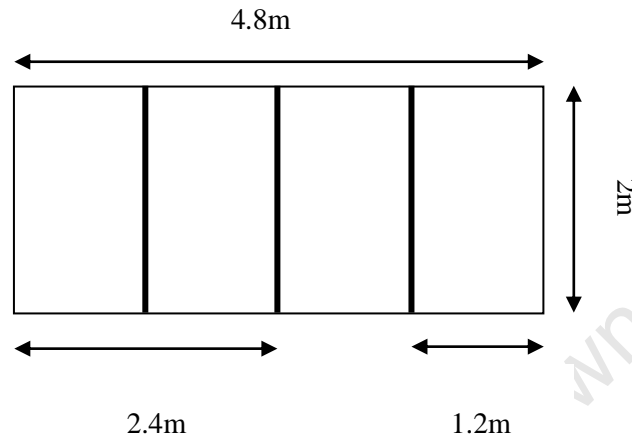


Figure 6.8: Layout 2 (Timber partitions)

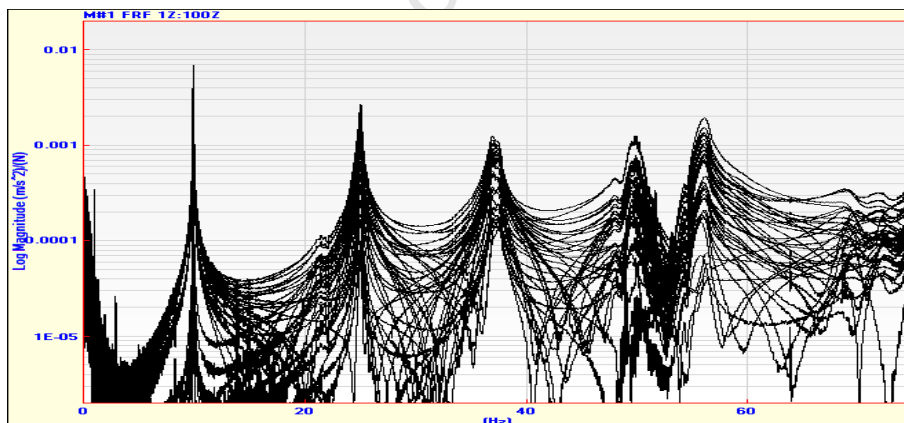
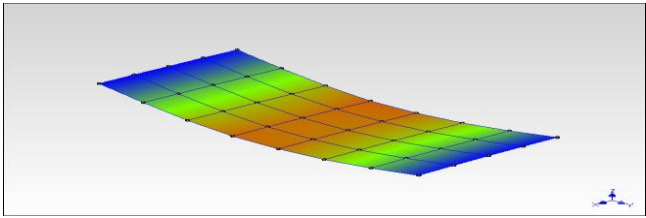
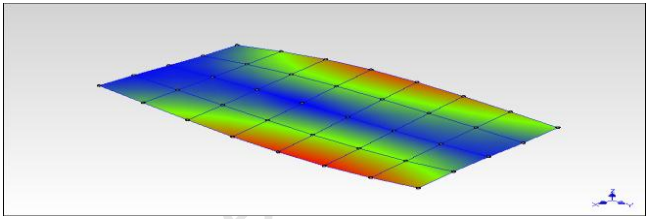
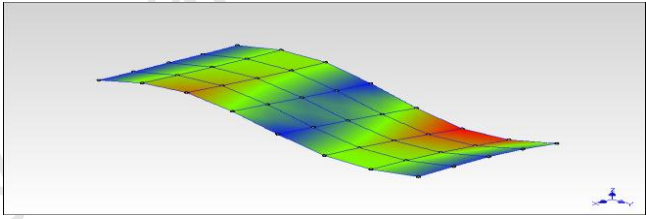
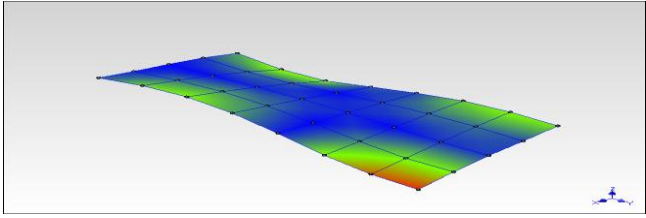
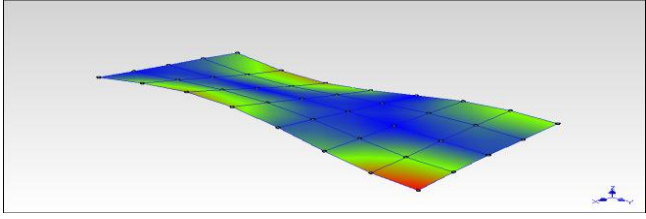


Figure 6.9: FRFs of test floor as per Layout 2

The natural frequencies below 75 Hz of the test floor as per Layout 2 with their associated mode shapes and damping ratios are given in Table 6.3.

Table 6.3: Measured modal parameters of test floor as per Layout 2

Mode description	Frequency (Hz)	Damping ratio (%)	Mode shape
1 st Bending	9.81	0.4	
1 st Torsion	24.6	1.2	
2 nd Bending	36.9	1.46	
2 nd Torsion	49.9	2.34	
2 nd Torsion	56.1	2.49	

6.5 Layout 3: Timber partitions

Figure 6.10 is a sketch of the test floor as per Layout 3. The FRFs of the test floor with the timber half-height partitions as per Layout 3 are displayed in Figure 6.11.

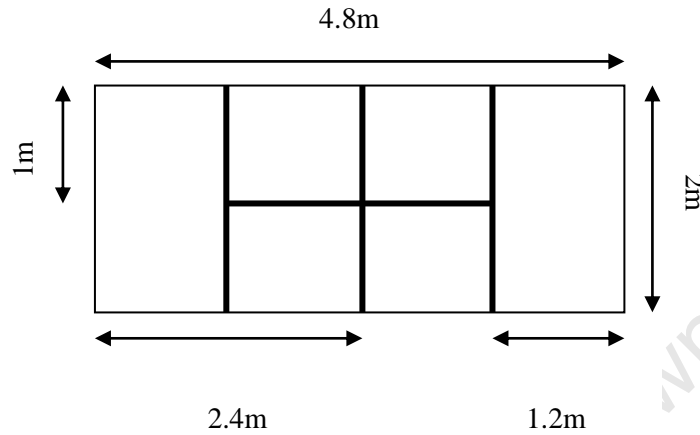


Figure 6.10: Layout 3 (Timber partitions)

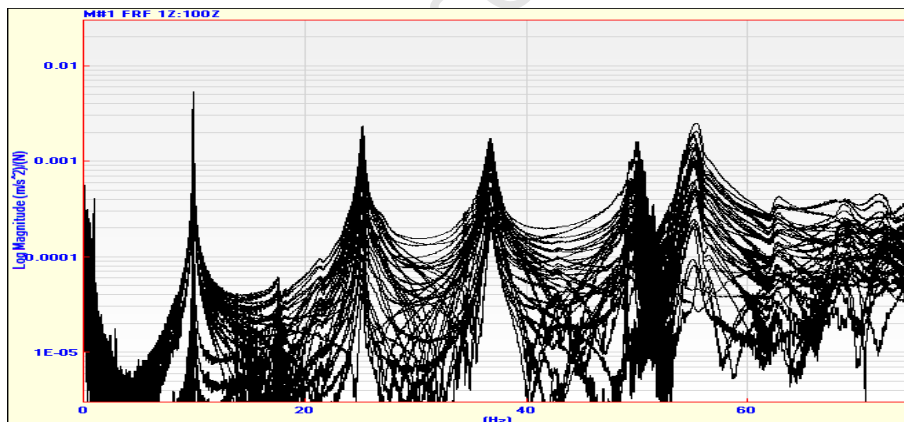
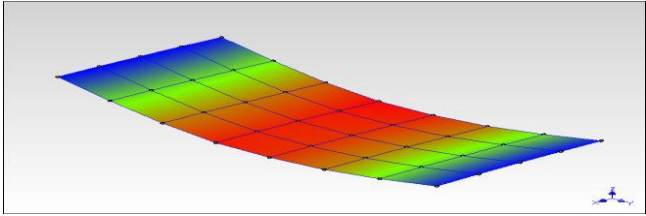
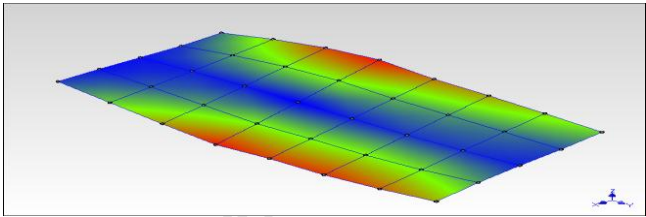
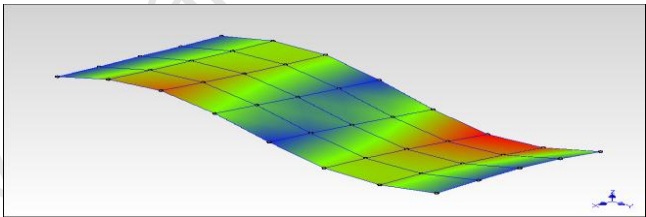
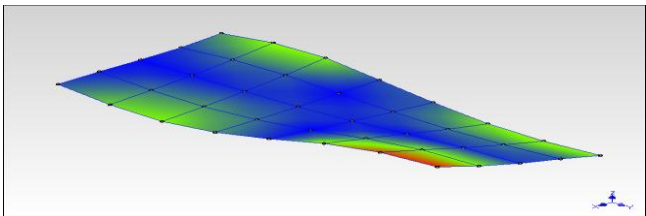
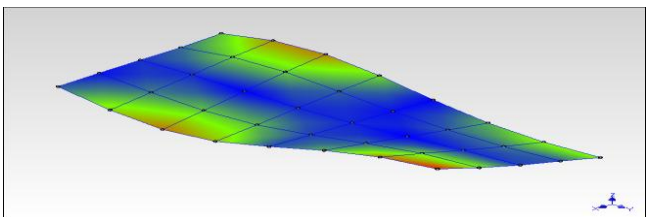


Figure 6.11: FRFs of test floor as per Layout 3

The natural frequencies below 75 Hz of the test floor as per Layout 3 with their associated mode shapes and damping ratios are given in Table 6.4.

Table 6.4: Measured modal parameters of test floor as per Layout 3

Mode description	Frequency (Hz)	Damping ratio (%)	Mode shape
1 st Bending	9.69	0.4	
1 st Torsion	24.6	1.1	
2 nd Bending	36.8	1.7	
2 nd Torsion	49.9	2.84	
2 nd Torsion	55.2	1.53	

6.6 Layout 4: Timber partitions

Figure 6.12 is a sketch of the test floor as per Layout 4. The FRFs of the test floor with the timber half-height partitions as per Layout 4 are displayed in Figure 6.13.

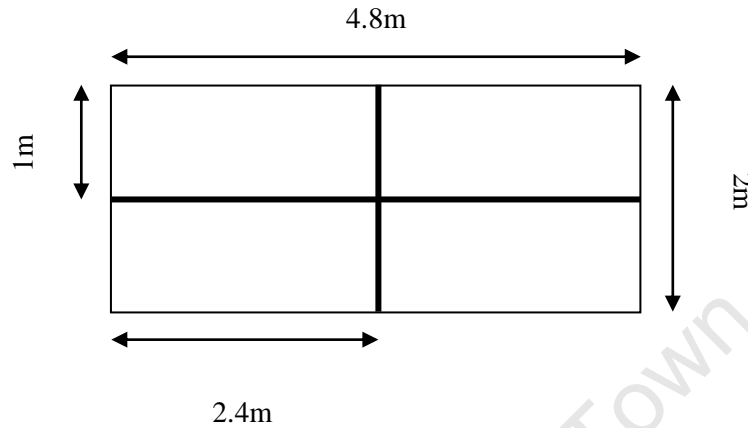


Figure 6.12: Layout 4 (Timber partitions)

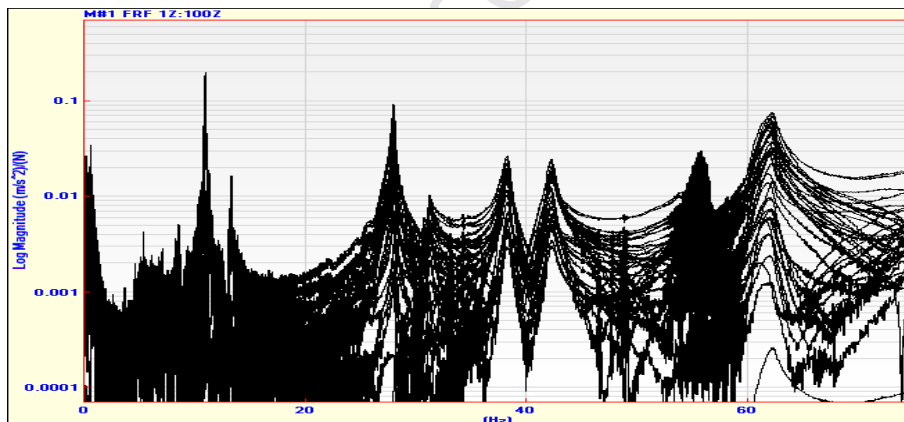
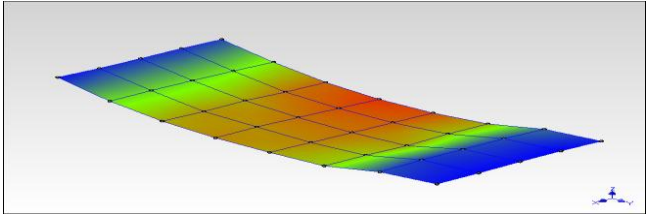
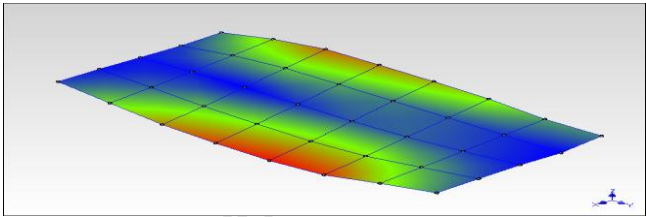
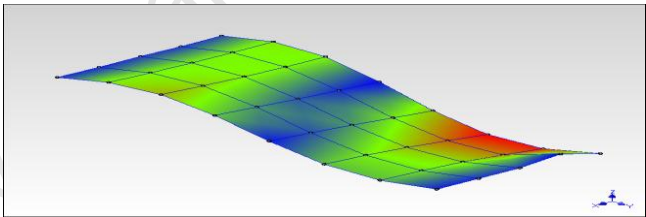
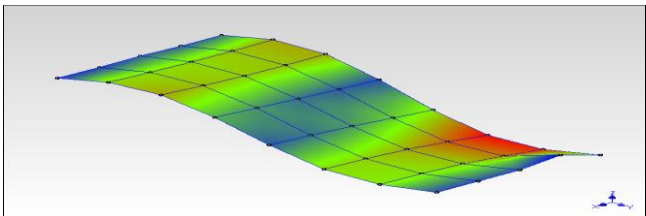
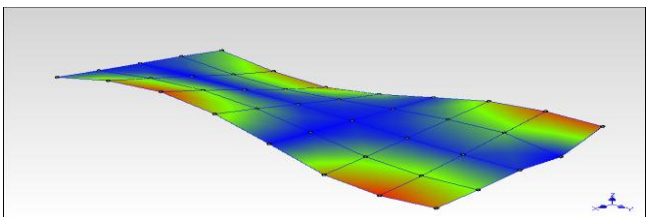


Figure 6.13: FRFs of test floor as per Layout 4

The natural frequencies below 75 Hz of the test floor as per Layout 4 with their associated mode shapes and damping ratios are given in Table 6.5.

Table 6.5: Measured modal parameters of test floor as per Layout 4

Mode description	Frequency (Hz)	Damping ratio (%)	Mode shape
1 st Bending	9.52	0.7	
1 st Torsion	25.5	2.1	
2 nd Bending	37.9	1.85	
2 nd Bending	42.2	2.91	
2 nd Torsion	62.1	2.36	

6.7 Timber full-height partition

Layout 1 was used to simulate full-height partitioning. A steel frame was used in order to prevent the partition from rotating at the top. Therefore the sketch in Figure 6.6 also applies to the test floor with full-height timber partition. The FRFs of the test floor with full-height timber partition are displayed in Figure 6.14.

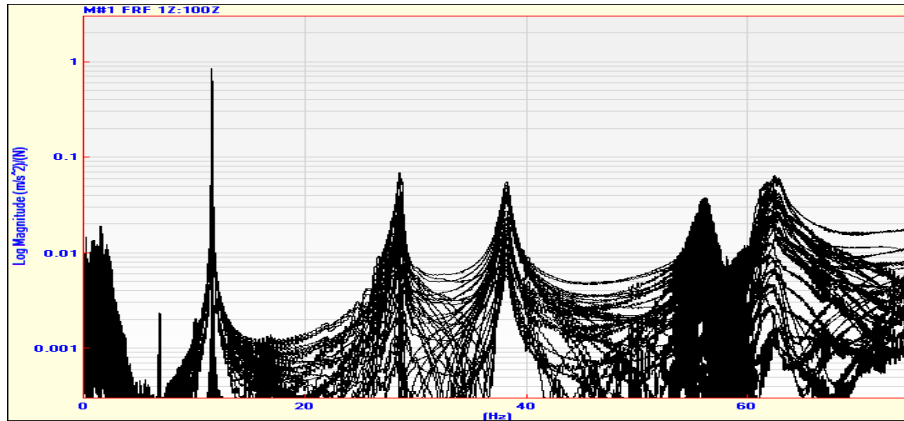


Figure 6.14: FRFs of test floor with full-height timber partition

Figure 6.15 shows the response at a node to impulse excitation of the test floor with full-height timber partition. Figure 6.16 shows the logarithmic decrement process in Modal 1.20 for the test floor with full-height timber partition. Figure 6.17 shows the results of the damping studies at a node of the test floor with full-height timber partition obtained from Modal 1.20.

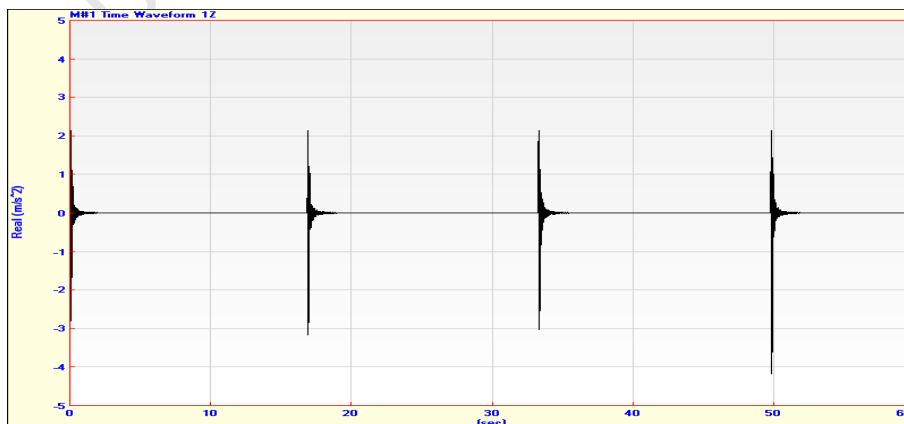


Figure 6.15: Impulse response at a node of the test floor with full-height timber partition

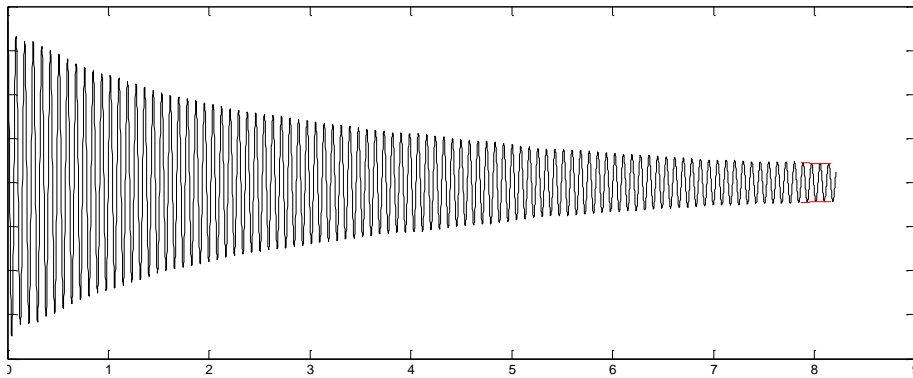


Figure 6.16: Logarithmic decrement in Modal 1.20 for test floor with full-height timber partition

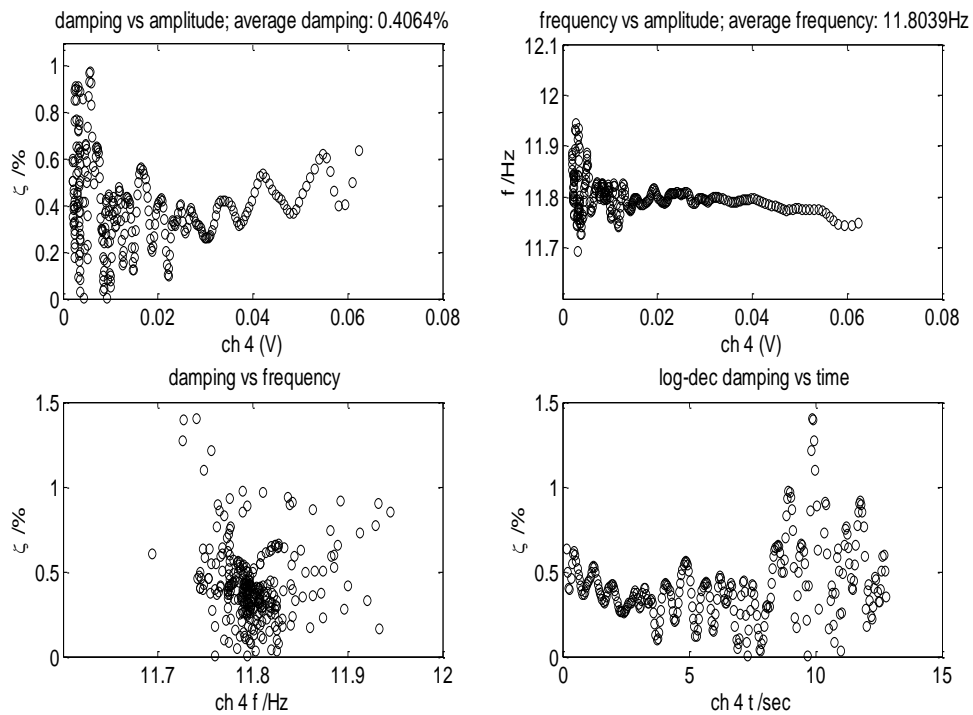
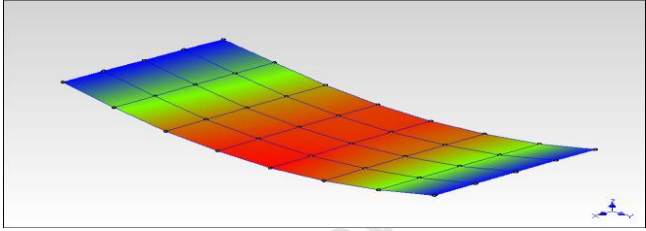
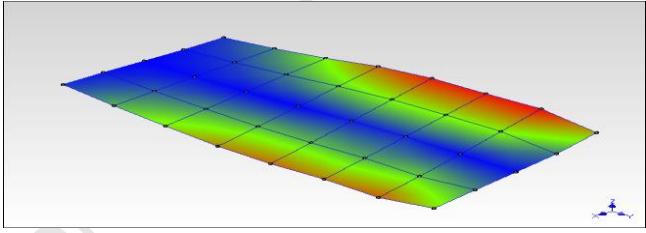
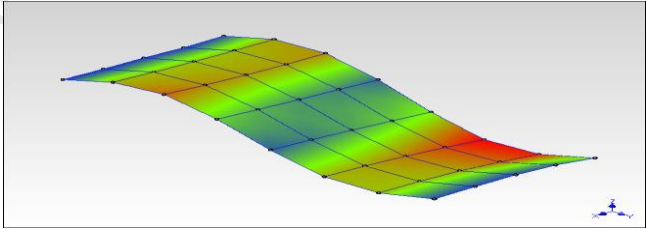
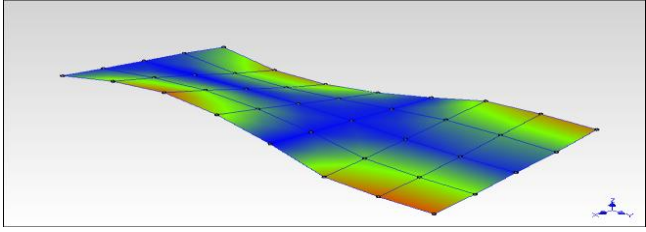


Figure 6.17: Damping studies for the test floor with full-height timber partition

The natural frequencies below 75 Hz of the test floor with full-height timber partition together with their associated mode shapes and damping ratios are given in Table 6.6.

Table 6.6: Measured modal parameters of test floor with full-height timber partition

Mode description	Frequency (Hz)	Damping ratio (%)	Mode shape
1 st Bending	12.5	0.41	
1 st Torsion	29.6	0.9	
2 nd Bending	38.3	2.44	
2 nd Torsion	62.1	1.7	

6.8 Brick partitions

The layout used for the test floor with half-height as well as full-height brick partition is shown in Figure 6.18.

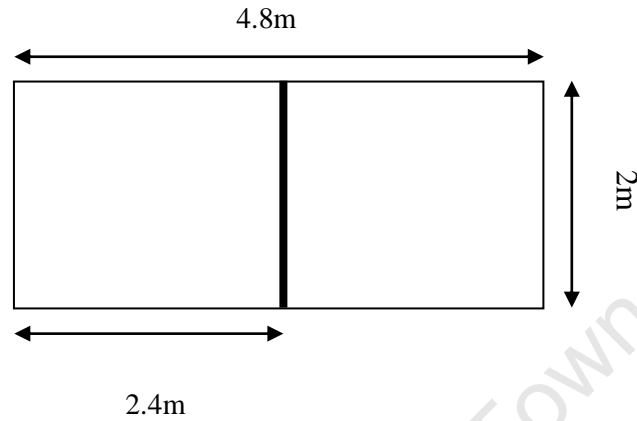


Figure 6.18: Layout used for brick partition

6.8.1 Half-height brick partition

The FRFs of the test floor with half-height brick partition are displayed in Figure 6.19.

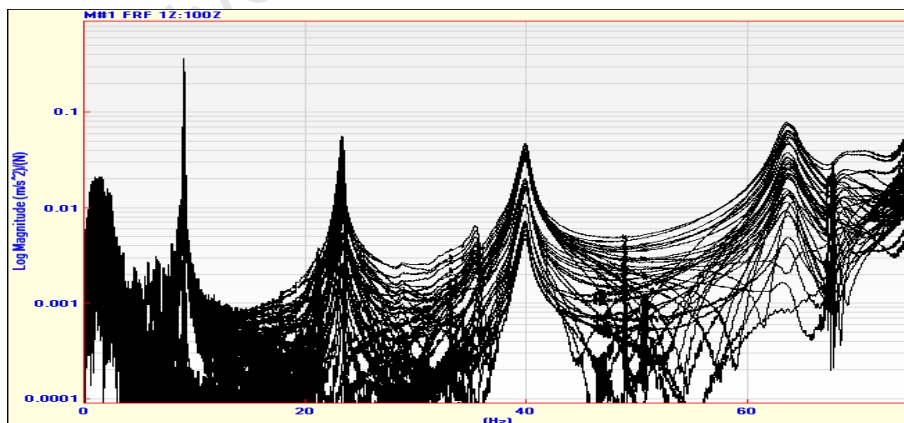


Figure 6.19: FRFs of test floor with half-height brick partition

Figure 6.20 shows the response at a node to impulse excitation of the test floor with half-height brick partition. Figure 6.21 shows the logarithmic decrement process in Modal 1.20 for the test floor with half-height brick partition.

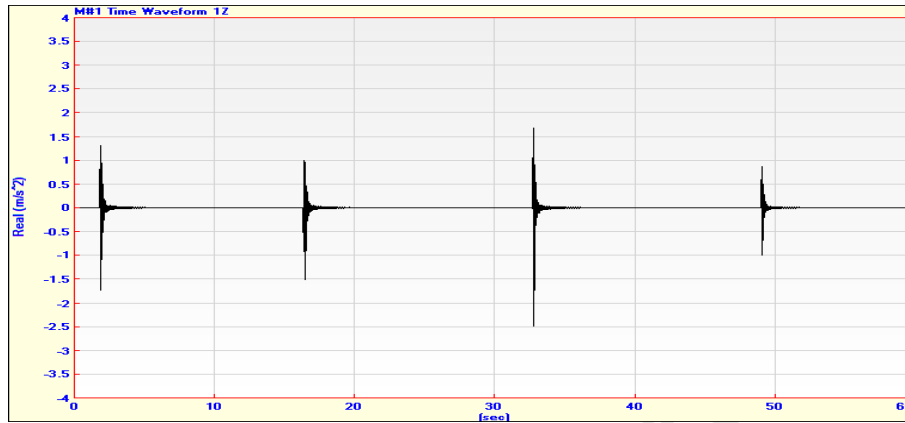


Figure 6.20: Impulse response at a node of the test floor with half-height brick partition

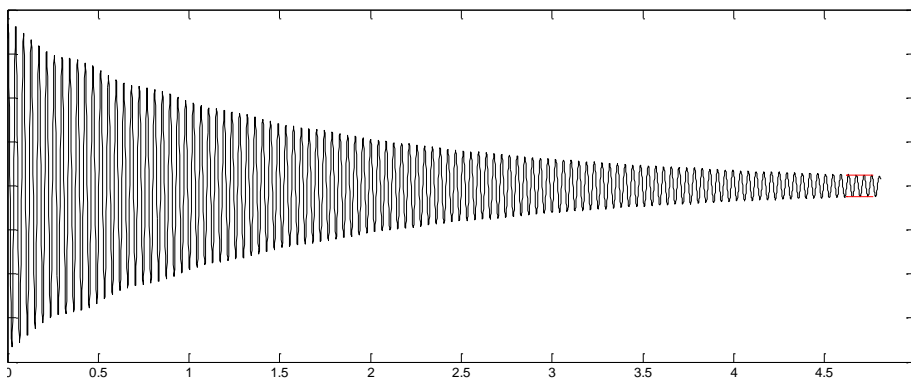
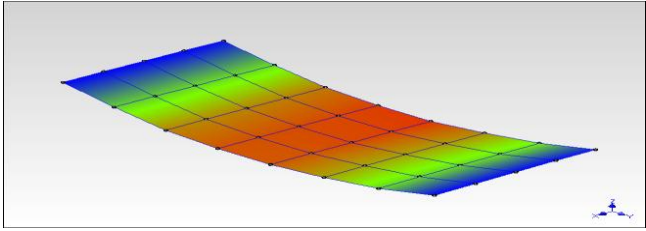
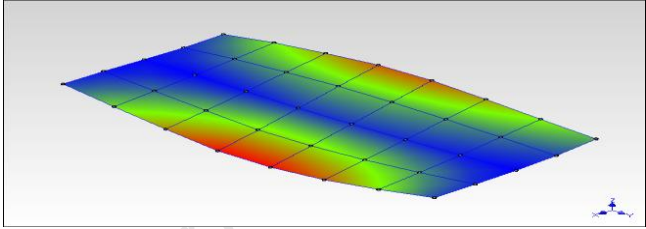
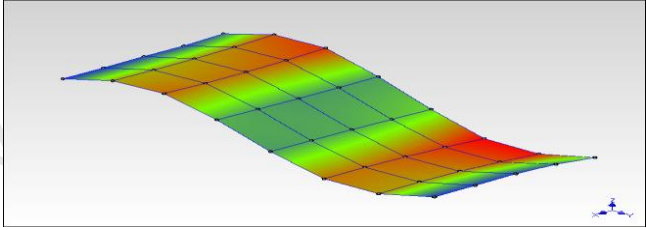
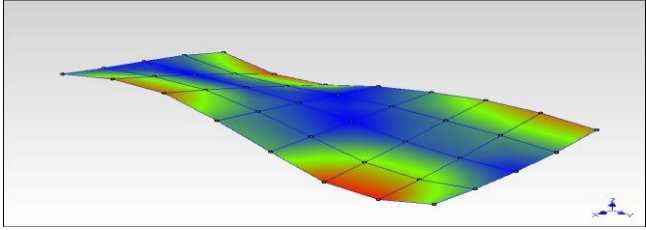


Figure 6.21: Logarithmic decrement in Modal 1.20 for the test floor with half-height brick partition

The natural frequencies below 75 Hz of the test floor with half-height brick partition together with their associated mode shapes and damping ratios are given in Table 6.7.

Table 6.7: Measured modal parameters of test floor with half-height brick partition

Mode description	Frequency (Hz)	Damping ratio (%)	Mode shape
1 st Bending	8.88	0.3	
1 st Torsion	22.3	0.4	
2 nd Bending	39.8	2.87	
2 nd Torsion	63.5	1.61	

6.8.2 Full-height brick partition

The FRFs of the test floor with full-height brick partition are displayed in Figure 6.22.

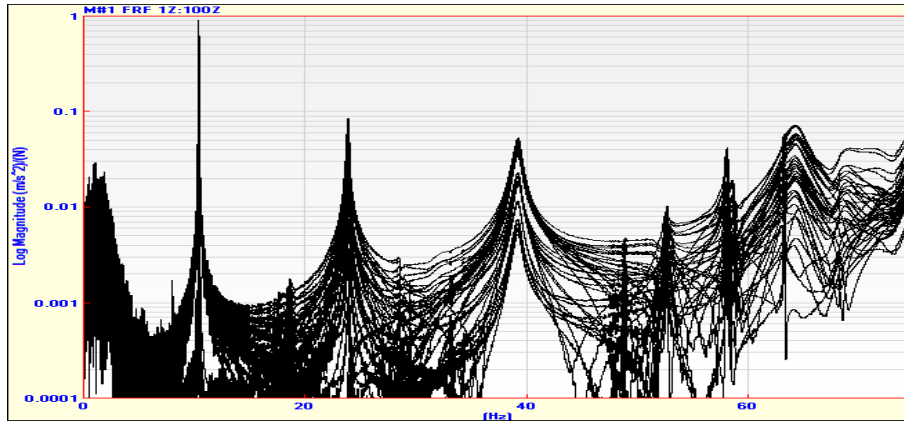


Figure 6.22: FRFs of test floor with full-height brick partition

Figure 6.23 shows the results of the damping studies at a node of the test floor with full-height brick partition obtained from Modal 1.20.

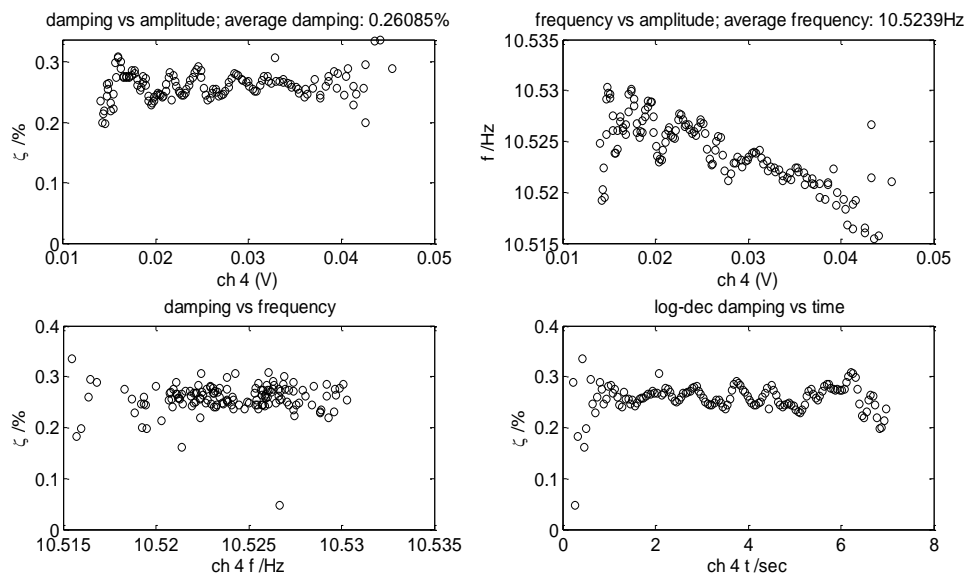
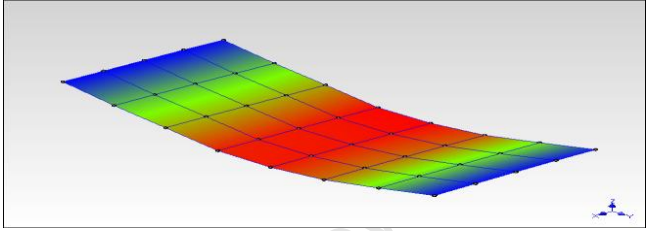
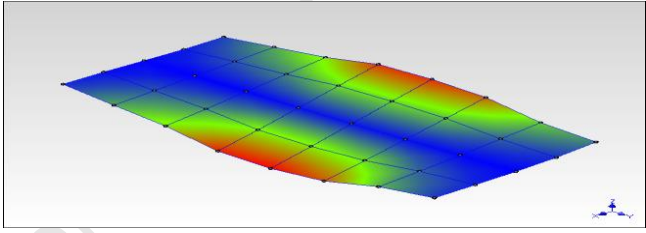
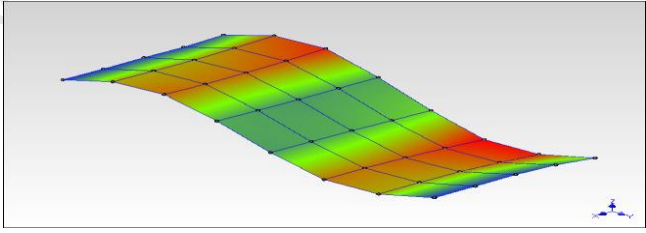
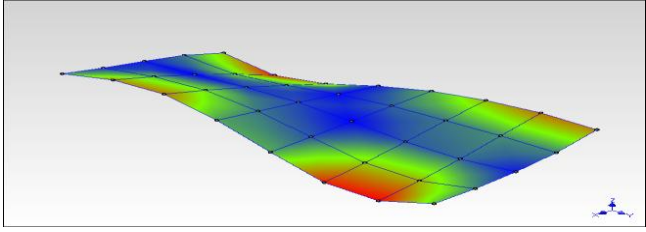


Figure 6.23: Damping studies for the test floor with full-height brick partition

The natural frequencies below 75 Hz of the test floor with full-height brick partition together with their associated mode shapes and damping ratios are given in Table 6.8.

Table 6.8: Measured modal parameters of test floor with full-height brick partition

Mode description	Frequency (Hz)	Damping ratio (%)	Mode shape
1 st Bending	10.2	0.3	
1 st Torsion	23.8	0.4	
2 nd Bending	39.2	2.71	
2 nd Torsion	64	2.88	

6.9 Effects of partitions

6.9.1 Timber partitions

The natural frequencies and damping ratios of the test floor before and after the installation of various configurations of timber partitions are presented in Table 6.9 and Table 6.10 respectively.

Table 6.9: Comparison of natural frequencies prior and post timber partitioning

Mode	Bare floor (Hz)	Half-height				Full-height (Hz)	Description
		Layout 1 (Hz)	Layout 2 (Hz)	Layout 3 (Hz)	Layout 4 (Hz)		
1	10.1	9.95	9.81	9.69	9.52	12.5	1 st Bending
2	25.7	24.7	24.6	24.6	25.5	29.6	1 st Torsion
3	38.1	37.7	36.9	36.8	37.9	38.3	2 nd Bending
4	56.1	52.2	49.9	49.9	42.2	62.1	2 nd Torsion 2 nd Bending (Layout 4)
5		57.5	56.1	55.2	62.1		2 nd Torsion

The natural frequencies of the test floor decreased following the installation of half-height timber partitions. This decrease in natural frequencies implies that the increase in mass following the installation of half-height timber partitions was more significant than any increase in stiffness. This decrease in natural frequencies was expected since literature suggests that half-height partitions can decrease the natural frequencies of the floor that supports them.

The bare floor only had four modes of vibration below 75 Hz. The installation of half-height timber partitions introduced a fifth mode of vibration. This new mode of vibration is similar to the fourth mode except for Layout 4. With regards to half-height timber partitions, Layout 4 is the most effective since it has the highest natural frequency for the fifth mode and changes the fourth mode of the test floor from 2nd Torsion to 2nd Bending.

The natural frequencies of the test floor increased following the installation of full-height timber partition. This increase in natural frequencies implies that the increase in

stiffness following the installation of full-height timber partition was more significant than any increase in mass. This increase in natural frequencies was expected since literature suggests that full-height partitions can increase the stiffness of the floor that supports them and thereby increasing its natural frequencies. The mode shapes of the test floor did not change following the installation of full-height timber partition.

Table 6.10: Comparison of damping ratios prior and post timber partitioning

Mode	Bare floor (%)	Half-height				Full-height (%)	Description
		Layout 1 (%)	Layout 2 (%)	Layout 3 (%)	Layout 4 (%)		
1	0.4	0.4	0.4	0.4	0.7	0.41	1 st Bending
2	0.5	0.7	1.2	1.1	2.1	0.9	1 st Torsion
3	0.75	1.75	1.46	1.7	1.85	2.44	2 nd Bending
4	1.5	1.67	2.34	2.84	2.91	1.7	2 nd Torsion 2 nd Bending (Layout 4)
5		1.85	2.49	1.53	2.36		2 nd Torsion

The damping ratios of the test floor increased following the installation of half-height as well as full-height timber partitions except for the first mode of the first three layouts of the half-height partitions. The damping of the first mode for these three layouts did not change following the installation of the half-height partitions. The increase in damping ratios for the other modes was expected since literature suggests that partitions can increase the damping of the floor that supports them. With regards to half-height partitions, Layout 4 is the most effective since it has higher damping ratios than the other three layouts. Layout 4 has increased the damping ratio of the fundamental mode by 75 %.

The relationships between the natural frequencies of the bare floor and the natural frequencies of the floor with various configurations of timber partitions are displayed in Figure 6.24. The relationships between the natural frequencies of the bare floor and the damping ratios of the floor with various configurations of timber partitions are displayed in Figure 6.25.

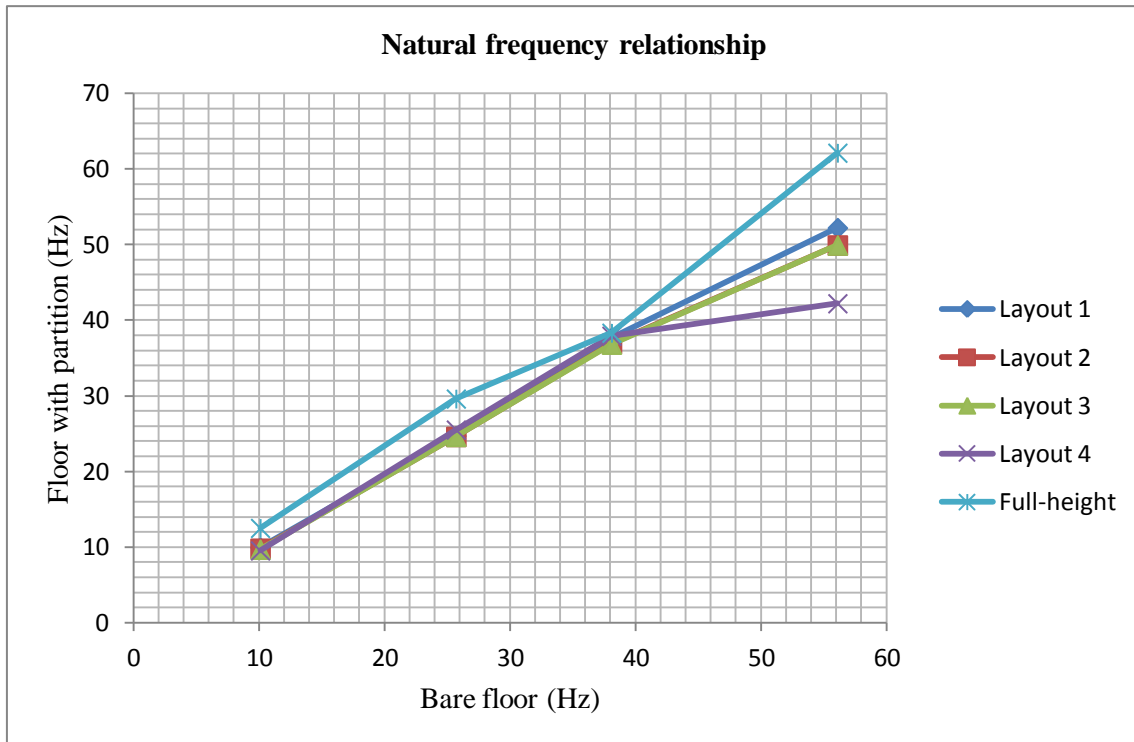


Figure 6.24: Natural frequency relationships for floors with timber partitions

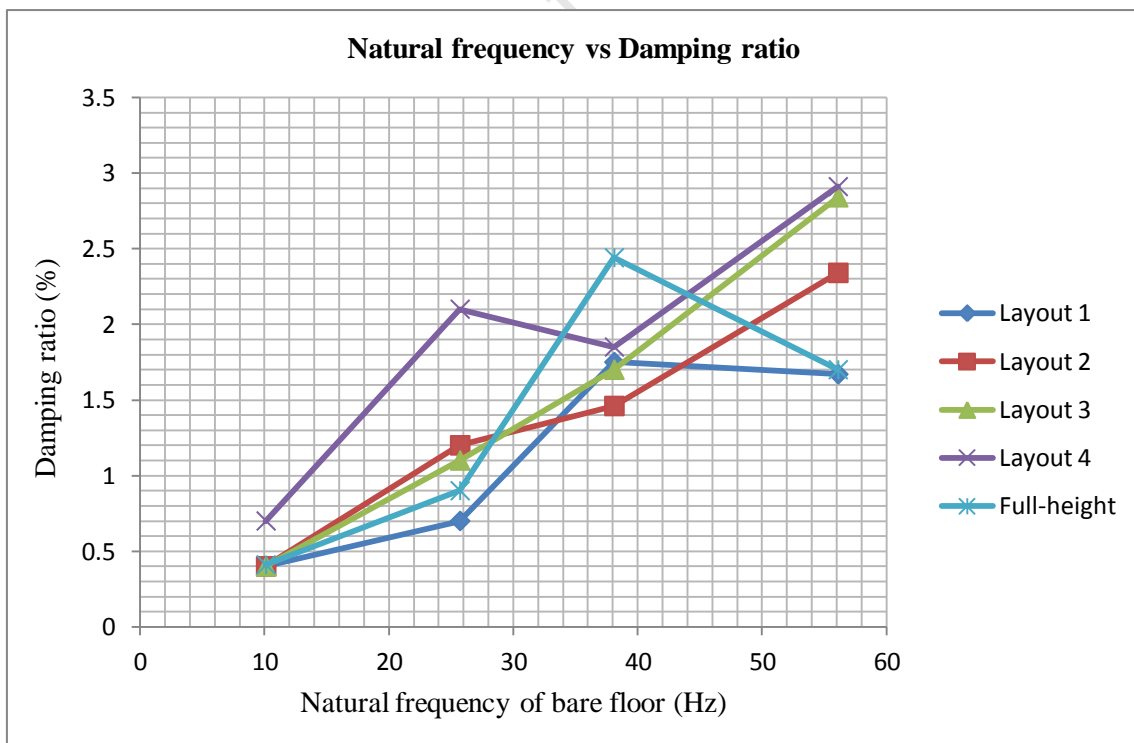


Figure 6.25: Natural frequency and damping ratio relationships for floors with timber partitions

6.9.2 Brick partitions

The natural frequencies and damping ratios of the test floor before and after the installation of brick partitions are presented in Table 6.11 and Table 6.12 respectively.

Table 6.11: Comparison of natural frequencies prior and post brick partitioning

Mode	Bare floor (Hz)	Half-height (Hz)	Full-height (Hz)	Description
1	10.1	8.88	10.2	1 st Bending
2	25.7	22.3	23.8	1 st Torsion
3	38.1	39.8	39.2	2 nd Bending
4	56.1	63.5	64	2 nd Torsion

The natural frequencies of the test floor decreased following the installation of half-height brick partition for the first two modes. This decrease in natural frequencies implies that the increase in mass following the installation of half-height brick partition was more significant than any increase in stiffness. This decrease in natural frequencies was expected since literature suggests that half-height partitions can decrease the natural frequencies of the floor that supports them.

The natural frequencies of the test floor increased following the installation of the half-height brick partition for the last two modes. This increase in natural frequencies implies that the increase in stiffness following the installation of half-height brick partition was more significant than any increase in mass. This increase in natural frequencies was unexpected since literature does not suggest that half-height partitions can increase stiffness. This result shows that half-height brick partitions can also increase the stiffness of the floor that supports them. The mode shapes of the test floor did not change following the installation of half-height brick partition.

The natural frequencies of the test floor increased following the installation of the full-height brick partition except for the second mode. This increase in natural frequencies implies that the increase in stiffness following the installation of full-height brick partition was more significant than any increase in mass. This increase in natural

frequencies was expected since literature suggests that full-height partitions can increase the stiffness of the floor that supports them.

The natural frequency of the test floor decreased for the second mode following the installation of full-height brick partition. This decrease in natural frequency implies that the increase in mass following the installation of full-height brick partition was more significant than any increase in stiffness. This decrease in natural frequency was not expected since it does not conform with literature. This decrease in natural frequency can be attributed to the inefficiency of the steel frame in providing full restriction at the top of the brick wall.

Table 6.12: Comparison of damping ratios prior and post brick partitioning

Mode	Bare floor (%)	Half-height (%)	Full-height (%)	Description
1	0.4	0.3	0.3	1 st Bending
2	0.5	0.4	0.4	1 st Torsion
3	0.75	2.87	2.71	2 nd Bending
4	1.5	1.61	2.88	2 nd Torsion

The damping ratios of the test floor decreased for the first two modes following the installation of the half-height as well as full-height brick partitions. This decrease in damping ratios was unexpected since literature does not suggest that partitions can decrease the damping of the floor that supports them.

The damping ratios of the test floor increased for the last two modes following the installation of the half-height as well as full-height brick partitions. This increase in damping ratios was expected since literature suggests that partitions can increase the damping of the floor that supports them.

The relationships between the natural frequencies of the bare floor and the natural frequencies of the floor with various configurations of brick partitions are displayed in Figure 6.26. The relationships between the natural frequencies of the bare floor and the damping ratios of the floor with various configurations of brick partitions are displayed in Figure 6.27.

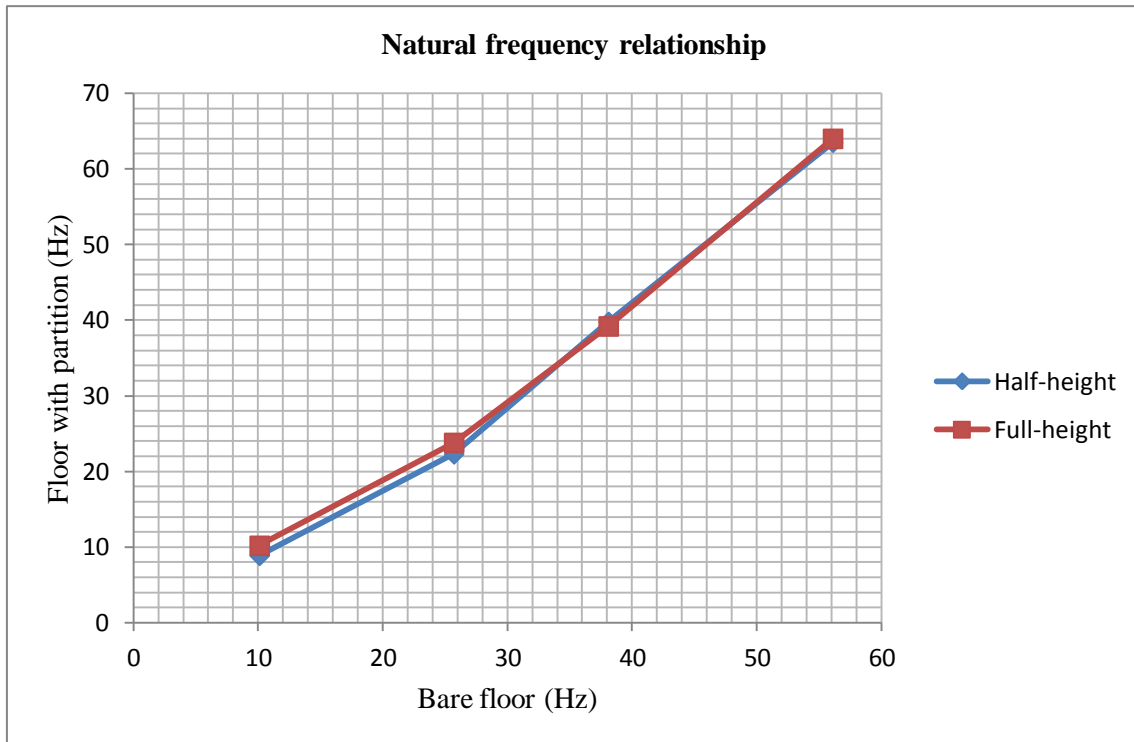


Figure 6.26: Natural frequency relationships for floors with brick partitions

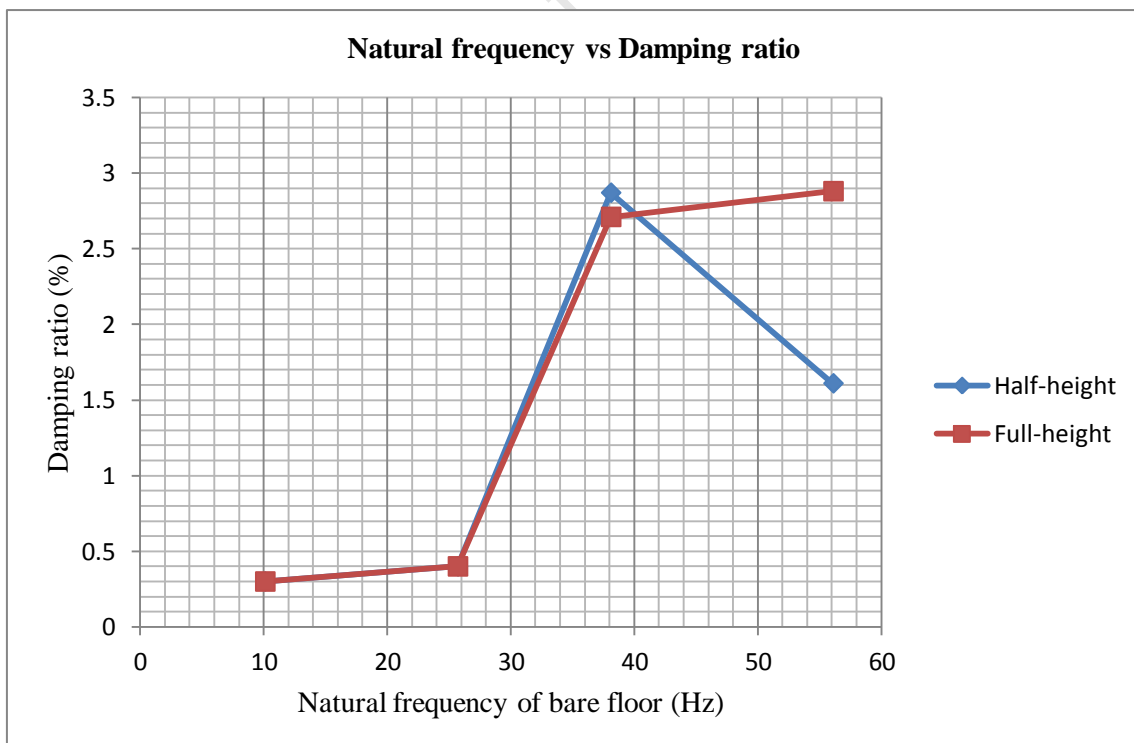


Figure 6.27: Natural frequency and damping ratio relationships for floors with brick partitions

6.10 Proposed method for the account of partitions on the vibration serviceability of concrete floors

The results obtained in this research project are similar to those obtained by Fatali (1999) where full-height partitions were found to increase the stiffness of the floor supporting them leading to an increase in natural frequencies of the floor. And half-height partitions were found to increase the damping of the floor supporting them. From the results obtained by Fatali (1999) and those obtained in this research project, it can be concluded that the modal parameter of interest when dealing with full-height partitions is the natural frequency since full-height partitions were found to increase the stiffness of the floor supporting them. The modal parameter of interest when dealing with half-height partitions is the damping ratio since half-height partitions were found to increase the damping of the floor supporting them. Table 6.13 shows the damping ratios recommended by different design guidelines as well as those proposed as a result of this research project.

Table 6.13: Damping guidelines from different codes of practice including the proposed guideline as a result of the research project

	Bare floors (%)	Floors with half-height partitions (%)	Floors with full-height partitions (%)
SCI P076	1.5	3	4.5
SCI P331	1.1	3	4.5
AISC	2	3	5
CSA	3	6	12
Proposed	1.5	3	3

Some damping ratios obtained in this research project are similar to those recommended by SCI P076 (1989), SCI P331 (2004) and AISC (1997). The damping ratios recommended by CSA (1989) are double those recommended by the other codes of practice as well as those obtained from this research project. Therefore the damping ratios recommended by the SCI P076 (1989), SCI P331 (2004) and AISC (1997) can be considered reasonable and used in design of floors for vibration serviceability to account for the presence of half-height partitions. The damping ratios recommended by CSA (1989) are an overestimation. These values are double those recommended by the

other codes of practice as well as those obtained in this research project. Therefore the damping ratios recommended by CSA (1989) are overestimated and should not be used as a guideline to estimate damping ratios for concrete floors.

The proposed model by Fatali (1999) to account for the effects of full-height partitions on the vibration serviceability of simply supported beams can be used to quantify the effects of full-height partitions on the vibration serviceability of simply supported concrete floors since the latter usually behave as simply supported beams. Therefore the effects of full-height partitions on the vibration serviceability of simply supported concrete floors can be modelled using:

$$f_{oc}^2 = f_o^2 + \frac{K_p}{2\pi^2 \rho b h L} \sin^2\left(\frac{\pi a}{L}\right) \quad (6.1)$$

where f_{oc} is the frequency of the floor after the full-height partition has been installed, f_o is the floor's frequency before installation of the full-height partition, K_p is the stiffness of the partition material, a is the distance of the full-height partition from the nearest support, L is the span length, ρ is the density of the floor material (i.e. concrete), b is the width of the floor slab and h is the thickness of the floor slab.

Proposed design guideline:

Given a simply supported concrete floor supporting partitions, the effects of the latter on the vibration serviceability of the simply supported concrete floor can be quantified using the following suggested steps:

Step 1: Calculate the fundamental frequency for the bare floor using the methods described in Section 2.2.

Step 2: If the floor supports half-height partitions, use Table 6.13 to estimate the appropriate damping ratio.

Step 3: If the floor supports full-height partitions, its fundamental frequency can be estimated using Equation 6.1.

Step 4: After estimating the fundamental frequency of the floor supporting the full-height partitions, its response factor can then be estimated using the methods described in Section 3.5.

6.11 Conclusion

The half-height brick and timber partitions were found to decrease the natural frequencies of the floor supporting them. They were also found to increase the damping of the floor supporting them. It was further found that half-height brick and timber partitions do not change the mode shapes of the floor supporting them. The full-height brick and timber partitions were found to increase the natural frequencies and damping of the floor supporting them. It was further found that full-height brick and timber partitions do not change the mode shapes of the floor supporting them.

The results obtained from this research project are similar to those obtained by Fatali (1999). It can be concluded from these results that the modal parameter of interest when dealing with full-height partitions is the natural frequency since full-height partitions were found to increase the stiffness of the floor supporting them. It can also be concluded that the modal parameter of interest when dealing with half-height partitions is the damping ratio since half-height partitions were found to increase the damping of the floor supporting them.

Some damping ratios obtained in this research project are similar to those recommended by SCI P076 (1989), SCI P331 (2004) and AISC (1997). The damping ratios recommended by CSA (1989) are double those recommended by the other codes of practice as well as those obtained in this research project. Therefore the damping ratios recommended by SCI P076 (1989), SCI P331 (2004) and AISC (1997) can be considered reasonable and used in design of concrete floors for vibration serviceability to account for the presence of half-height partitions.

The proposed model by Fatali (1999) to account for the effects of full-height partitions on the vibration serviceability of simply supported concrete beams can be used to quantify the effects of full-height partitions on the vibration serviceability of simply

supported concrete floors. This is because the latter usually behave as simply supported concrete beams and the results obtained in this research project are similar to those obtained by Fatali (1999).

The next chapter will present the results of the modal tests carried in the field on a full-scale conventionally reinforced concrete floor in order to confirm the laboratory results.

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7 FIELD WORK

7.1 Introduction

The results of the modal tests carried in the field are presented in order to confirm the laboratory results. The results of the modal test before and after the installation of full-height brick partitions are presented in Table 7.1 and Table 7.2 respectively. These results include the first five mode shapes with their associated natural frequencies and damping ratios.

7.2 Results

The first five mode shapes of the bare floor with their associated natural frequencies and damping ratios are given in Table 7.1. Those of the test floor with the full-height brick partitions with their associated natural frequencies and damping ratios are given in Table 7.2. The signal processing option in ME'Scope was used to analyse the measured responses of the test floor. After signal processing, the curve fitting method in ME'Scope was used to estimate the modal parameters i.e. natural frequencies, damping ratios and mode shapes.

Table 7.1: Measured modal parameters of field bare floor

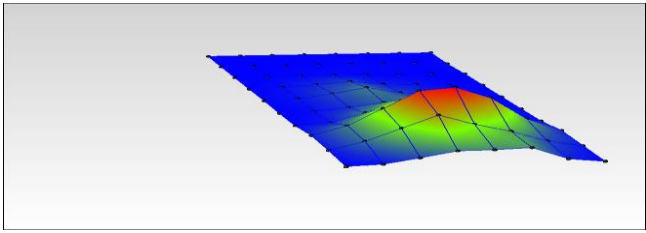
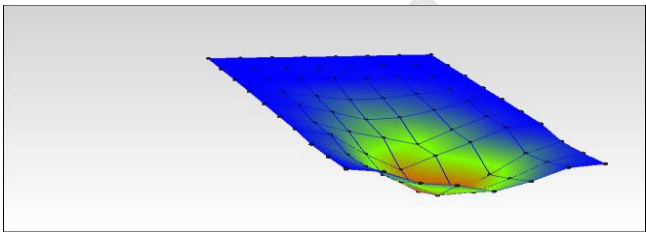
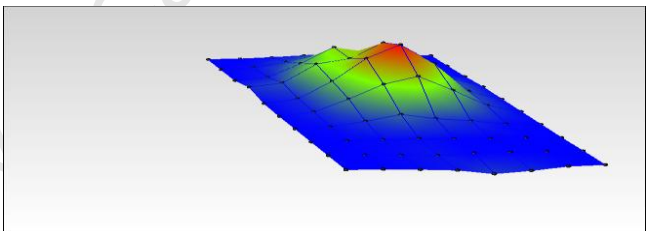
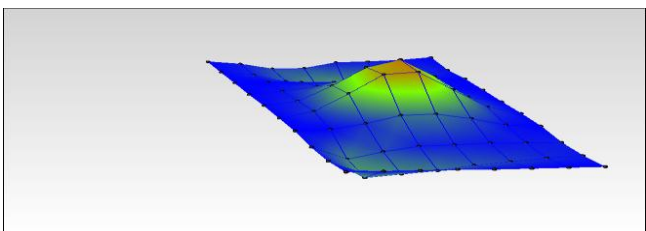
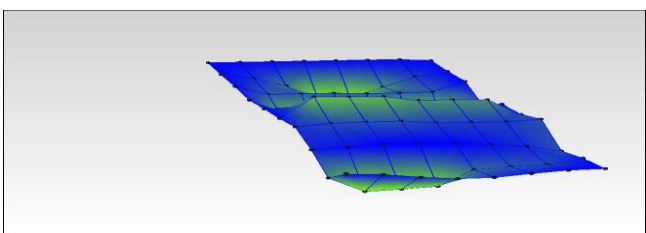
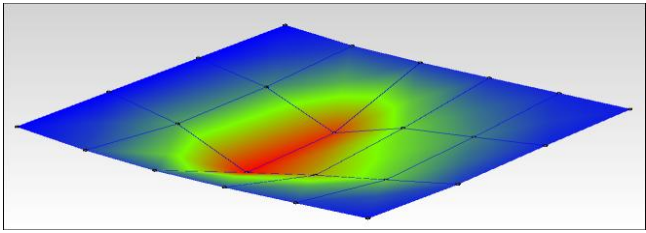
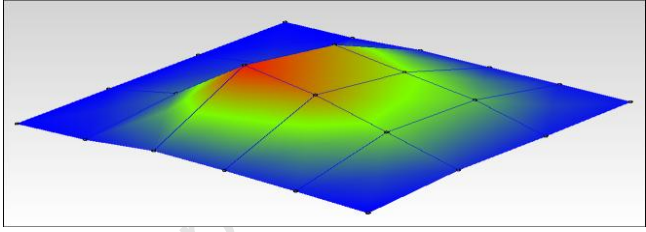
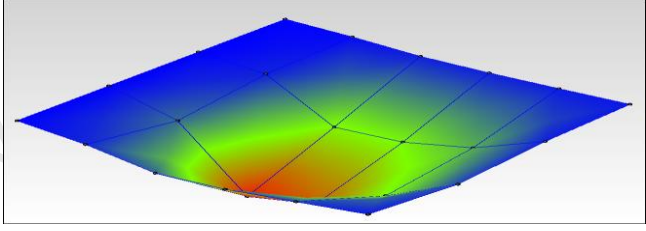
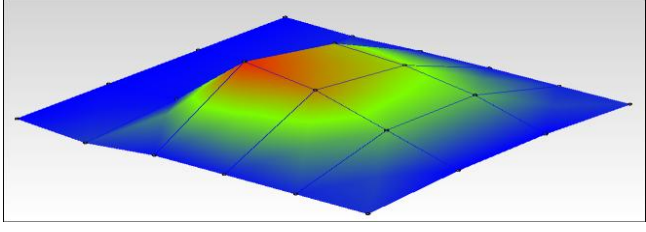
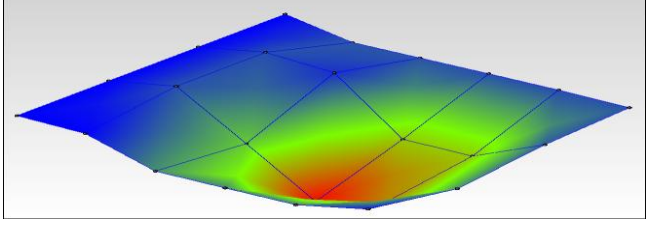
Mode description	Frequency (Hz)	Damping ratio (%)	Mode shape
1 st Bending	12.5	0.12	
1 st Bending	13.3	0.26	
1 st Bending	15.5	2.38	
1 st Bending	18.6	1.27	
1 st Bending	22.2	0.6	

Table 7.2: Measured modal parameters of field floor post partitioning

Mode description	Frequency (Hz)	Damping ratio (%)	Mode shape
1 st Bending	16.1	0.4	
1 st Bending	32.3	2.51	
1 st Bending	34.9	1.23	
1 st Bending	41.6	2.79	
1 st Bending	49.8	0.2	

7.3 Effects of full-height brick partitions

The natural frequencies and damping ratios of the test floor before and after the installation of the full-height brick partitions are presented in Table 7.3 and Table 7.4 respectively.

Table 7.3: Comparison of natural frequencies prior and post partitioning

Mode	Bare floor (Hz)	Post-partition (Hz)	Description
1	12.5	16.1	1 st Bending
2	13.3	32.3	1 st Bending
3	15.5	34.9	1 st Bending
4	18.6	41.6	1 st Bending
5	22.2	49.8	1 st Bending

The natural frequencies of the test floor for the first five modes increased following the installation of the full-height brick partitions. This implies that the increase in mass was offset by the large increase in stiffness following the installation of the full-height brick partitions. Therefore the increase in stiffness was more significant than any increase in mass following the installation of the partitions. The natural frequency of the test floor for the first five modes increased by 29 %, 143 %, 125 %, 124 % and 124 % respectively following the installation of the full-height brick partitions. These results confirm the laboratory results where full-height partitions increase the stiffness of the floor supporting them and thereby increasing its natural frequencies.

The mode shapes did not change following the installation of the full-height brick partitions. The 1st bending mode remains the most dominant mode of vibration for the first five modes before and after the installation of the full-height brick partitions.

Table 7.4: Comparison of damping ratios prior and post partitioning

Mode	Bare floor (%)	Post-partition (%)	Description
1	0.12	0.4	1 st Bending
2	0.26	2.51	1 st Bending
3	2.38	1.23	1 st Bending
4	1.27	2.79	1 st Bending
5	0.6	0.2	1 st Bending

The damping ratio increased for some modes following the installation of full-height brick partitions. But it decreased for the third and fifth mode. The results show a significant increase in damping for the first two modes. These results confirm the laboratory results where full-height partitions increase the damping of the floor supporting them. The reductions recorded for the third and fifth mode were unpredictable and do not conform with literature.

The relationship between the natural frequencies of the bare floor and the natural frequencies of the floor with the full-height brick partitions is displayed in Figure 7.1. The relationship between the natural frequencies of the bare floor and the damping ratios of the floor with the full-height brick partitions is displayed in Figure 7.2.

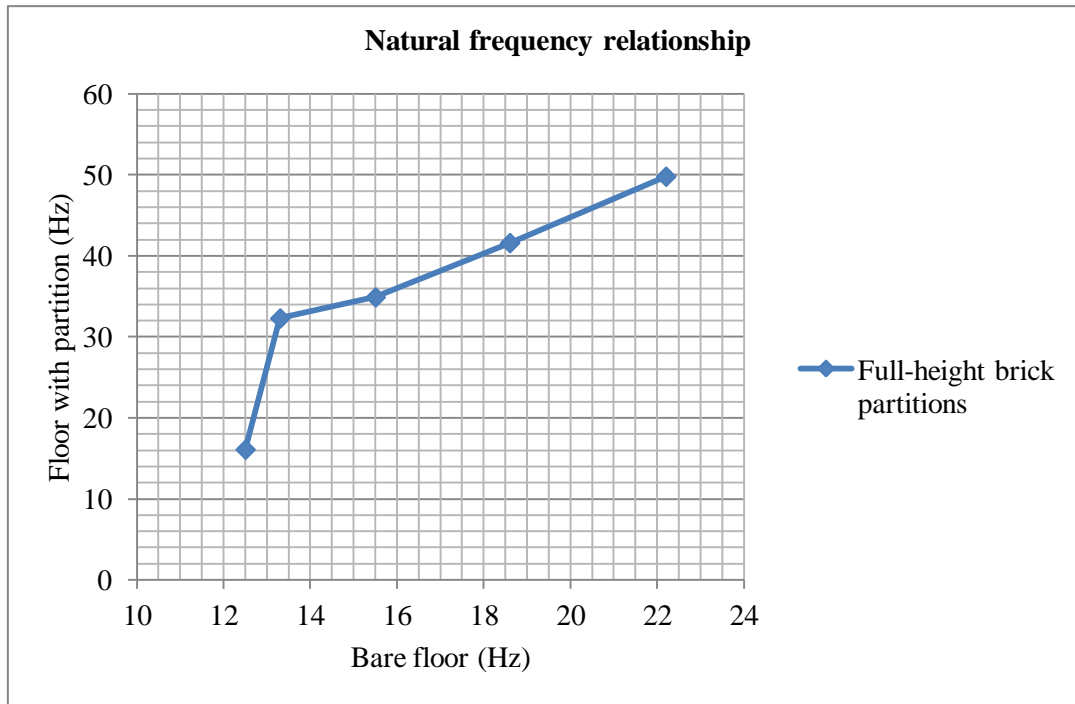


Figure 7.1: Natural frequency relationship between bare floor and floor with full-height brick partitions

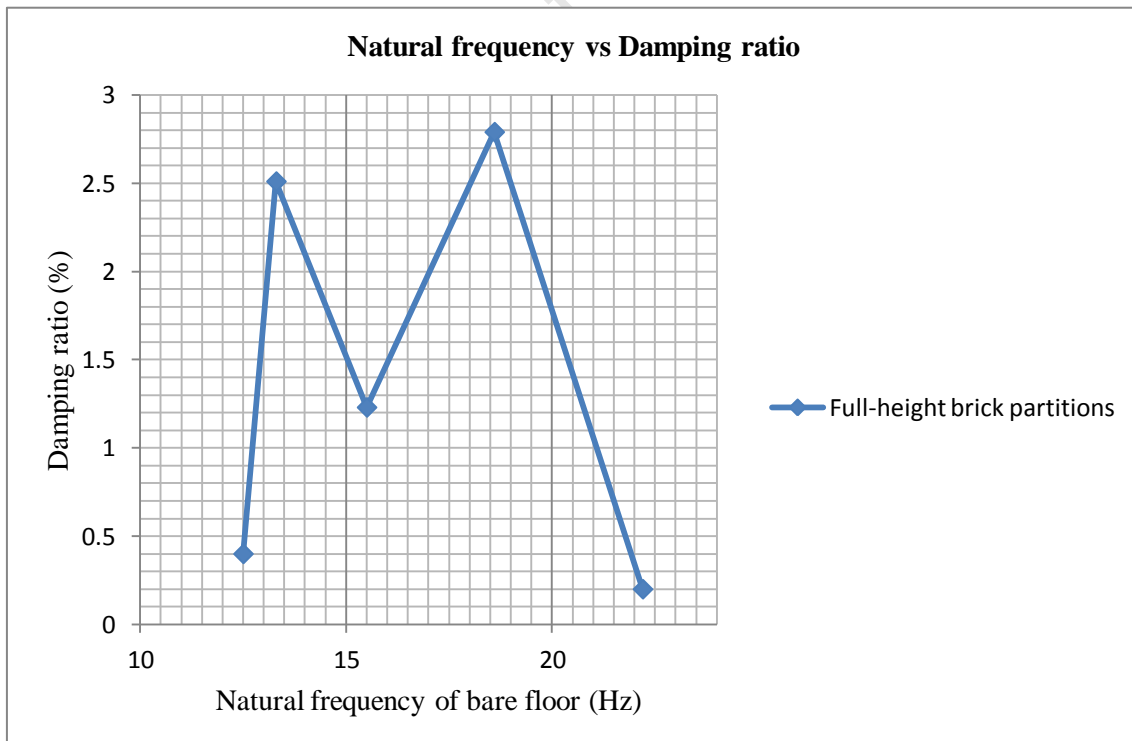


Figure 7.2: Natural frequency and damping ratio relationship for floor with full-height brick partitions

7.4 Conclusion

The results obtained from the modal tests carried in the field on a full-scale conventionally reinforced concrete floor supporting full-height brick partitions confirm the experimental results obtained in the laboratory where full-height brick partitions were found to increase the natural frequencies and damping of the floor supporting them. These results also confirm the experimental results obtained in the laboratory where full-height brick partitions were found not to change the mode shapes of the floor supporting them.

The results obtained in the field on a full-scale conventionally reinforced concrete floor confirm the laboratory results on the effects of full-height partitions on the vibration serviceability of concrete floors. Therefore it can be concluded that the modal parameter of interest when dealing with full-height partitions is the natural frequency since full-height partitions were found to increase the stiffness of the floor supporting them.

The next chapter will conclude the research project, highlight the main findings and give recommendations for future work.

8 SUMMARY AND CONCLUSIONS

8.1 Introduction

This research project has investigated the effects of partitions on the vibration serviceability of concrete floors. The focus of this research project was on prestressed concrete floors because of their long spans and slenderness. The growing demand to construct long, slender floors with minimum supports for aesthetic and economic reasons especially in modern building developments has resulted in increased floor slenderness leading to vibration problems. As a result, vibration serviceability has become the governing design criterion for many of these new civil engineering structures. It is known that long span, slender floors possess lower natural frequencies and reduced damping leading to vibration serviceability problems. It is also known that the vibration serviceability of long span, slender concrete floors may be improved through the installation of non-structural elements such as partition walls. Since it is known that partitions can improve the vibration serviceability of concrete floors, research into the effects of partitions on the vibration serviceability of concrete floors is merited.

This dissertation has described tests done on a prestressed pre-tensioned concrete floor slab subjected to continuous and impulse vibrations. The continuous vibrations were generated by an electrodynamic shaker and the impulse vibrations were generated by an instrumented impulse hammer. The responses of the test floor before and after the installation of various configurations of partitions were measured. The test procedures used in the University laboratory were also used on a full-scale conventionally reinforced concrete floor slab in order to confirm the laboratory results. In this chapter, the findings on the effects of partitions on the vibration serviceability of concrete floors are presented and recommendations are given as to their use in design. Suggestions for future research on the effects of partitions on the vibration serviceability of concrete floors are given in Section 8.6.

8.2 Experimental procedures

8.2.1 Loading apparatus

The excitation was generated by a APS Dynamics Modal 400 Electro-Seis electrodynamic shaker and a Dytran Model 5803A 5.4 Kg instrumented impulse hammer. The electrodynamic shaker gives more satisfactory results than the instrumented impulse hammer. Besides giving more satisfactory results, the electrodynamic shaker also produces FRFs of better quality with fewer frequency domain averages resulting in a shorter test time. In this research project, the electrodynamic shaker excitation was used mainly to extract the natural frequencies and mode shapes of the test floor. The instrumented impulse hammer excitation was used mainly for damping studies.

8.2.2 Measurement apparatus

Force-balanced QA 700 accelerometers with a sensitivity of 8 V/g mounted to base plates were used to measure the responses of the test floor. The Data Physics Signal Calc Mobilyser was used to acquire the data from the accelerometers. The drive power for the electrodynamic shaker was obtained from the power amplifier APS 145. A chirp excitation running from 5 Hz to 180 Hz was used to excite the floor with the electrodynamic shaker. The electrodynamic shaker was set to operate in the free armature mode. A personal computer was used to store, analyse and present the data. The curve fitting method in Vibrant Technologies ME'Scope was used to estimate the natural frequencies and mode shapes of the test floor. Modal 1.20 by Brownjohn (2009) was used to estimate the damping ratios of the test floor. Modal 1.20 uses the logarithmic decrement method to estimate damping.

8.2.3 Partitions

Plywood was used for half-height as well as full-height timber partitions. The plywood had a thickness of 21 mm. A brick wall was constructed to simulate half-height as well as full-height brick partitioning. The difference between half-height and full-height was based on the fixity at the top of the partitions. The half-height partitions were not fixed horizontally at the top, therefore they were free to rotate. The half-height timber

partitions were fixed to the concrete floor by four steel brackets spaced at 600 mm centres. Full-height brick and timber partitions were fixed horizontally at the top. A steel frame was built to provide restriction at the top of the plywood and brick wall in order to simulate full-height partitioning. Four layouts were used to simulate half-height timber partitioning. One layout was used to simulate full-height timber, half-height brick and full-height brick partitioning. The brick and timber partitions had a height of 1.20 m.

8.3 Findings

8.3.1 Effects of half-height partitions

Half-height partitions were found to decrease the natural frequencies of the floor supporting them. This is caused by the increase in mass being more significant than any increase in stiffness. Half-height partitions were also found to increase the damping of the floor supporting them. It was found that half-height partitions do not change the mode shapes of the floor supporting them. These findings were consistent and independent of the type of partition (i.e. brick or timber).

8.3.2 Effects of full-height partitions

Full-height partitions were found to increase the natural frequencies of the floor supporting them. This is caused by the increase in stiffness following the installation of the full-height partitions being more significant than any increase in mass. Full-height partitions were also found to increase the damping of the floor supporting them. It was found that full-height partitions do not change the mode shapes of the floor supporting them. These findings were consistent and independent of the type of partition (i.e. brick or timber).

8.3.3 Response factor

The simplified calculation of impulsive response presented in Section 3.5 was used to calculate the response factor as well as the total impulsive peak velocity response of the test floor before and after the installation of partitions.

The response factor of the bare floor was found to be 4.2. This response factor did not change following the installation of various configurations of partitions. The response factor was dependent on the geometry and material properties of the test floor. It did not depend on the modal parameters, therefore it was not influenced by the installation of partitions. The total impulsive peak velocity responses calculated for different test set-ups are shown in Table 8.1.

Table 8.1: Total impulsive peak velocity response for different test set-ups

Layout	Total impulsive peak velocity response (mm/s)
bare floor	10
Half-height timber partition: Layout 1	10
Half-height timber partition: Layout 2	10
Half-height timber partition: Layout 3	10
Half-height timber partition: Layout 4	10
Full-height timber partition	7.5
Half-height brick partition	10
Full-height brick partition	8.75

The total impulsive peak velocity response of the test floor did not change following the installation of the half-height partitions. But it decreased following the installation of the full-height timber and full-height brick partition by 25 % and 12.5 % respectively. This decrease in total impulsive peak velocity response following the installation of full-height partitions can be mainly attributed to the increase in floor's stiffness.

8.3.4 Field testing

Modal testing on a full-scale conventionally reinforced concrete floor is reported in Chapter 7. The methodology presented in Chapter 5 was used to estimate the modal parameters of the floor before and after the installation of full-height brick partitions. The instrumented impulse hammer and electrodynamic shaker were used to excite the test floor. The instrumented impulse hammer was used before the installation of partitions. The electrodynamic shaker was used after the installation of partitions. It was found that the fundamental frequency of the test floor increased by 29 % following the

installation of full-height brick partitions. It was also found that the damping ratio of the fundamental mode of the test floor tripled following the installation of full-height brick partitions. The mode shapes did not change following the installation of full-height brick partitions.

8.3.5 Conclusions

The results obtained from this research project are similar to those obtained by Fatali (1999). It can be concluded from these results that the modal parameter of interest when dealing with full-height partitions is the natural frequency since full-height partitions were found to increase the stiffness of the floor supporting them. It can also be concluded that the modal parameter of interest when dealing with half-height partitions is the damping ratio since half-height partitions were found to increase the damping of the floor supporting them.

Some damping ratios obtained in this research project are similar to those recommended by SCI P076 (1989), SCI P331 (2004) and AISC (1997). The damping ratios recommended by CSA (1989) are double those recommended by the other codes of practice as well as those obtained in this research project. Therefore the damping ratios recommended by SCI P076 (1989), SCI P331 (2004) and AISC (1997) can be considered reasonable and used in design of concrete floors for vibration serviceability to account for the presence of half-height partitions. The damping ratios recommended by CSA (1989) are an overestimation. These values are double those recommended by the other codes of practice as well as those obtained in this research project. Therefore the damping ratios recommended by CSA (1989) should not be used as a guideline for concrete floors.

The proposed model by Fatali (1999) to account for the effects of full-height partitions on the vibration serviceability of simply supported concrete beams can be used to quantify the effects of full-height partitions on the vibration serviceability of simply supported concrete floors. This is because the latter usually behave as simply supported concrete beams and the results obtained in this research project are similar to those obtained by Fatali (1999).

The results obtained in the field on a full-scale conventionally reinforced concrete floor confirm the laboratory results on the effects of full-height partitions on the vibration serviceability of concrete floors.

The half-height brick and timber partitions improve the vibration serviceability of the concrete floors supporting them by increasing their damping. The full-height brick and timber partitions improve the vibration serviceability of the concrete floors supporting them by increasing both their damping and stiffness. This increase in stiffness leads to an increase in natural frequencies.

8.4 Research limitations

The choice of dimensions for the laboratory tested slab was mainly influenced by the available space in the laboratory without taking into account conventional practices. The choice of dimensions for partitions was mainly influenced by the size of the test floor as well as available space in the laboratory without taking into account conventional practices. The arrangement of partitions was mainly influenced by previous similar researches in order to have a basis of comparison.

The steel frame used to simulate full-height partitioning was not tested independently in order to determine its stiffness. The latter would have provided a check and an independent insight into its stiffness contribution to the overall floor slab.

The lateral movement at the top of each wall was not monitored in order to quantify and verify the extent of rotation at the top of both full and half-height partitions.

8.5 Proposed guidelines

The lack of damping is the main cause of the resonant vibration of floors (Ljunggren, 2006). Therefore by increasing damping, the vibration serviceability of floors will improve significantly since it was found by Lenzen (1966) that occupants of a building using a given floor could tolerate higher initial response if the damping was increased.

The results from this research project show that partitions increase damping. But this increase depends on the layout of the partitions with respect to the mode shapes. Therefore in order to achieve maximum increase in damping from the installation of partitions on a given floor, the partitions should be installed perpendicular as well as parallel to the mode shape of interest.

The results obtained in this research project and those obtained by Fatali (1999) show that the modal parameter of interest when quantifying the effects of full-height partitions on the vibration serviceability of concrete floors is the natural frequency since full-height partitions were found to increase the stiffness of the floor supporting them. The modal parameter of interest when quantifying the effects of half-height partitions on the vibration serviceability of concrete floors is the damping ratio since half-height partitions were found to increase the damping of the floor supporting them. Therefore the effects of partitions on the vibration serviceability of concrete floors can be quantified at design stage by following the proposed method in Section 6.10.

8.6 Future work

The results obtained in this research project have given scope for further research into the effects of partitions on the vibration serviceability of concrete floors. The possibilities for future investigations and researches are discussed below.

Parametric studies: The effects of partitions on the vibration serviceability of concrete floors were investigated mainly through modal testing in this research project. These effects can be investigated further through parametric studies in order to develop proper design guidelines.

Analytical models: Following the parametric studies on the effects of partitions on the vibration serviceability of concrete floors, numerical models can be developed that will enable engineers to account for these effects at design stage.

Damping: The effects of partitions on the vibration serviceability of concrete floors can be investigated further with an emphasis on damping since the latter is the major cause of the resonant vibration of floors.

Other partition types: The effects of partitions such as steel, aluminium and glass on the vibration serviceability of concrete floors are yet to be investigated.

Walking tests: Walking tests at different walking frequencies can be carried in order to investigate the effects of partitions on the floor vibration responses (RMS acceleration, RMS velocity, VDV and peak acceleration response).

Steel brackets: The influence of the steel brackets used as connections for the timber partitions in this research project can be investigated in order to understand their contribution to the floor's overall stiffness.

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