The Concrete Centre

Hospital Floor Vibration Study

Comparison of Possible Hospital Floor Structures With Respect To NHS Vibration Criteria

The Concrete Centre

Hospital Floor Vibration Study

Comparison of Possible Hospital Floor Structures With Respect To NHS Vibration Criteria

November 2004

Ove Arup & Partners Ltd
13 Fitzroy Street, London W1T 4BQ
Tel +44 (0)20 7636 1531 Fax +44 (0)20 7755 2150
www.arup.com

Job number 116142-00

CONTENTS

EXECUTIVE SUMMARY

Typical floor designs have been produced to meet NHS floor vibration criteria, using concrete only and steel / concrete composite solutions.

When compared with typical office floors, where floor vibration criteria are less onerous, it is found that material quantities for composite floors must be increased significantly to meet the requirements specified by the NHS. (Up to 180% increase in total mass.). For concrete floors this relative increase is much smaller (as little as 15% increase in total mass).

This report was prepared by Arup on behalf of The Concrete Centre in connection with Arup project number 116142 (Concrete Centre Project FB 435). It takes into account our client's particular instructions and requirements and addresses their priorities at the time. This report was not intended for, and should not be relied on by, any third party and no responsibility is undertaken to any third party in relation to it.

1. INTRODUCTION

All buildings experience structural vibration, which can arise from a variety of different sources inside and outside the building. At the design stage of a vibration-sensitive building it is necessary to assess the expected levels of vibration in relation to the intended use of the building, and design the structure accordingly. For hospitals, guidance on acceptance criteria for vibration is given in NHS Estates guidance 2045 pt 2 (HTM) [1]. The most onerous performance criteria apply to night wards and operating theatres, and in these locations vibration issues often govern floor design.

Various types of floor structure are feasible for use in hospital buildings including steel/composite, pre-stressed concrete and reinforced concrete forms of construction. Due to the higher mass inherent in concrete floors it is believed that some concrete forms of construction may be more economical than steel/composite in meeting onerous vibration criteria

The objective of this study is to investigate the relative performance of these different forms of construction for hospital use. The vibration performance is assessed against the acceptance criteria given in [1] for operating theatres, night wards and offices.

No attempt has been made to cost to any solution, but material quantities are given for each design.

The vibration performance of the floors in this study has been assessed using techniques developed over 15 years by Arup, and which are currently used extensively by Arup and others. We believe that this is the only method currently available that is able to make a fair comparison between floors of widely differing construction. Whilst the Arup method has been extensively validated and peer reviewed there is as yet no recognised “standard” method of performing such calculations. Consequently the designs here may differ from those produced by others using different calculation techniques.

2. DESIGN REQUIREMENTS

To facilitate comparison between structural forms all floors have been designed using a consistent set of design requirements such as layout, loading and vibration performance criteria. These requirements are detailed in this section.

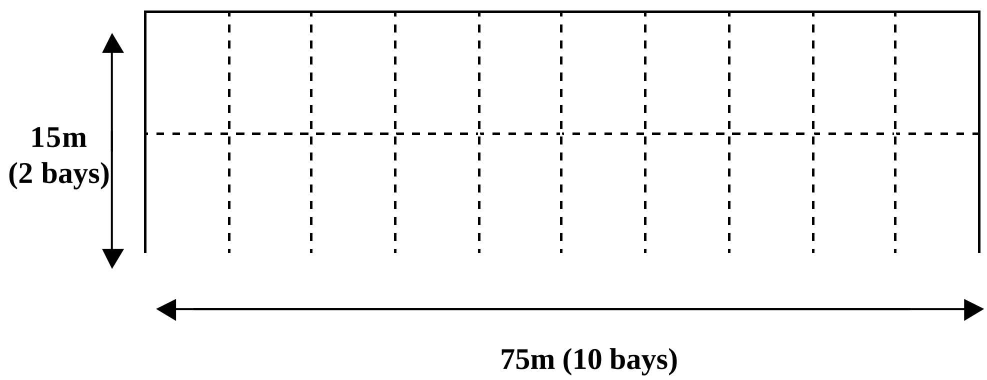
2.1 Floor Layout

A fixed floor layout of a 75x15m floor plate made up of 7.5x7.5m bays has been considered for each floor structure.

The layout selected reflects the typical overall size and spans found in hospital construction and the desire for floors only 2 or 3 bays wide to maximise the amount of space lit by natural light.

An investigation into the effect of varying the span was not undertaken as a survey of recent projects found that the bay size for a hospital is generally governed by architectural issues and is in the region of 6.5 – 8.5m; a span of 7.5m was therefore considered to be representative.

Figure 2.1: Assumed Floor Layout



2.2 Design Loads

In detailed design different design loads may be considered for floors of differing uses. In this study floors for use as offices, wards and operating theatres have been examined. However to allow the floors to be easily compared the same design loads have been considered for all cases.

The following design loads have been considered:

Self weight	As calculated for each structure considered
Services and Finishes	1.0 kN/m^2
Partitions	1.0 kN/m^2
Live Load	4.0 kN/m^2

2.3 Structural Performance

Sufficient structural checks have been performed for each floor design using the relevant codes and standards to demonstrate the floor is a feasible structural solution. These checks are summarised below.

2.3.1 Durability and Fire Resistance

The floor designs have been checked for durability under mild exposure conditions and for 1hr fire resistance.

2.3.2 Strength

The floor designs have been checked to ensure they meet the Ultimate Limit State strength requirements in bending and shear.

For the concrete designs punching shear has been checked assuming a realistic minimum sized column. The punching shear checks have been limited to checking that sufficient shear reinforcement could be provided to prevent punching shear failure, but shear reinforcement has not been designed.

Steel decking has been checked for construction loads using propped or unpropped construction as appropriate.

2.3.3 Deflections

The floor designs have been checked to ensure they meet the serviceability limit state criteria given below.

<u>Concrete Slabs: As given in BS8110</u>

span/250 (total load)

<u>Composite Slabs: As described in BS5950 Part 4</u>

Construction Stage	span/130 (slab self weight including ponding)
Composite Stage	span/350 (Imposed Load)
	span/250 (Total Applied Load)

2.4 Vibration Performance

This study has examined the dynamic response of various floor designs to the normal activities of the building occupants (i.e. walking) and compared these to the NHS requirements for vibration. Other sources of vibration were not considered.

It is important to understand that human tolerance of vibration is variable and subjective. The governing British Standard is BS6472:1992 which defines the typical threshold of human perception of vibration and recommendations on vibration levels that will lead to a low probability of adverse comment. The level of continuous vibration that can be accepted in different situations is expressed as a multiple of the vibration level at the threshold of human perception. This multiple is denoted as ‘response factor’ or ‘R’ factor. The response factor can be thought of as a measure of human perception or annoyance. Vibration corresponding to a response factor of 1 is at the limit of human perception. Continuous vibration is considered to be for 16 hours during the day, and 8 hours at night time.

In general footfall induced vibration is not continuous but intermittent. Human acceptance of intermittent vibration can be assessed by combining vibration levels with the periods of time for which they are expected to occur to calculate a vibration ‘dose’ values (VDV). The method of calculation is described in an Appendix to BS6472 and this method is referred to in Section 3 of Health Technical Memorandum 2045 [1]. A VDV based approach to vibration acceptability essentially allows the target response factor to be adjusted depending on the duration of exposure. This is discussed in more detail in Appendix E.

For the purpose of this study all vibration has been considered continuous and the target response factors are those shown in the table below. The office floors presented here have been designed to meet strength and deflection criteria with no account taken of their dynamic performance. Their acceptability as office floors though can be judged with reference to the target below.

Use	Target Response Factor For Continuous Vibration
Office	Normally either 4.0 or 8.0.
Night Ward	1.4
Operating Theatre	1.0

2.5 Other

On all real projects there will be further design requirements to be met such as acoustic, services or future flexibility requirements. These have not been considered in this study.

3. VIBRATION PERFORMANCE ANALYSIS METHOD

3.1 Analysis Method

The vibration of each floor due to footfalls has been predicted by dynamic analysis. A computer finite element model is assembled for each floor, and its modal properties (natural frequencies, modeshapes, modal masses) determined. The vibration response under the action of a person walking has then been calculated using the Arup method [3] and summarised in the paper in Appendix F.

This method applies the same first principles approach to any form of floor construction, and has been calibrated against measurements on many real floors. It is to be published in a revision to TR43 Appendix G and is the only prediction method available that we consider gives a fair comparison between widely different forms of floor design. Further details can be found in Appendices E and F.

3.2 Assumptions

3.2.1 Damping

Most design guidance and published literature suggests that damping for various types of floor construction varies from 1.5% to 4.5% of critical. It is clear from the available data that concrete structures have somewhat higher intrinsic damping than composite floors, however the results are very variable.

In this study all floors are assumed to have 3.0% of critical damping. This is considered a reasonable and perhaps slightly conservative estimate given the extent of full height partitioning normally found in hospitals.

3.2.2 Mass

Vibration calculations are sensitive to the mass of the structure being analysed and the best estimate of in-service mass should be used. Over estimating the mass can often result in unconservative predictions of dynamic response.

100 kg/m^2 additional mass representing the likely imposed dead and live loads has been included on all the floors considered.

3.2.3 Footfall rates

The following ranges of footfall rates (steps per second) are typical:

1.5-1.8Hz “Normal walking ” for cellular areas

1.8-2.0Hz “Someone who is in a hurry”

2.0-2.4Hz “A very brisk pace” considered likely only in corridors

It is proposed to consider walking frequencies in the range of up to 2.0 Hz. These walking frequencies are the highest expected for people using cellular areas such as operating theatres or walking around at night.

Higher responses than those predicted here may be possible if, for instance, in a corridor located so that it runs across the centre of the bays in the floor plate.

3.2.4 Partitions

It has been assumed that the partitions used will not significantly affect the dynamic properties of the floor i.e. relatively lightweight partitions are used instead of stiff blockwork walls.

3.2.5 Columns

Columns can stiffen a floor structure by providing some rotational restraint to the beams or slab. This action is considered in this study since it is a realistic effect. 300x300 rectangular concrete columns and 254x254x107UC steel columns are assumed for concrete and composite construction respectively.

3.2.6 Façade Restraint

For the very small strains associated with pedestrian induced vibration of floor structures, façades generally provide sufficient restraint to the edges of a floor so that the floors can be considered to be vertically restrained. This has been assumed in this study.

4. CURRENT PRACTICE

4.1 Feasible Floor Structures

Various types of floor structure are feasible for use in hospital buildings including both steel and reinforced concrete forms of construction.

Many factors in addition to vibration performance affect the choice of floor structure for a particular design – cost, speed of construction, structural depth, ease of forming penetrations, future flexibility etc. It is therefore difficult to identify an "optimum design" without knowledge of the priorities for a particular project. This study does not seek an optimum 'total design' but determines the minimum-sized floor structures of each type to meet the required vibration criteria in addition to strength and deflection requirements.

From the wide range of feasible floor structure types those currently most commonly considered for healthcare projects were selected. This study investigates the vibration performance of the following floor types:

1. Reinforced concrete flat slab
2. Reinforced concrete post tensioned slab
3. Conventional steel and concrete composite floor
4. Slimdek construction.

4.2 Survey Of Typical Hospital Floor Designs

It must be demonstrable that the floor designs selected for the comparison are designs that are being used by engineers working in the healthcare sector. The designs examined have therefore been based upon designs from one of the following sources:

1) Existing or proposed designs for recent hospital developments.
2) Exemplar designs recommended by healthcare clients.
3) Published literature by industry bodies.

A survey of published literature and proposed floor structures for healthcare projects was undertaken to identify typical types of floor structure used. The results are summarised in the tables below. Although the general use of the floors are specified in these tables the actual vibration performance of the designs is unknown.

4.2.1 Reinforced Concrete Slabs

Example	Use	Bay Size /m	Type	Thickness /mm
1	Office	7.5 x 7.5	Flat	280
2	Operating theatres/night wards	8.1 x 8.1	On beams	450
3	Operating theatres/night wards	7.2 x 9.6	Ribs 1.2mc/c	450
4	Operating theatres/night wards	6.6 x 7.6	-	400
5	Operating theatres/night wards	7.2 x 7.2	Flat – some beams in theatres	300
6	Operating theatres/night wards	7.2 x 6.0	Flat	300

4.2.2 Post-Tensioned Reinforced Concrete Flat Slab

Example	Use	Bay Size /m	Thickness /mm
7	Office	8.0 x 8.0	225
8	Night Wards	8.0 x 8.0	265
9	Operating Theatres	8.1 x 8.1	250
10	Operating Theatres	8.0 x 8.0	290
11	Operating Theatres	7.6 x 8.1	315

4.2.3 Conventional Steel and Concrete Composite Floor

Example	Use	Bay Size	NWC / LWC	Overall slab depth (mm)	Decking	Beam Depth Prim / Sec (mm)
12	Office	7.5 x 7.5	LWC	130	Ribdeck Al	457UB/305UB
13	Night Wards	7.02 x 7.02	NWC	160	Ribdeck 80	533UB/406UB
14	Night Wards	8.1 x 8.1	NWC	140 + 40 screed	Holorib	533UB/406UB
15	Night Wards/ Operating Theatres	11.3 x 7.2	NWC	300	Multideck 60	625 / 574 CellBeam
16	Operating Theatres	7.2 x 7.2	NWC	175 + 40screed	Holorib	406UB
17	Operating Theatres	8.1 x 8.1	NWC	200 + 40screed	Holorib	533UB/406UB
18	Operating Theatres	6.4 x 9.2	LWC	200	-	678 / 603 deep (W sections)

4.2.4 Slimdek/Slimflor Type Construction

The examples below include the worked example given in the SCI hospital floor guide.

Example	**Use**	**Bay Size**	**Overall slab depth/ mm**	**Decking**	**Beam Depth \mm**
19	Office	7.5 x 7.5	200	N/a slimflor	305UC+ 510x15 flange plate
20	Operating Theatres	7.5 x 7.5	316	SD225 Comflor	300ASB(FE)153
21	Operating Theatres (Lab)	6.6 x 6.0	316	SD225 Comflor	300ASB(FE)153
22	Operating Theatres	Up to 8.0x8.0	320	SD225	Up to 300ASB196
23	Operating Theatres	7.2 x 7.2	290 + 80 topping	PMFComflor 210	UC Slimflor beams

5. SELECTED FLOOR DESIGNS

Three designs have been examined for each type of floor construction. In each case a floor has been designed to give the vibration performance suitable for use as an office, a night ward and an operating theatre.

The "office design" is intended as a benchmark, giving the structure required to satisfy only the structural performance criteria, without considering vibration performance.

5.1 Reinforced Concrete Flat Slab

The three reinforced concrete flat slab designs analysed are specified in detail in Appendix A.

The slab depths of the three designs are given in Table 5.1. Normal weight C32/C40 concrete has been assumed.

Table 5.1: Reinforced Concrete Flat Slab Designs

Use	**Depth /mm**
Office	300mm
Night Ward	330mm
Operating Theatres	350mm

5.1.1 Design Method

The RC flat slabs were designed using BS8110 to meet the requirements specified in Section 2. The slabs were reinforced to give the required ultimate capacity and to meet the detailing requirements given in BS8110.

5.1.2 Calculation of the Cracked Stiffness

The vibration performance of RC flat slabs is significantly affected by the extent of cracking. The reinforcement used therefore affects the stiffness of the slab and must be considered in the vibration calculation.

The construction load case is considered to govern the extent of in-service cracking of RC flat slabs. In this study, the construction load was taken to be 1.5 times the self-weight of the slab to allow for the propping loads from a slab being constructed above. In all cases this load was higher than the serviceability load case.

In order to calculate the overall reduction in stiffness due to cracking, the slab was divided into areas with similar reinforcement and moment demand. The secant stiffness of the cracked slab was calculated in each area using Oasys Adsec, assuming a linear compressive stress strain curve and considering tension stiffening as described in ICE Note 372. The self-weight was considered as a long-term load in the cracking analysis and additional loads considered as short term .

The stiffness of the slab in the vibration analysis model was modified to match the calculated cracked stiffnesses. The stiffnesses assumed are to be found in the relevant part of the appendices.

5.2 Post-Tensioned Reinforced Concrete Flat Slab

The three post-tensioned flat slab designs analysed are specified in detail in Appendix C.

The slab depths of the three designs are given in Table 5.1. Normal weight C32/C40 concrete has been assumed.

Table 5.2: Post-Tensioned Reinforced Concrete Flat Slab Designs

Use	**Depth /mm**
Office	220mm
Night Ward	250mm
Operating Theatres	290mm

5.2.1 Design Method

The post tensioned flat slabs were designed to BS8110 using Rapt software. The designs were limited to those classified as Class 1 or Class 2 as defined in BS8110-Part 4.

5.2.2 Calculation of the Cracked Stiffness

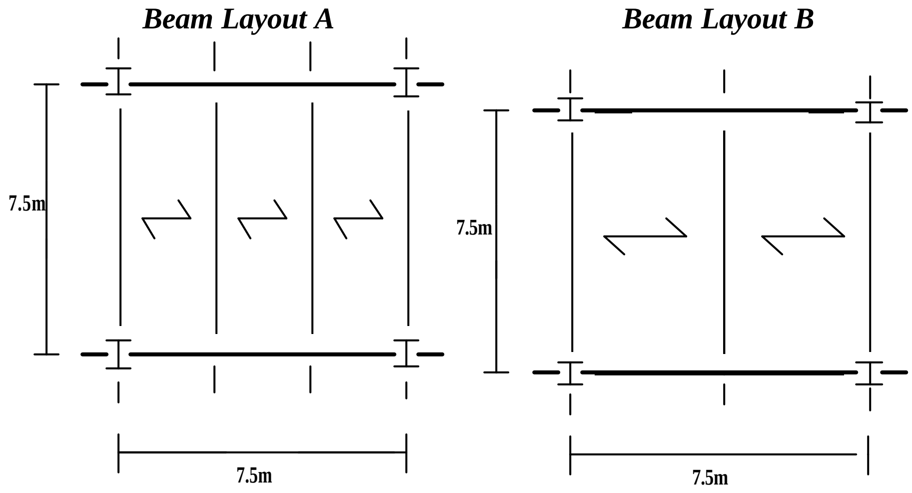
The post-tensioned slabs designed are all classified as Class 1 or Class 2. Therefore they are substantially un-cracked under serviceability loads. Post- tensioned slabs with areas classified as Class 3 are likely to have an inferior vibration performance due to a reduction in stiffness due to cracking.

5.3 Conventional Steel and Concrete Composite Floor

The imposition of onerous vibration requirements on a composite floor design has significant consequences in terms of beam layout.

Layout A below is commonly used for a normal office floor. For the increased beam size required to meet the vibration criterion for an operating theatre though, layout B may be a more efficient design. Therefore designs using both beam layout A and layout B were analysed for the floors governed by vibration requirements (i.e. night wards and operating theatres).

Figure 5.3: Typical Beam Layouts for Composite Floors



The five conventional steel and concrete composite floor designs analysed are specified in detail in Appendix B. An overview is given in Table 5.3. S355 steel has been assumed.

Table 5.3: Conventional Steel And Concrete Composite Floor Designs

Use	Beam Layout	Slab	Primary Beams	Secondary Beams	Concrete	Decking
Office	A	130mm	457UB	305UB	C32/C40 LWC	Ribdeck AL 0.9
Night Ward 1	A	200mm	533UB	406UB	C32/C40 NWC	Holorib 0.9
Night Ward 2	B	200mm	533UB	406UB	C32/C40 NWC	Holorib 0.9 (Propped)
Operating Theatre 1	A	250mm	533UB	406UB	C32/C40 NWC	Holorib 1.2
Operating Theatre 2	B	250mm	533UB	406UB	C32/C40 NWC	Holorib 0.9 (Propped)

5.3.1 Design Method

The composite floors have been designed to BS5400 using Oasys Compos and published load tables from various steel decking manufacturers. A design that allows unpropped construction has been used wherever possible. The only case where this was not possible was for beam layout B, where the required span of slab was not possible without using propping.

In addition to the loads quoted in section 2.2, the following load has also been considered:

- Construction live : 1.5 kN/m². (ref 5950-4 cl 2.3.2)

Oasys Compos is able perform all necessary checks to ensure compliance with the relevant codes (BS 5950-3 and –4). The overall strength utilisation is calculated based on the composite section and reported in appendix B. Note that to give a single figure for utilisation, a weighted average of the individual beams has been taken.

5.4 Slimdek Type Construction

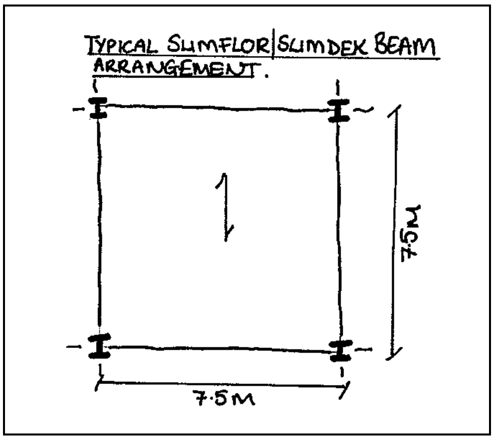
The three Slimdek designs analysed are specified in detail in Appendix D. An overview is given in Table 5.4. Normal weight C32/C40 concrete and S355 steel has been assumed.

Table 5.3: Slimdek Floor Designs

Use	Slab Depth /mm	Beam Size	Steel Decking
Office	316	300 ASB 153	SD225 1.25
Night Ward	420	300 ASB 155	SD225 1.25
Operating Theatres	420 +50mm screed	300 ASB 185	SD225 1.25

The beam layout considered is shown in Figure 5.4.

Figure 5.4: Typical Beam Layout for Slimflor/Slimdek Construction



5.4.1 Design Method

The slimdek designs have been designed to BS5400 using Corus Construction Centre ASB and Comdek design software and published load tables.

The designs assume unpropped beam construction and propped slab construction.

6. COMPARISON OF FLOOR DESIGNS AND CONCLUSIONS

This section compares the vibration performance and various other design parameters of the different floor designs. Table 6.1 is a breakdown of material quantities for each of the floors and figures 6.1 and 6.2 plot structural depth, self weight, natural frequency and response factor for each design.

The vibration performance results, including contour plots of response factor for each floor, are given in detail in Appendices A-D.

The benefits of reduced material quantities, mass, dynamic response or structural depth are clear but care should be taken when considering the natural frequency of floors. Although it is an important dynamic parameter, it does not necessarily follow that a floor with a higher frequency will have a lower response factor. In fact the reverse may be true if the frequency is increased by removing mass.

The response factors presented here are based on the highest 1-second rms during a pedestrian walk past or other source. To assess acceptability, these values may be compared directly to the base curves of BS6472 if the vibration is essentially continuous. If the vibration is not continuous then benefit may be taken of this, and the vibration dose assessed explicitly by calculating an eVDV using equations 3 or 4 of Appendix E of this report, and compared with the VDV criteria of BS6472 Appendix A. Alternatively, the R factor of individual events may be reduced to an equivalent R for continuous vibration using figure 2 of Appendix E.

There are many other factors which will affect the choice of structural form for a real project and no attempt has been made here to assess issues such as speed of construction or cost.

For a floor subject to the design requirements of section 2 though, the following observations may be made.

- Composite designs will in general be lighter, but have greater structural depth than other types of floors.
- Slimdek has a thinner overall profile than the conventional composite floors, but uses more material (both steel and concrete).
- Post tensioned concrete floors have the smallest overall construction depth for all designs considered here
- The relative increase in material quantities required to improve the dynamic performance of an ordinary floor designed for strength and deflection only in order to meet the requirements for a night ward or an operating theatre, is significantly higher for composite floors than it is for concrete floors.
- Part of this weight increase is caused by the change in type of concrete from lightweight to normal weight. This, though, reflects normal design practice.
- Of the floors that have been designed to meet strength and deflection criteria only, the dynamic performance of the concrete designs is significantly better than that of the composite designs.

Table 6.1: Comparison of different floor designs

	Steelwork		Decking		Rebar/Prestressing		Concrete		Total mass		Total thickness		1st Natural Frequency	Response factor
	kg/m²	% change	kg/m²	% change	kg/m²	% change	m³/m²	% change	kg/m²	% change	mm	% change	Hz	
Composite														
Office	24.04	0	9.18	0	2.23	0	0.107	0	227	0	536	0	7.15	7.19
Night Ward A	49.49	106	12.56	37	3.03	36	0.192	80	525	131	733	37	10.87	1.25
Night Ward B	42.52	77	12.56	37	6.17	177	0.192	80	521	129	733	37	10.73	1.42
Op Theatre A	54.99	129	16.88	84	3.96	77	0.242	127	656	188	783	46	12.40	0.83
Op Theatre B	45.12	88	12.56	37	6.17	177	0.242	127	644	183	783	46	11.66	0.94
Flat Slab														
Office	n/a	n/a	n/a	n/a	33.09	0	0.300	0	753	0	300	0	5.24	2.79
Night Ward	n/a	n/a	n/a	n/a	28.24	-15	0.330	10	820	9	330	10	7.43	1.34
Operating Theatre	n/a	n/a	n/a	n/a	27.74	-16	0.350	17	868	15	350	17	8.97	0.90
Post tensioned														
Office	n/a	n/a	n/a	n/a	7.54	0	0.220	0	536	0	220	0	7.38	1.95
Night Ward	n/a	n/a	n/a	n/a	7.54	0	0.250	14	608	13	250	14	8.28	1.40
Op Theatre	n/a	n/a	n/a	n/a	5.86	-22	0.290	32	702	31	290	32	9.49	0.96
Slimdek														
Office	52.97	0	16.31	0	9.94	0	0.154	0	449.2	0	316	0	6.72	6.30
Night Ward	53.87	1.7	16.31	0	24.97	151	0.258	67	714.9	59	424	34	8.59	1.32
Op Theatre	63.99	20.8	16.31	0	24.97	151	0.297	93	817.9	82	470	49	9.60	0.86

Figure 6.1: Natural Frequencies Of The Different Floor Designs

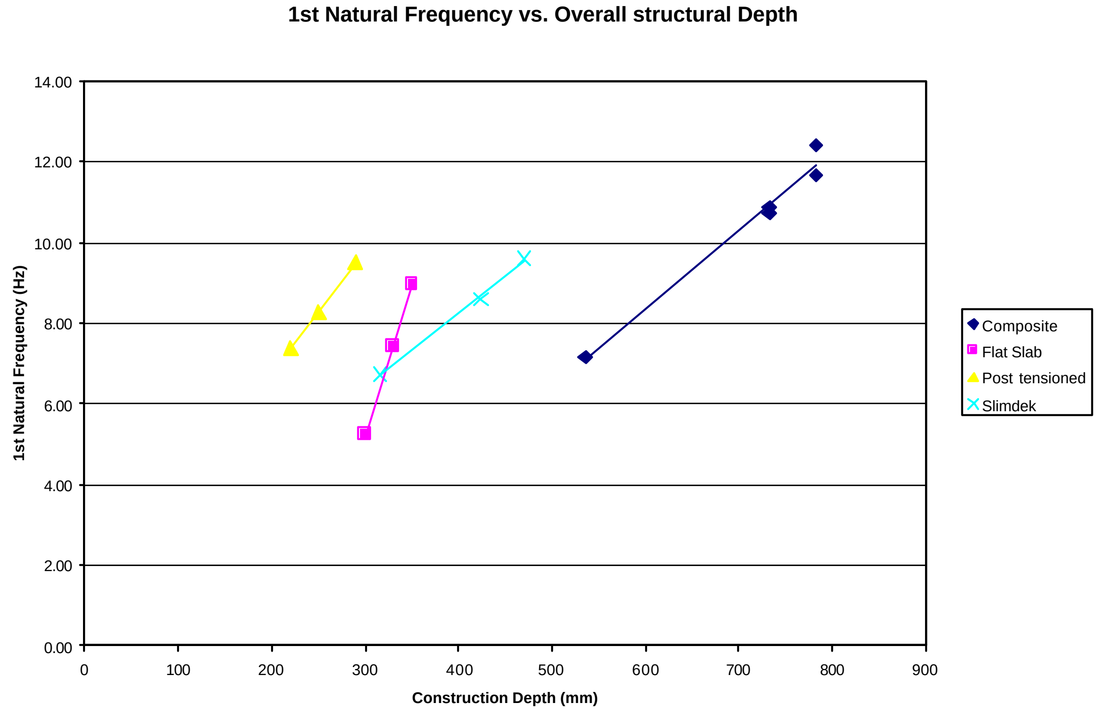
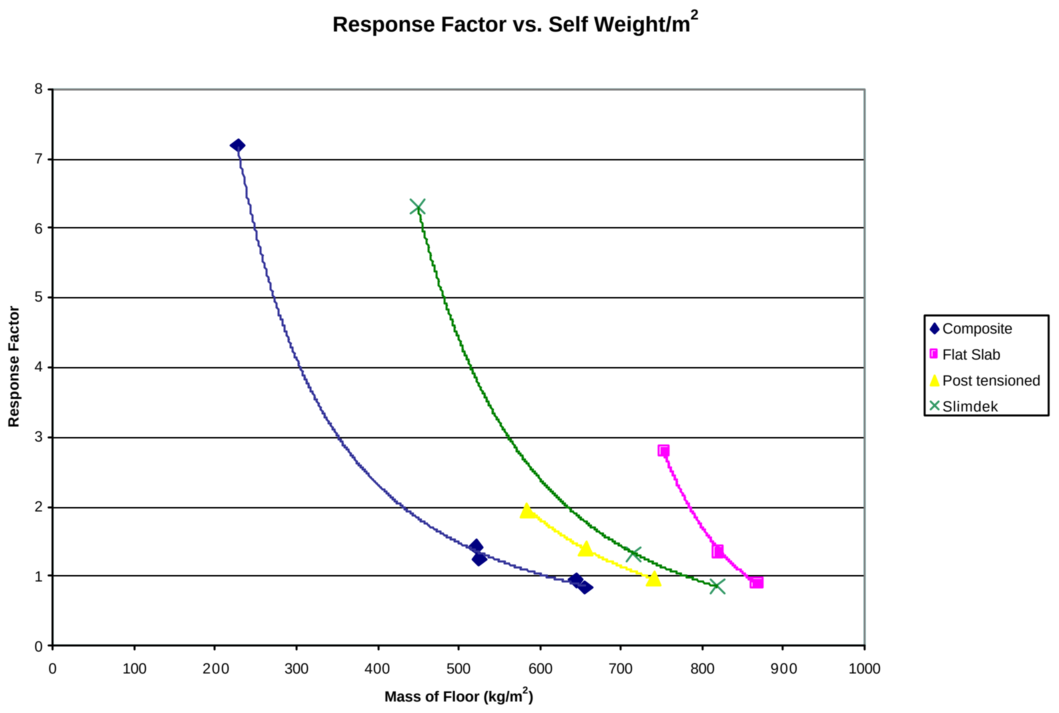


Figure 6.2: Response Factors And Masses Of The Different Floor Designs



REFERENCES

[1] Acoustics. Design Considerations. Health Technical Memorandum 2045. NHS Estates. HMSO

[2] BS 6472:1992 Guide to Evaluation of Human Exposure To Vibration in Buildings (1Hz to 80Hz)

[3] Willford, M. and Young P. *Towards a Consistent Approach to the Prediction of Footfall-Induced Structural Vibration* Internal Arup Publication