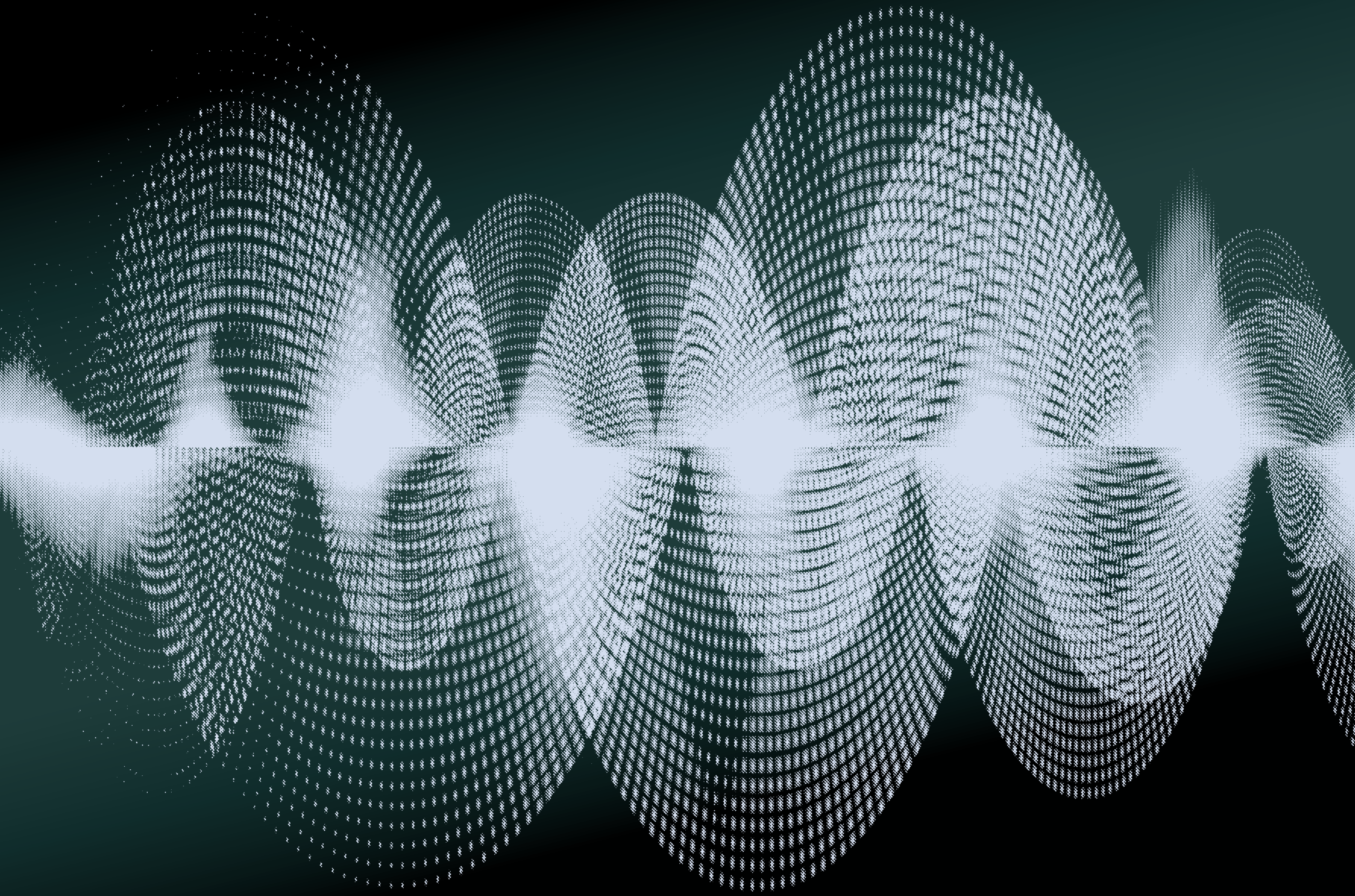
STEEL CONSTRUCTION

Floor Vibration



Steel for Life and the British Constructional Steelwork Association (BCSA) are working closely together to promote the effective use of structural steelwork. This collaborative effort ensures that advances in the knowledge of the use of constructional steel are shared with industry professionals.

Steel is, by some margin, the most popular framing material for multi-storey buildings in the UK and has a long track record of delivering high quality and cost-effective structures with proven sustainability benefits. Steel can be recycled and re-used continuously, and offers a wide range of additional advantages such as health and safety benefits, speed of construction, quality, efficiency, innovation, offsite manufacture and service and support.

The steel sector is renowned for keeping specifiers abreast of the latest advances in areas such as fire protection of structural steelwork and achieving buildings with the highest sustainability ratings. Recent publications have provided detailed guidance on Fire Protection and CE Marking and what it means for the construction sector. Guidance is provided on all relevant technical developments as quickly as is possible.

The sector's go to resource website – *www.steelconstruction.info* – is a free online encyclopedia for UK construction that shares a wealth of up-to-date, reliable information with the construction industry in one easily accessible place.

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Contents

Project features

12 Hammersmith Grove

The 10-storey 12 Hammersmith Grove will offer speculative Grade A office space, ground floor and mezzanine level retail space and a generous double-height entrance foyer.

Designed by architect Flanagan Lawrence, 12 Hammersmith Grove is a steel-framed composite designed structure, utilising long-span cellular beams throughout for economy and to allow the integration of services within the structural void.

Two centrally placed cores provide the steel frame with its stability, while the majority of the structural grid follows a 7.5 m × 10 m pattern throughout the building. This grid also incorporates some longer spans of up to 15 m on all floors.

To incorporate the 15 m long spans, make sure the beams were stiff enough to negate any footfall vibration, and have big enough holes to accept all of the services and thereby keep floor-to-ceiling heights the same, the cellular beams are all 650 mm deep sections. They incorporate 450 mm diameter service holes and support a metal deck with a 150 mm thick slab.

Introduction

In recent years, there has been an increase in demand for buildings that are fast to construct, have large uninterrupted floor areas and are flexible in their intended final use. Modern design and construction techniques enable steel construction to satisfy these demands and deliver structures which are competitive in terms of overall cost.

For most multi-storey commercial buildings, straightforward steel construction will meet the required vibration performance criteria without modification. For more vibration-sensitive applications, such as hospital operating theatre floors or research laboratories, steel's advantages can be utilised, although stiffer solutions may be necessary. Even if a stiffer floor is required, steel remains the most cost-effective and lightweight solution.

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Article of interest:

- FLOOR VIBRATIONS

Long-span applications, for which steel is the only option, have been found to offer good dynamic performance, despite common preconceptions that steel composite floors are thought to be livelier than concrete ones. This is because the stiffer beams and large mass of the long-span floor plates, which participates in any motion, reduce the magnitude of the vibration response. The steel sector has extensive experience in designing steel structures to ensure compliance with even the strictest vibration performance criteria.

Steel structures can meet even the strictest vibration performance criteria

This guide is an introduction to the subject of floor vibrations. It describes what they are, what levels are acceptable and how they are assessed, and introduces a new web-based simple design tool.

What are floor vibrations and why are they important?

The term ‘vibrations’ when applied to floors refers to the oscillatory motion experienced by the building and its occupants during the course of normal day-to-day activities. This motion is normally vertical (up and down), but horizontal vibrations are also possible. In either case, the consequences of vibrations range from being a nuisance to the building users to causing damage to the fixtures and fittings or even (in very extreme cases) to the building structure. The severity of the consequences will depend on the source of the motion, its duration and the design and layout of the building.

Floor vibrations are generally caused by dynamic loads applied either directly to the floor by people or machinery.

The most common source of vibration that can cause nuisance in building applications is human activity, usually walking. Although small in magnitude, walking-induced vibrations can cause a nuisance to people working or living in the building, especially to the use of sensitive equipment or to those engaged in motion-sensitive activities, e.g. surgery. Naturally, the problem is more acute for more vigorous types of human activity such as dancing and jumping and therefore designers of buildings featuring a gymnasium or dance studio should take extra care to limit the vibrations in the rest of the building.

Machinery-induced vibrations are best dealt with at source through the provision of isolating mounts or motion arresting pads. Machines installed in factories tend to produce the most severe vibrations due to their size and the nature of their operation. However, floor vibration is rarely a problem in most factories, since it is accepted by the workforce as part of the industrial environment.

Once constructed, it is very difficult to modify an existing floor to reduce its susceptibility to vibration, as only major changes to the mass, stiffness or damping of the floor system will produce any perceptible reduction in vibration amplitudes. It is important therefore that the levels of acceptable vibration be established at the concept design stage, paying particular attention to the anticipated usage of the floors. The client must be involved in this decision, as the specified acceptance criteria may have a significant impact on the design of the floor and the cost of construction.

Aberdeen Community Health & Care Village

Criteria such as the size, shape, multiple uses and a constrained site all lead to a steel-framed solution for the Community Health and Care Village in Aberdeen.

Described as a hospital without beds, the centre includes departments for minor surgery, dentistry, radiology, sexual health services, physiotherapy, dietetics, speech and language therapy, as well as careers advice and information. With such a variety of uses to be accommodated within a single highly flexible, three level 17,251 m^2 structure, steelwork was always going to be the framing material of choice.

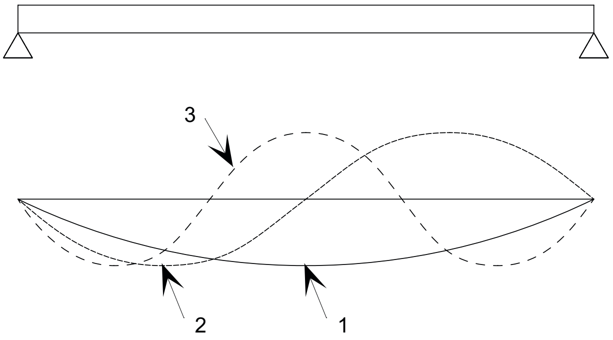
Because of the nature of the intended usages within the structure, such as clinical operations, vibration was an important design consideration and the stringent vibration standard required for hospitals had to be met. Compliance of the steel floor plate was demonstrated using the methodology to calculate vibration response given in SCI’s guide P354.

Basic theory

Continuous systems

A beam has a mass, stiffness and boundary conditions at the supports that define its behaviour. The system has a fundamental frequency which corresponds to the first (lowest) mode of vibration. In this mode, the vibration reaches maximum amplitude in one position (an antinode), at mid-span of the beam. In the second mode, two antinodes are present at quarter points and so on. This system is described as continuous because there are theoretically an infinite number of modes of vibration. The vibration is the result of an input force which can either be continuous as produced by walking, or discrete such as a single heel-drop on a floor beam.

Mode shapes of a simply supported beam

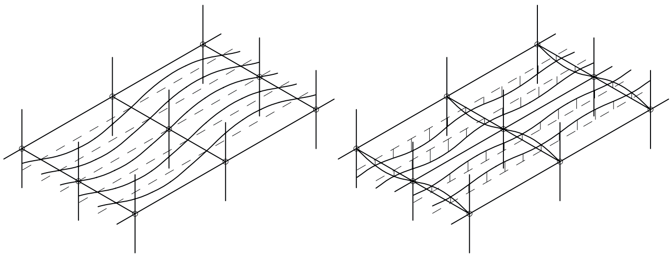


The fundamental frequency of a simply supported beam may be estimated from the mid-span deflection using the following expression. The formula also gives a reasonable estimate for fixed-ended beams and cantilevers if the appropriate deflection is calculated.

$$f_1 = \frac{18}{\sqrt{\delta}} (\delta \text{ in millimetres}).$$

Floors also behave as continuous structural systems. In steel buildings they often consist of primary and secondary beams arranged in a regular orthogonal grillage with a composite floor slab. The whole floor is a continuous horizontal structural system supported at the columns. Because of the continuity, excitation in one part of a floor can be felt some distance away, if the frequency of the forcing function, the response of the floor and the degree of damping are unfavourable. An example would be where vibrations are felt some distance away from a person walking along a corridor.

Typical mode shapes for steel-concrete floor systems

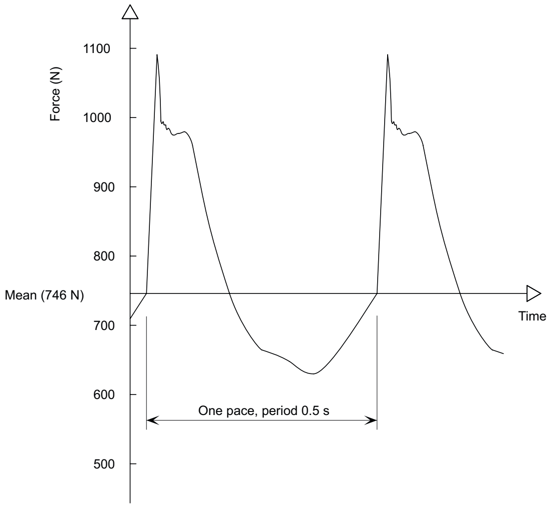


The natural frequency of the whole floor system may be estimated using the equation given previously where δ is the sum of the component deflections for slab, secondary and primary beams. In estimating the natural frequency of a floor system, the actual loads must be considered - usually, the permanent loads and 10% of the unfactored imposed loads.

Human induced vibration

The forcing function due to footfalls from walking at a fixed pace has been measured and plotted as shown below. The range of walking pace frequencies used in design is from 1.8 Hz to 2.2 Hz. For enclosed spaces, a design pace frequency of 1.8 Hz is recommended because slower walking speeds are likely where walking distances are shorter.

Typical force time plot for walking

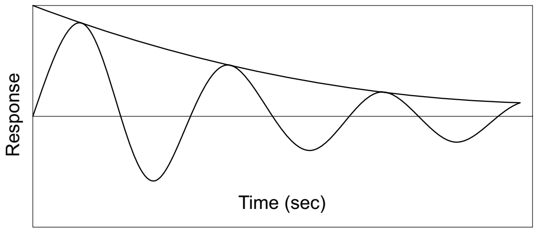


Design the floor to have a natural frequency of over 3 Hz

Damping

Damping refers to the loss of mechanical energy in a system. There are many sources of damping in a building, including friction at the connections, non-structural components such as partitions, furniture and fit-out. As energy is taken out of the system through the damping, the amplitude of the response reduces until the motion eventually ceases. The amount of damping will determine the duration of the response and can be important in situations involving resonance.

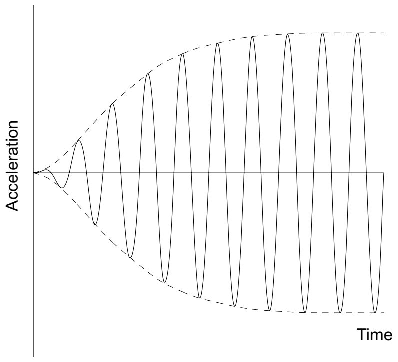
Damping



Resonant response

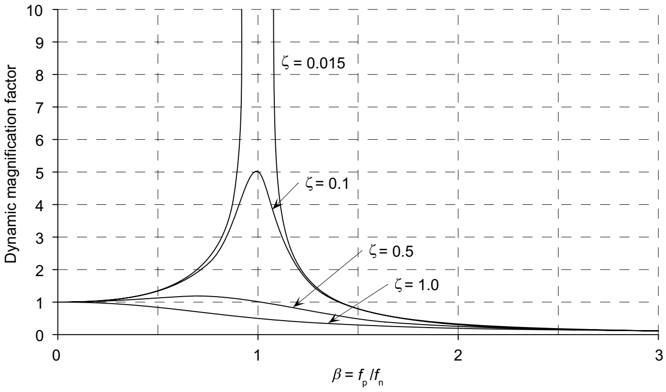
When a continuous force is applied to a system with the same frequency as that of the system, each successive load cycle will add to the response, causing the amplitude to increase. In the absence of damping, the amplitude will increase to a magnitude well in excess of the level of response resulting from a single load cycle. This is known as resonance and, if allowed to develop in a structure, can result in unacceptably high responses and damage to the structure. Fortunately, in building structures, the damping is usually sufficient for the energy to be dissipated over a number of cycles and very large amplitudes of vibration do not occur. Instead, the response settles down to a steady state having a constant amplitude. In this state, each new cycle of load merely replenishes the energy lost to damping.

Resonant response



Nevertheless, despite damping, the steady state amplitude is several times the initial amplitude, and this response may still be problematic to the building designer. The degree of magnification, known as the Dynamic Magnification Factor (DMF), depends on the ratio of the frequency of the loading function (f_p) to the natural frequency of the structure (f_n) and the level of damping expressed in terms of the damping ratio (ζ).

Dynamic magnification factor for accelerations



Resonance on the fundamental frequency (the worst case) may be avoided by designing the floor to have a natural frequency of over 3 Hz. This ensures that the fundamental frequency of the floor will be higher than the lowest harmonic of walking.

Damping ratio for various floor types

Damping ratio (ζ)	Floor construction and finishes
0.5%	For fully welded steel structures (eg staircases)
1.1%	For completely bare floors or floors where only a small amount of furnishings are present
3.0%	For fully fitted out and furnished floors in normal use
4.5%	For a floor where the designer is confident the partitions will be located to interrupt the relevant mode(s) of vibration (i.e. perpendicular to the main vibrating elements of the critical mode shape).

Technology and Innovation Centre, University of Strathclyde

Long spans and the ease of internal reconfiguration over the life of the building were key reasons for choosing a steel solution for this research facility in Glasgow. Known as the Technology and Innovation Centre (TIC), it provides office, conference facilities and laboratory space for students, academics and industry experts to work jointly on solutions to challenges in a diverse range of sectors

The north block of the TIC houses most of the facility's laboratories on levels 4, 5, 6 and 7. The steel frame and precast slab in this area were stiffened in order to achieve the very onerous vibration requirements specified for the laboratories. The slab is thicker at 300 mm, compared to 150 mm elsewhere within the building and additional secondary beams were employed at 2 m centres.

Heavier steel sections and a thicker slab were used in this area to make this part of the floor plate approximately six times stiffer than would normally be required for static loadings. This additional mass and stiffness was provided to achieve a reasonable standard of instrument performance. The design generally delivers a floor response factor of 1.0 at mid-span locations and a response factor of 0.5 or better at column and core locations.

What levels of floor vibrations are acceptable?

Generally, the vibration of floors is considered to be a serviceability issue, primarily related to the discomfort of building occupants or damage to sensitive equipment. Where there is sensitive equipment, it is a relatively straightforward matter to specify the maximum permissible acceleration. However, discomfort to humans cannot be directly quantified, since perception and tolerance vary between individuals and are highly dependent on a number of factors including:

- the type of activity;
- the time of day when activity is being undertaken;
- the type of environment where the activity is taking place;
- the direction of the vibration;
- the amplitude of the vibration;
- the frequency of the vibration;
- the source of the vibration;
- the level of damping;
- the duration of exposure.

The most convenient vibration response to measure has been found to be acceleration so human response to vibration is normally expressed in terms of acceleration. The maximum or peak value of acceleration is not considered to be the most suitable value. Instead the rms (root mean square) value is used because this measure gives a better indication of vibration over time and sharp peaks in acceleration in an otherwise low response are less significant.

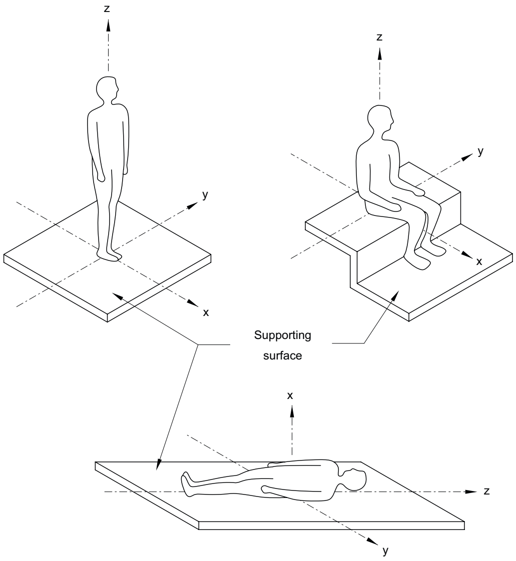
The base value of rms acceleration which can be perceived depends on the direction of vibration relative to the human body. The z axis corresponds to the direction of the spine and the base value in this direction is higher than in orthogonal directions.

This means that x or y axis accelerations are more easily felt. The base values for acceleration are as follows:

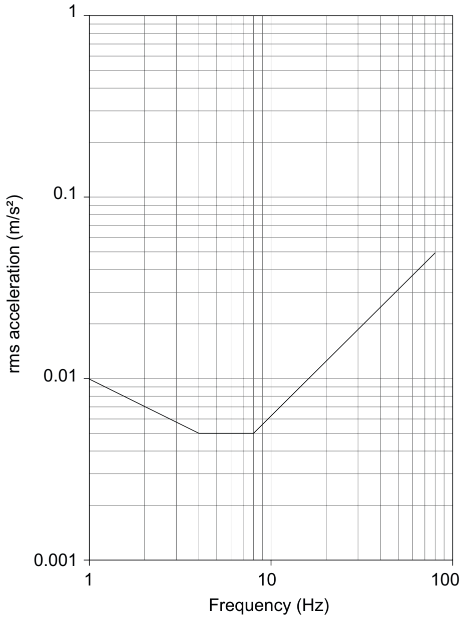
- $a_{rms} = 5 \times 10^{-3}$ ms^{-2} for z-axis vibrations;
- $a_{rms} = 3.57 \times 10^{-3}$ ms^{-2} for x- and y- axis vibrations.

The perception of vibration also depends on frequency: humans have been found to be most sensitive to vibrations of frequency between 4 and 8 Hz. Extensive research into human response to vibrations has been embodied in international standards. In the UK, the relevant standard is BS 6472, which covers many vibration environments in buildings. The wide coverage is achieved by setting out a frequency-weighted base curve and a set of multiplying factors corresponding to different circumstances. The line is called an isoperceptability line. The area below the line represents vibrations which are imperceptible to most people.

Directions for vibration



Baseline acceleration for the z-axis



Acceptance levels for continuous vibrations are given as multiplying factors which represent limits on the value of calculated response factors. The response factor is defined as the calculated weighted rms acceleration divided by the appropriate base value. The acceptance levels represent 'low levels of adverse comment' on the vibrations. The acceptance levels are expressed in this way because the perception of vibration is not an absolute and is not constant from person to person. The intention is that the levels of acceleration will be acceptable to most people.

Design values for response factors are given in BS 6472, but for certain circumstances different values have been recommended by the SCI. Values for hospitals are defined in HTM 08-01. There may be other circumstances where the client for the building specifies lower limits on vibration response for example because particular items of equipment require it.

Vibrations from footfalls are generally intermittent because walking activities are not usually continuous. A cumulative measure of the response has been found to be more reliable in determining the acceptability of short term vibrations. Guidance is given in BS 6472. Vibration levels are allowed to be higher than for continuous vibrations, as long as the occurrence is rare. The perception levels are expressed in terms of vibration dose values. Some design guidelines do not make allowances for intermittent vibrations for sensitive areas.

Stobhill Hospital, Glasgow

Steel frames can meet the even the most onerous acceptance levels

Response factors from SCI-P354

Place	Multiplying factor for exposure to continuous vibration
Office	8
Shopping mall	4
Dealing floor	4
Stairs – Light use (e.g. offices)	32

Response factors from HTM 08-01

Place	Multiplying factor for exposure to continuous vibration
Operating theatre, precision laboratory, audiometric testing booth	1
Wards	2
General laboratories, treatment areas	4
Offices, consulting rooms	8

Isaac Newton Academy

Located in Ilford, east London the £30M 1,250 pupil secondary school which specialises in maths and music, opened in September 2012.

A number of reasons contributed to steelwork being used as the project's framing solution, such as speed of construction, the number of long spans within the buildings and the material's economy of construction. A particularly challenging part of the design was the dynamic loading in the sports hall, which projects 54 m out over a car park. The engineers had to cater for potential rhythmic bouncing taking place in the sports hall while avoiding too many columns protruding into the public space below

The 18.7 m wide beam is supported by five sets of paired columns. After initially positioning the columns on the outer edges, the design team decided to bring the first four inwards by 2.35 m each side to reduce the span to 14 m. This provided greater structural rigidity while preserving the visual effect of levity. This short reduction in span made a big difference to the structural dynamic response.

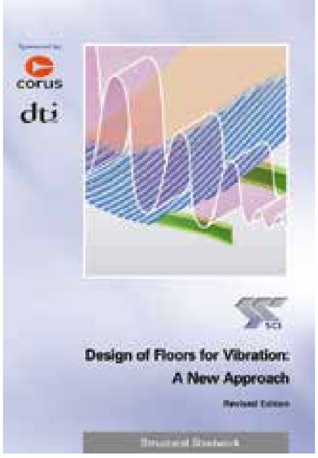
How can floor vibrations be assessed?

Improvements in vibration performance after construction are likely to be difficult to achieve and very costly. The assessment of vibrations should therefore be carried out as part of the serviceability checks on the floor during the design process. The vibration performance of the floor can be assessed using manual methods, a new simplified web-based tool or finite element methods. Where a BIM model of the building is being created by the design team, the model should contain all the necessary information required to carry out the analysis.

Manual methods

Simplified assessment can be carried out by hand methods of analysis, although such calculations are generally conservative and in some cases to a great extent. Various methods are available, one of which is set out in SCI publication P354. To avoid the possibility that walking activities could cause resonance or near-resonant excitation of the fundamental mode of vibration of the floor, neither the floor structure as a whole nor any single element within it should have a fundamental frequency of less than 3 Hz. The assessment procedure involves the following steps:

- calculate the natural frequency of the floor system;
- determine the modal mass, i.e. the mass participating in the vibration;
- calculate the critical rms acceleration and the response factor;
- compare the response factor with the acceptance criteria for continuous vibration.

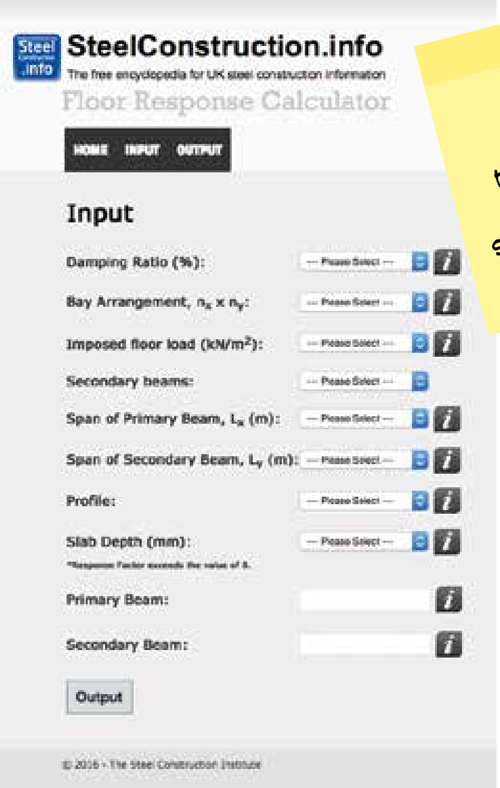


If the response factor is not acceptable, try a more comprehensive method of analysis such as the new simplified web-based tool or finite element modelling.

Simplified web-based tool

A new *Floor Response Calculator* is available on www.steelconstruction.info that allows designers to make an immediate assessment of the dynamic response of a floor solution. The results from this tool provide an improved prediction of the dynamic response compared to the 'manual method' in SCI P354. The tool may be used to examine complete floor plans or part floor plans, comparing alternative beam arrangements.

The tool reports the results of approximately 19,000 arrangements of floor grid, loading and bay size, which have been investigated using finite element analysis. The designer must select between a variable action of 2.5 kN/m^2 and 5 kN/m^2, being typical imposed loads on floors. 0.8 kN/m^2 is added to allow for partitions. The designer must also select the arrangement of secondary and primary beams, with typical spans, which depend on the arrangement of the beams. Secondary beams may be placed at mid-span or third points. The pre-set damping ratio of 3% is recommended for furnished floors in normal use.



Input

Damping Ratio (%): — Please Select —
Bay Arrangement, $n_x \times n_y$: — Please Select —
Imposed floor load (kN/m^2): — Please Select —
Secondary beams: — Please Select —
Span of Primary Beam, L_x (m): — Please Select —
Span of Secondary Beam, L_y (m): — Please Select —
Profile: — Please Select —
Slab Depth (mm): — Please Select —
*Response Factor exceeds the value of 8.
Primary Beam:
Secondary Beam:

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A simplified web-based tool is available on www.steelconstruction.info

When a decking profile is selected, an appropriate range of slab depths are then available to be selected. Generally, thicker slabs will produce a lower response factor. When selecting the slab depth, solutions which result in a response factor higher than 8 (the limit for a typical office) are highlighted.

The primary and secondary beams are selected automatically as the lightest sections which satisfy strength and deflection requirements; these cannot be changed by the user. The selection of the lightest sections is made to produce the most conservative dynamic response, as stiffer beams will reduce the response.

A visual plot of the response is also provided for both the steady state and transient response. Hovering over the plot shows the response factor. Generally the higher response will be in an end bay, where there is no continuity. The fundamental frequency of the floor is presented on the output screen.

If the actual design differs from the pre-set solutions in the tool, users should note the following:

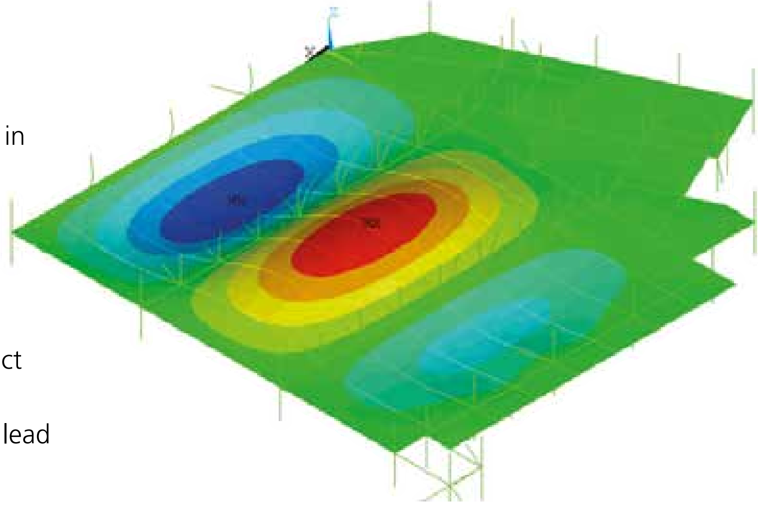
- Using stiffer beams will reduce the response
- Using thicker slabs, and stiffer beams, will reduce the response
- The gauge of the decking has no significant impact on the response factor
- Voids that break the continuity of beam lines will lead to higher response factors

Finite element analysis

The most accurate and detailed assessments of floor vibrations are made using finite element (FE) analysis. Simple methods can be applied with reasonable accuracy for orthogonal grids but where a floor plate is not orthogonal (e.g. curved in plan), simple methods are inadequate. In FE analysis the floor slab, beams, columns, core walls and perimeter cladding are modelled with finite elements with appropriate restraints applied to the elements in the model. A model of the whole building is often already available for Building Information Modelling (BIM) and an individual floor can be extracted and modified to provide a model that is suitable for vibration analysis.

A modal analysis is carried out first to determine the natural frequencies, mode shapes and modal masses. Steady state and transient responses are then calculated for each mode of vibration and each harmonic of the forcing function (the walking activity). The modal responses are then added up for all the mode shapes and harmonics considered, and a predicted rms acceleration calculated for each point on the floor. The final step is to divide the acceleration by the base value to determine the response factor. The results can be plotted in a contour plot.

Finite element analysis



Mitigation

If the floor response is found to be unacceptable during the design assessment, the designer has some freedom to make adjustments to the structural arrangement such that the vibration response is reduced to acceptable levels. Possible measures include increasing the mass, stiffness and damping of the floor, and relocating or reducing the length of corridors.

Case studies

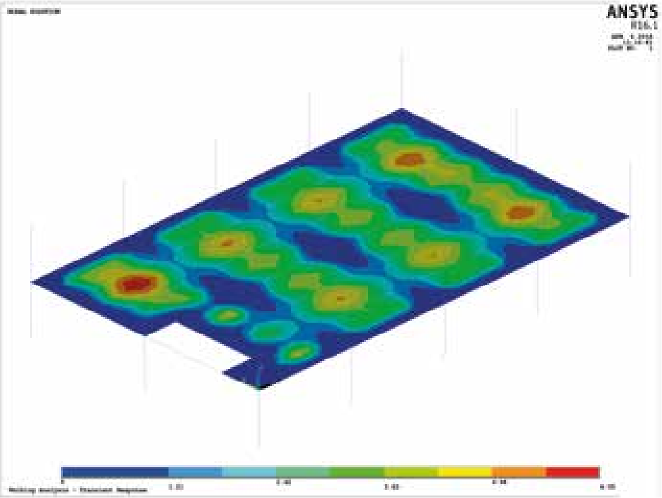
1: SCI office building

The floor of the SCI's office was examined using manual methods, the new simplified web-based tool and detailed FE analysis. The building footprint is 24 m (4 bays) long and 14.9 m (2 bays) wide. The floor plate is 130 mm thick normal weight concrete supported on a re-entrant profile metal deck 1.2 mm thick. Primary castellated beams 686 mm deep spanning 7.45 m support 305 mm deep secondary beams spanning 6 m at about 2.48 m centres. Both primary and secondary beams act compositely with the slab. Design loading (including 10% imposed loading) is 4.21 kN/m^2.

The maximum deflection assuming slab, secondary and primary beams are participating (primary beam mode) was 3.75 mm giving a natural frequency of 9.3 Hz. The fundamental frequency of less than 10 Hz indicates that the low frequency recommendations are relevant. A peak acceleration of 47.4 × 10^{-3} ms^{-2} was calculated using a value of damping determined by testing of 4.68% of critical damping. This relatively high value of damping can be attributed to the number of full-height partitions present at the time of testing. The maximum response factor was found to be 9.48. This exceeds the recommended limit for continuous vibrations. Vibration dose values were calculated which indicated that the floor could be traversed up to 2400 times in a 16 hour day i.e. 150 times per hour for a low probability of adverse comment. This level of activity was considered unlikely and the floor can be classed as acceptable.

The *Floor Response Calculator* was used to examine the same bay arrangement with spans selected from the database that were the closest to the actual layout (7.2 m span primary beams and 6 m span secondary beams). Damping was assumed to be 3% of critical. A 130 mm deep normal weight slab on a re-entrant profile deck with imposed loading of 2.5 kN/m^2 with 0.8 kN/m^2 for partitions was selected. Beam depths returned by the new simplified web-based tool were lighter and shallower (less stiff) than those actually used: primary beams were 406 × 140 UB 46 and secondary beams were 254 × 102 UB 22. The fundamental frequency was found to be 10.1 Hz with the maximum steady state response factor R of 3.4 and maximum transient response factor of 9.2. The transient response factor exceeds the recommended value for offices of 8.

Detailed FE analysis using ANSYS assumes positional fixity of the edge beams by the cladding and models the columns explicitly with positional restraint at mid-height. The beam sizes correspond to the hand analysis. The analysis produced a set of natural frequencies for the floor of 11.06 Hz for mode 1 up to 21.5 Hz for mode 10. The response factor for a walking analysis with 3% critical damping was summed for the mode shapes and harmonics and the maximum steady state response factor found to be 1.66 and the maximum transient response factor determined as 6.05. This is less than the recommended value of 8 for offices and the floor design is therefore acceptable. The contour plot of the response factors across the floor plate is shown in the figure.



Model	Natural Frequency (Hz)	Steady State Response Factor	Transient Response Factor
Manual method	9.3	9.5	-
Floor Response Calculator	10.1	3.4	9.2
FE analysis	11.06	1.67	6.9

Comparison of the three methods shows that the manual method is very conservative and indicates an unacceptable result, despite the higher damping. The *Floor Response Calculator* results are similar to the FE analysis, although slightly higher, and show the same characteristics: lower steady state and higher transient responses. The steady state result is acceptable but the transient result is high. However, it must be remembered that the new simplified web-based tool automatically selects the lightest sections which satisfy strength and deflection requirements. As mentioned previously, these were lighter and shallower (i.e. less stiff) than those actually used, so the real response would be expected to be lower than that predicted by the *Floor Response Calculator*. This is indeed reflected in the modelling used in the FE analysis, which is the most detailed and returns the lowest value, illustrating the value of this approach.

Walbrook Building

Built on a City of London site directly opposite Cannon Street Station, the 10 storey Walbrook Building is an L shaped structure providing 3,693 m² of retail space and 35,283 m² of office floorspace.

The project required more than 6,000t of structural steelwork, is located within the height limitation band imposed by the nearby St Paul's Cathedral, and received a commendation in the Structural Steel Design Awards 2012.

The superstructure generally consists of structural steel columns and beams with composite floor slabs cast in-situ on metal decking with cellular beams used extensively to facilitate services distribution. Two atria from third to ninth floor allow increased daylight penetration into the office space.

The frame is designed for a target maximum vibration Response Factor of six, while still maximising the areas of column free space and minimising construction depth.

Case studies

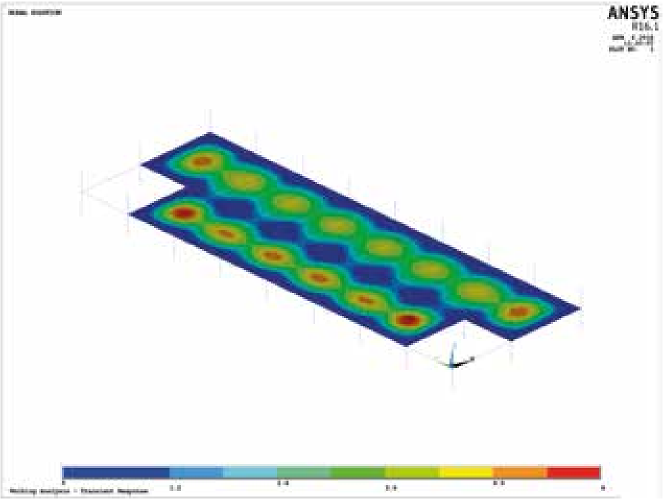
2: Composite floor with dissimilar spans

A theoretical floor layout adapted from SCI publication P387 was examined with a footprint 48 m long and 16.5 m wide. Eight bays of primary beams spanning 6 m support secondary beams at mid-span. Secondary beams in two bays of 9 m and 7.5 m span across the building. Both primary and secondary beams act compositely with the floor slab which consists of a 150 mm deep normal weight concrete slab on a 1.0 mm thick re-entrant profile deck. The primary beams are 457 × 152 UB 52 and the secondary beams are 356 × 127 UB 33 and 406 × 140 UB 46 in the shorter and longer spans respectively. The design loading (including 10% imposed loading) is 4.44 kN/m^2

The maximum deflection assuming slab and secondary beams participate (secondary beam mode) is 8.73 mm giving an estimated natural frequency of 6.1 Hz. The low frequency recommendations apply and assuming 3% of critical damping, the peak acceleration is calculated to be 46.8×10^{-3} ms^{-2}, resulting in a maximum response factor of 9.35. This exceeds the recommended value of 8 so vibration dose values should be considered.

The *Floor Response Calculator* was used to examine a 4 × 2 bay arrangement, closest to the proposed footprint. Equal spans of 7.5 m and 9 m were considered in turn. Secondary beams were as for the manual calculations. A 150 mm thick normal weight slab on a re-entrant profile deck was selected. The imposed floor loading was 2.5 kN/m^2 with 0.8 kN/m^2 for partitions. Primary beams were 356 × 171 UB 45 for the shorter secondary beams. The fundamental frequency returned was 10.4 Hz. The response factors were: steady state 2.3, transient 7.3. For the 9 m span secondary beams, the primary beam was the same serial size but 51 kg/m in weight. The fundamental frequency was found to be 9.1 Hz and the response factors: steady state 4.3 and transient 6.1. The response factors are less than the recommended value of 8 for offices.

Detailed FE analysis using ANSYS was carried out, with the floor beams used as in the manual calculations, starting with a modal analysis. The fundamental mode is a secondary beam mode with a natural frequency of 8.95 Hz. The first 10 modes have natural frequencies between 8.95 Hz and 11.7 Hz. A walking analysis assuming 3% critical damping produced peak response factors of 4.2 for steady state conditions and 6.0 for transient conditions.



Model	Natural Frequency (Hz)	Steady State Response Factor	Transient Response Factor
Manual method	6.1	9.4	-
Floor Response Calculator	10.4[*1] 9.1[*2]	2.3[*1] 4.3[*2]	7.3[*1] 6.1[*2]
FE analysis	9.0	4.2	6.0

Notes:
[*1] For the case of equal 7.5m spans
[*2] For the case of equal 9m spans

Comparison of the results shows that the manual method gives a low estimate of the fundamental frequency of the floor and a correspondingly high response factor. The results are very conservative. The *Floor Response Calculator* result for the longer spans and the detailed FE analysis give very good agreement in this case, because the new simplified web-based tool arrangement corresponds closely to the FE model.

Manchester Cancer Research Centre

The Manchester Cancer Research Centre (MCRC) building provides space for 150 cancer researchers whose work will focus on understanding how cancer starts, develops and progresses, as well as 100 clinical trials support staff.

Situated overlooking a busy thoroughfare, the structure is a local landmark with its visually exciting cantilevers and sloping facades. This complex structural design had to incorporate both research laboratories and offices and this led to the decision to employ a hybrid approach to the structural frame. The building is divided in half by the entrance and a large lightwell. Three interlinked laboratory wings are positioned on one side of this open space with the offices on the other side.

The three levels of office accommodation have been constructed using a composite solution with steelwork supporting steel floor decking. In the laboratory areas a steel frame supporting precast planks is utilised to accommodate the varying degrees of vibration performance required for the research equipment. The planks vary in depth, up to a maximum 350 mm thickness, depending on the equipment to be installed and the soffits have been left exposed to optimise thermal mass, thereby helping to cool the building, although this was of secondary importance to the vibration issue.

Summary

For most multi-storey commercial buildings, straightforward steel construction will meet the required vibration performance criteria without modification. For more vibration-sensitive applications, such as hospital operating theatre floors or research laboratories, steel's advantages can be utilised, although stiffer solutions may be necessary. Even if a stiffer floor is required, steel remains the most cost-effective and lightweight solution.

The term 'vibrations' when applied to floors refers to the oscillatory motion experienced by the building and its occupants during the course of normal day-to-day activities. The most common source of vibration that can cause nuisance in building applications is human activity, usually walking. Although small in magnitude, walking-induced vibrations can cause a nuisance to people working or living in the building, especially to the use of sensitive equipment or to those engaged in motion-sensitive activities, e.g. surgery.

Building floors have a number of modes of vibration, each of which has a natural frequency. These modes of vibration can be excited as the building is used, producing a large response (a phenomenon called resonance) if the frequency of the exciting force is close to a mode of vibration of the floor. Walking is a common source of input force and resonance at the walking frequency can be avoided if the floor has a fundamental frequency of more than 3 Hz.

Human response to vibration is usually measured in terms of acceleration, and acceptance values are expressed in terms response factor: the ratio of predicted rms acceleration to a base value. These are compared with acceptance criteria which have been defined in design standards for different spaces. The values vary from 1.0 for critical working areas (e.g. hospital operating theatres) to 8 for offices and higher values for other places e.g. stairs.

Improvements in vibration performance after construction are likely to be difficult to achieve and very costly. The assessment of vibrations should therefore be carried out as part of the serviceability checks on the floor during the design process. The vibration performance of the floor can be assessed using manual methods, a new simplified web-based tool or finite element methods.

Manual methods are generally conservative, overestimating the vibration response, in some cases to a great extent. The new simplified web-based tool allows designers to make an immediate, and more accurate, assessment of the dynamic response of a floor solution as it is being developed early in the design process. The most accurate and detailed assessments of floor vibrations are made using finite element (FE) analysis.

Creechurch Place, London

Creechurch Place, is a 19-storey T-shaped office development currently (April 2016) being built close to 30 St Mary Axe (The Gherkin) in an area of the City dubbed the insurance district because of the abundance of underwriters. The site occupies an important position in the City of London and the aim is to deliver a new, modern, flexible and efficient office building of the highest quality.

The construction will deliver a structure comprising two levels of basement, ground floor and

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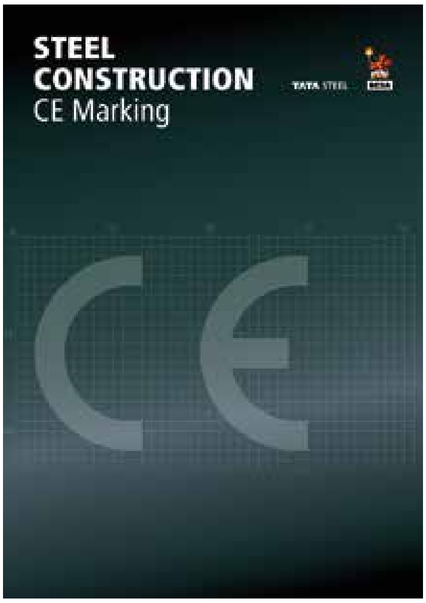

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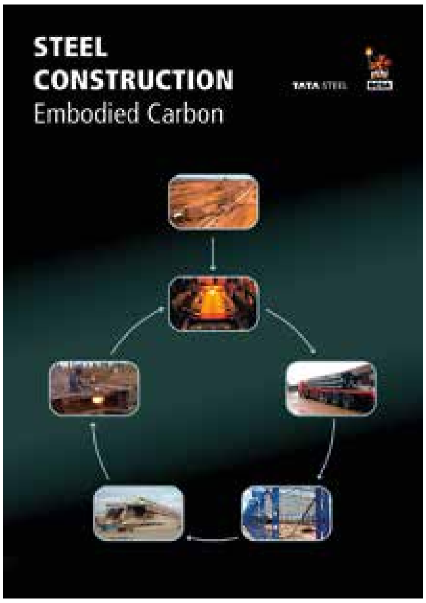

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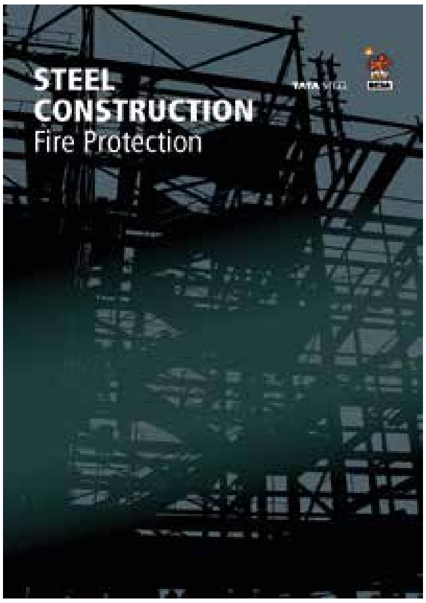

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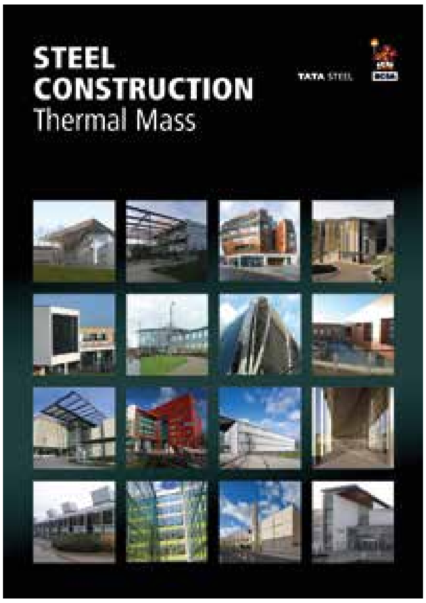

STEEL CONSTRUCTION
Thermal Mass

17 upper storeys, plus rooftop plant, providing 25,350 m² of flexible, Grade A commercial office space and 284 m² of retail/café space. The design for the majority of the tower was always a steel building as the material enables the structure to have long clear spans, which would not have been possible with concrete.

The steel frame is based around a regular grid offering open-plan office space with column-free spans of up to 16.5 m-long. Only two internal columns are present throughout the entire structure.

William Hare has installed cellular beams throughout the majority of the structural frame to allow the building's services to be accommodated within the structural void.

Despite the long spans, the use of cellular beams was not an issue for the floor vibrations. Ramboll used its experience of in situ testing to demonstrate that through careful consideration of the layout and interactions between the cellular beams, they could still be used efficiently, without having to adopt the more traditional method of using heavier beams to increase the stiffness.

Steel for Life

Steel for Life is a wholly owned subsidiary of BCSA, created in 2016, with funding provided by sponsors from the whole steel supply chain. The main purpose of Steel for Life is to communicate the advantages that steel offers to the construction sector. By working together as an integrated supply chain for the delivery of steel-framed solutions, the constructional steelwork sector will continue to innovate, educate specifiers and clients on the efficient use of steel, and market the significant benefits of steel in construction.

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