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FOOTFALL INDUCED VIBRATION IN LONGSPAN COMPOSITE STEEL BEAMS USED IN TWO PROJECTS AT THE UNIVERSITY OF AUCKLAND

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ABSTRACT

Floor vibration due to human activity has become increasingly recognised by structural engineers, architects, and building owners as an inherent issue in long-span steel framed floor systems. In the past, attention was primarily focused on strength and deflection serviceability limits. However, as designers seek to push the limits on structural spans, grid spacings and adopt light-weight, low damping structural steelwork floor systems, more detailed consideration is required of the design tools and processes available to analyse and predict the vibration performance of floor systems.

Selection from published criteria of an "acceptable" vibration limit is sometimes possible depending upon the intended use of the space and the availability of manufacturers' data for any vibration sensitive equipment. Building Owners and User Groups often have little understanding or quantitative "feel" for what performance the proposed "acceptable vibration limit" actually represents. The theoretical predication of vibration performance against actual measured performance can sometimes vary significantly. This can lead to dispute post-construction as to whether the floor has an "acceptable" level of vibration. Post construction remediation of a space that is deemed to be "too lively" is often difficult, therefore, it is important that the vibration design criteria proposed are discussed and agreed and the limits of theoretical predications of vibration performance are clearly understood by all parties at the outset.

Beca Carter Hollings and Ferner Ltd (Beca) are currently in the process of designing two projects at the University of Auckland, utilising long-span partial-composite cellular steel beams. Both buildings will utilise existing structural frame layouts and foundations. As the new structure is to be built on the existing foundations, there is a necessity to keep it as lightweight as possible. The question of vibration sensitivity has been raised as a potential issue as both buildings contain research laboratories. An in-depth investigation has been conducted into the factors affecting vibration performance in order to give the Client and User Groups confidence that footfall induced vibration will not be an issue with the proposed floor structure.

1. Introduction

Client requirements, coupled with architectural and cost constraints, have demanded new buildings to provide large uninterrupted floor spaces, which are fast to construct with a high degree of adaptability for building services. In response to these issues, Engineers have pushed the limits on column and beam grid spacings. Where previously strength and serviceability deflections governed design, it is increasingly the dynamic performance of floors which require increased consideration. The use of high strength light-weight cellular steel beams and composite metal-deck floor systems has reduced construction costs through lighter loads imposed on foundations and reduced craneage requirements. A range of software, including finite element (FE) tools, are now available to design composite long-span floor systems providing consideration of both strength and vibration issues.

Beca are currently designing two projects at the University of Auckland (UoA) which comprise long-span partial-composite cellular steel beams and metal-deck floors. The two buildings are to be used for

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postgraduate research and teaching spaces, as well as office and laboratory areas. Due to the nature of the intended use, there is a need to minimise footfall induced floor vibration effects on occupants and laboratory equipment.

This paper outlines: the fundamental principles of vibration and factors to be considered during design, provides an outline of the two UoA projects, reviews the analysis and acceptance criteria adopted for the projects and summarises the on-site testing and validation of the analysis tools used.

2. Fundamental Principles of Vibration

To better understand the effect of footfall induced vibration on composite floor systems, it is necessary to understand the principles of vibration.

2.1 Frequency

The natural frequency of a system, given in hertz, Hz (cycles per second), is a measure of the rate at which the system vibrates[1]. When a cyclic force (e.g. walking) is applied to a structure, it will begin to vibrate. If the cyclic force is applied continuously, the motion of the structure will reach a steady-state (constant amplitude and frequency).

For floors with a frequency of less than 8Hz, resonance can occur from one of the first four harmonic components of walking activity coinciding with the natural frequency of the floor. This is known as resonant excitation. Conversely, for floors with a sufficiently ‘high frequency’ (such that the first four harmonic components of the walking activity do not cause resonance), the response is dominated by a train of impulses corresponding to the heel impacts; which is known as impulsive excitation.

2.2 Modal mass

A mode of vibration is characterised by a modal (natural) frequency and a mode shape. Each mode is independent of the other modes. All modes have different frequencies and different mode shapes. The modal mass of a system is a measure of how much mass is involved in the particular mode shape. A large modal mass will require a lot of energy to excite the mode. Systems with larger modal masses will therefore be less affected by footfall induced vibration.

2.3 Excitation

The forcing function from a walking activity is assumed to be perfectly sinusoidal. The excitation imposed to a floor is affected by the pace frequency, the length of walking path, and the location of the walking activity (excitation) relative to the receiver.

The pace frequency, f_p, used for design falls into the range[1]: $1.8Hz \leq f_p \leq 2.2Hz$

The excitation point and response point should be chosen to produce the maximum response of the floor. In most cases, the maximum response will be when excitation and receiver are at the point of maximum modal displacement.

2.4 Response

Calculation of floor vibration response considers the mass, stiffness and damping properties of the structure, and by applying an appropriate excitation function[2]. For low frequency floors, both the steady state response and transient response need to be checked, as the higher frequencies of the floor may result in the transient response being greater than the steady state[3]. For high frequency floors only the transient response needs to be checked.

The Response factor of a floor is the ratio between the calculated weighted RMS (root-mean-square) acceleration, and the base value given in BS6472[4]. This standard covers many vibration environments in buildings. Limits of satisfactory vibration magnitude are expressed in relation to a frequency-weighted ‘base curve’ and a series of multiplying response factors. A Response factor of 1 (R = 1) is the level of vibration that can just be perceived by humans. R=2 is twice as much as can just be felt (etc).

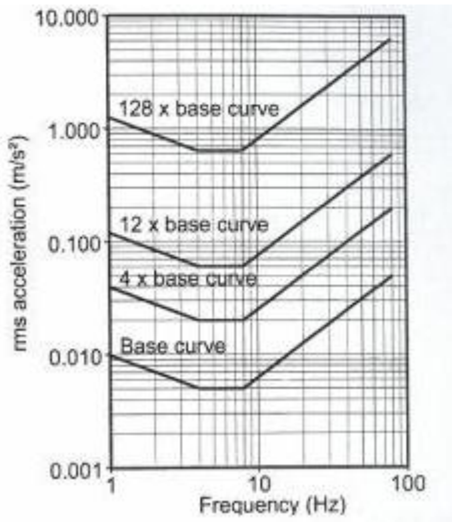

Figure 1. Building Vibration Curves For z-axis Vibrations[4]

2.5 Damping

Damping describes the amount of energy dissipation that occurs when a structure vibrates. With higher levels of damping, more energy is dissipated as sound and heat, which in turn, leads to lower levels of structural vibration[5]. The fact that no system will oscillate indefinitely without an applied load, shows that all structures contain some level of inherent damping. When calculating vibration responses, it is important to use a realistic estimate of structural damping. Experience with floors of similar construction will provide a more accurate estimate of the likely amount of damping that may be achieved.

3. University of Auckland Projects

3.1 University of Auckland – Science Centre Building B302

The proposed new 13 storey Science Centre Tower is located on the corner of Symonds Street and Wellesley Street East on the University of Auckland Central City Campus. The new structure is located on the site of an existing 3 storey building and will utilise the existing building grid set-out and foundations. As the new structure is to be built on the existing foundations, there is a necessity to keep it as light as possible.

The new structure is a steel braced frame building utilising Buckling Restrained Braces (BRB's). The gravity structure consists of steel welded I-section columns, supporting tapered steel primary beams spanning 6.4m, partial-composite long-span cellular secondary beams at 3.2m centres spanning 13.4m and 14.8m, with a 140mm-thick composite reinforced-concrete metal decking. The cellular beams are 800mm deep with 500mm diameter penetrations at regular centres, to allow for services reticulation. These beams have been designed as partial-composite members as a layer of visco-elastic material has been used over half the beam-span to provide additional damping to the floor system.

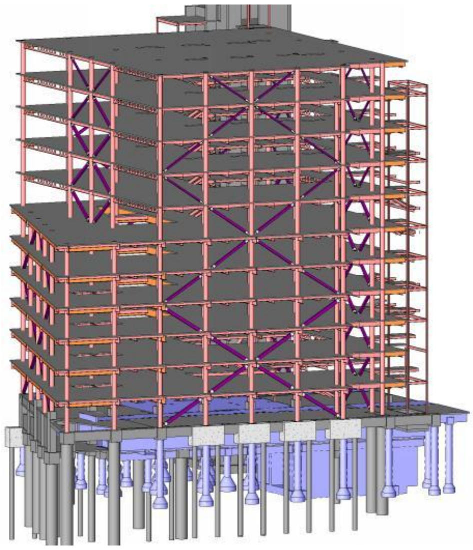

Figure 2. UoA Science Centre Building B302

3.2 University of Auckland – Faculty of Engineering Extension – B403/B404

The Faculty of Engineering is located on the corner of Grafton Road and Symonds Street on the University of Auckland Central City Campus. The existing School of Engineering Buildings B403 and B404 are four level reinforced concrete structures. The proposed extension comprises an additional six new lightweight stories be built above the existing.

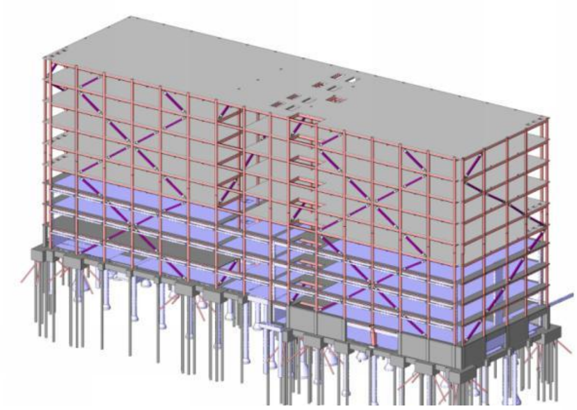

Figure 3. UoA Engineering School Building

The proposed structure is an exosketetal steel frame with BRB bracing, erected on the outside of the existing building envelope supporting the vertical and lateral loads of the new floors above. The gravity structure consists of steel primary beams spanning 6.2m, with partial-composite long-span cellular secondary beams at 3.1m centres spanning 12.2m and 13.4m, with a 140-thick composite reinforced-concrete metal decking. Like the proposed Science Centre Tower, the cellular beams have been designed as partial-composite members, as a layer of visco-elastic material has been used over half the span to provide additional damping to the floor system.

4. Design Assumptions / Considerations for Science Centre Building B302

Vibration issues arising from using long-span composite steel beams can often be minimised and mitigated, if the resulting issues are identified early in the design process. Early identification of factors contributing to a lively floor enables the Design Team to consider mitigation measures that can be easily incorporated into the design development.

The following items were encountered and considered during the design of the University of Auckland Science Centre project:

4.1 Floor Span and Structural Set-Out

The frequency of a floor system is directly related to its stiffness. The stiffness of the structure is inversely related to its span. Therefore, as the span of the floor or supporting beams increase, the stiffness decreases, creating a livelier floor. By providing a floor system and supporting structure that is not too slender for the required spans, vibration characteristics of the system can be controlled.

The University has a requirement to provide large clear-span spaces free of columns, to maximise efficiency of interior room layouts, and provide flexibility for future space planning layout changes to meet changing User Group needs. The existing building structural layout with columns at a grid spacing of 6.2m by 13.4m and 14.8m, provides architecturally efficient space planning and enables re-use of existing building foundations; but led to an inherently flexible structural system using steel structure.

Alternative grid options with additional columns, to reduce beam spans and stiffen the floor system, were investigated at an early stage. The alternative grid layouts resulted in a cheaper structure solution, with better vibration performance, however, the University decided that the reduction in space planning flexibility associated with these alternative layouts out-weighted the reduced cost and improved vibration performance.

Floor penetrations and atrium voids create areas of structural discontinuity, but are aesthetically pleasing. There are three main atrium void configurations up the height of the building. The vibration performance of the floor adjacent to the voids is found to be more sensitive than areas away from the voids. Special consideration of the vibration response of cantilevered balcony slabs and backspan beams at the atriums was required.

4.2 Floor Mass (Modal Mass Participation)

The amount of mass associated with a floor plate affects its vibration response. The mass used in the vibration analysis needs to accurately represent the mass actually present. For vibration assessment, the un-factored self-weight of the structure, plus super-imposed dead loads of items actually present (such as ceilings, floor covering, services etc.), plus a nominal 10% allowance for imposed live loads is recommended.

Adding mass to the floor system can reduce vibration response. For the Science Centre, the structure needs to be kept as light as possible so as not to overload the retained existing foundations, from the additional 10 floor levels. A 140-thick ComFlor60 profile metal decking was adopted given its long-span capability, and low mass properties.

4.3 Damping

The amount of damping assessed to be provided in the end state can considerably affect the final results of the vibration analysis. Guidelines are provided for the amount of damping that a given structural system and fit-out may provide; see Table 1, extracted from P354[1], below:

ζ	**Floor finishes**
0.5%	for fully welded steel structures, e.g. 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 that partitions will be appropriately located to interrupt the relevant mode(s) of vibration (i.e. the partition lines are perpendicular to the main vibrating elements of the critical mode shape).

Table 1. Critical Damping Ratios for Various Floor Types[1]

However, the actual amount of damping present may vary during the life of the building. The additional damping provided by fit-out (such as services, partitions, suspended ceilings, furniture and fixtures) may be reduced by future fit-out changes.

On the University projects, the level of damping provided by the base structure and limited architectural finishes was assumed to be 2%. To provide a long-term dependable level of damping, a viscoelastic layer (*Resotec*) was provided between the cellular beams top flange and concrete slab. The *Resotec* provides an additional 2% damping, regardless of the level of internal fit-out. The 'Base Case' for the vibration analysis of the structure therefore assumed a total of 4% damping.

4.4 Support/Restraint Conditions

For the purposes of floor vibration response, the beams can be assumed to be fixed-end restrained at interior supports, even if a nominal structural pin connection is provided, as the strains in the floor system induced during vibration are not large enough to overcome the frictional forces in the joints.

Vertical restraint is also applied to the floor by the façade connections at each floor slab around the perimeter of the building and balustrading around the perimeter of the atriums. Sensitivity of this assumption was checked by modelling the façade elements and the balustrades in a Finite Element (FE) model. Pinned vertical supports were modelled for these elements.

4.5 Effect of Partitions

Internal partitions provide a mechanism to interrupt the vibration response of a floor. The partitions can behave in one of two ways, depending on their detailing and connectivity. An internal partition wall that spans from a given floor to the floor above, with direct connection, will connect the floor slabs together and act to reduce vibration by mobilising the mass of both floors. An internal partition that does not connect directly to the floor above, but rather stops at the suspended ceiling will increase the damping to the floor.

To demonstrate what the system can achieve (as a minimum), a bare floor has been analysed, and this is considered as the 'Base Case'. This would be applicable, should open-plan layouts of the floor be required. A case modelling the variable effect of partitions proposed was considered and it was found that the partition walls significantly improved the floor vibration response.

4.6 Excitation

The response of a floor system differs across its width. Nodal lines form at stiff areas such as column and beam lines, and these areas will be less responsive than areas in the middle of the slab and beam. The excitation point and response point will generally produce the maximum effect when they are in the same location. In reality, these two points are not always going to coincide.

By considering the location, length and continuity of corridors and walking paths, the effect of the response generated can be controlled. The longer the walking path, the higher the dose of vibration that will be transmitted to other floor areas. By breaking up the walking paths or corridors into discrete lengths, the duration of continuous walking activity will reduce, and the dose of vibration will consequently decrease.

SCI P354[1] recommends that the 'average' mass for a human being, and hence, the assumed mass for the applied footfall source, is 76kg. This document also recommends a walking frequency of 1.8-2.2Hz to be used during design; these excitation masses and frequencies were used in the analysis of the University of Auckland projects.

The floors have been independently checked for footfall induced floor vibration, and for vibration response from mechanical plant. Mechanical plant is to be appropriately isolated, either on isolation bearing pads or positioned in areas where it will not cause adverse effect to the building occupants.

4.7 Composite Beam Action

Structural steel beams supporting metal deck floor slabs have the ability for the steel beams to be constructed composite with the concrete floor slab through shear stud connection. This composite shear stud connection significantly increases the stiffness of the support beam, improving the vibration characteristics of the floor system.

Composite design of long-span steel beams is generally required to provide a cost-effective solution to withstand ULS loads for strength and SLS loads for deflection. Although, when minimising the size of the steel beam for strength, this may give rise to susceptibility to dynamic loading, such as footfall induced vibration.

Once vibration is taken into account, there may be a need to increase the minimum beam size to provide additional stiffness. During Preliminary Design of the floor systems, it was found they were relatively lively using an 800mm deep composite cellular beam with 140mm thick ComFlor60 metal decking, if a minimum 2% damping was assumed.

Given that satisfactory vibration performance was not able to be obtained with 2% damping, it was decided to provide additional damping using a visco-elastic material inserted between the slab and steel beam. A proprietary visco-elastic product called *Resotec*, produced in the United Kingdom, developed by Arup Group, and distributed by Richard Lees Steel Decking, was selected. This product is capable of achieving an additional 2% damping when placed over the outer quarter spans of the steel beams. Shear studs are omitted from the Resotec regions and only provided over the middle half of the beam span providing full composite connection over the maximum moment region.

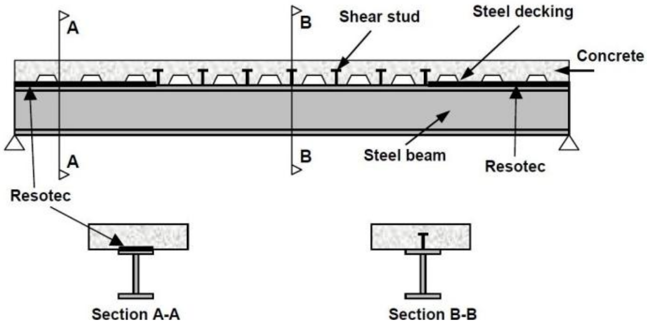

Figure 4. Partially Composite Beam with Resotec Visco-Elastic Layer

4.8 Acceptance Criteria

Consultation with the Client and User Groups of the building has been undertaken to ascertain the required vibration characteristics of the various areas within the building. For example, vibration requirements for a laboratory research space are more stringent than those for an academic office or post-graduate write-up space. Similarly, increased vibration response can be accepted in “active” areas such as public foyers and lobby areas.

To provide a reference datum of the amount of vibration currently experienced and deemed acceptable, various spaces within existing buildings was subject to vibration testing. Testing of existing spaces included measuring modal properties from various dynamic excitations, and data logging of background vibration levels over a 48 hour period. This provided baseline “acceptance criteria” based on existing normal usage, with a reference that was meaningful to the Client and User Groups.

The acceptance criteria finally adopted, as noted in Section 5.2, were based on a combination of the desires of the Client and User Groups, measurement of the vibration response of existing spaces, and guidance from industry documentation such as BS6472[4], SCI P354[1], ASHRAE 2003[6] and ISO2631[7] and published data for various items of research equipment.

4.9 Architectural Considerations

Space planning can affect how much of an issue vibration may be. The distribution of corridors, corridor lengths and relativity of excitation to receptors, will determine the effect of a given walking path. If these walking paths are confined to stiffer areas of floors, such as beam lines and/or columns, then the effect of the walking path can be minimised. The location of receptors to machinery or plant can also determine the effect of a continuous source of vibration. If all plant is confined to say the roof level plant room or basement, and typically there is no human occupancy or the floor is a slab on grade (in the case of the basement), then the effect of this plant will be minimised.

Specific users of a building may have the need to be situated in areas of low response, due to the nature of their work or the equipment they use. If this is the case, rather than trying to employ a solution across the whole floor plate, or even the entire building, it may be possible to situate them in a location that does not respond as much as other areas e.g. on a slab on grade, over a nodal zone, or away from sources or locations of excitation.

4.10 Post Construction Changes

Remedial action once a floor is in service is often challenging and expensive. It may be easier to reconfigure floors, move people or equipment away from vibration sources or walking paths, or alter the timing of the vibration activity, rather than look for intrusive solutions.

If the floor configuration is not able to be altered, then there may be a need to change the response of the floor system. This may be achieved by adding mass to the floor, which is not usually very effective and may affect other structural elements, increasing the stiffness of the floor support members by stiffening beam elements, adding additional columns, providing stiffeners under the floor slab, providing partition wall systems to lower deflections, provide damping mechanisms such as tuned mass dampers or specialist damping materials, or isolating vibration sources by using isolation pads under mechanical plant (etc).

5. Acceptance Criteria for University of Auckland Projects

5.1 Guidelines on Acceptability Limits

Correlation of the physical movement of a floor under excitation to a corresponding acceptance limit is hard to determine. The acceptability of movement is based on human perception, and can be subject to an individual's interpretation, unless quantitative values are assigned. As perception and discomfort can vary between humans, current standards propose criteria that will attract a 'low probability' of adverse comment. Research has been carried out to assess the effect of human response to vibration, and is captured in a number of international standards. Documents such as BS 6472:1992, BS 6841, ISO 10137, ISO 2631-1 and ISO 2631-2, cover many environments, and look to express the limits of satisfactory vibration magnitude in relation to a frequency-weighted 'base curve' and series of multiplying factors.

The base curves for vibration represent the threshold of human perception, defined by a 'base value', which is given as a Root Mean Square (RMS) acceleration of 5×10^{-3} ms^{-2} for z-axis vibrations and $3.57\times10^{-3}ms^{-2}$ for x- and y-axis vibrations[8]; see directions of vibration and base curves in figures 5 and 6 below. The base value of acceleration that can be perceived depends on the direction of incidence to the human body, where the z-axis corresponds to the direction of the human spine. As noted above, the x- or y-axis vibration is more easily perceived (has a lower base value for perception). Each of the base curves are increased by a multiplication factor (or Response Factor) depending on the minimum vibration perception deemed to be appropriate for a given environment.

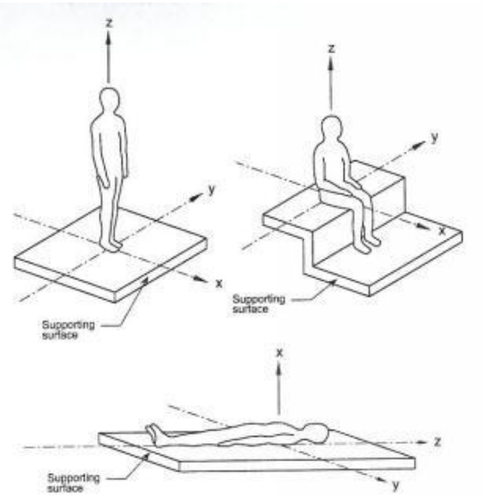

Figure 5. Directions of Vibration Defined in ISO 2631[7] and BS 6472[4]

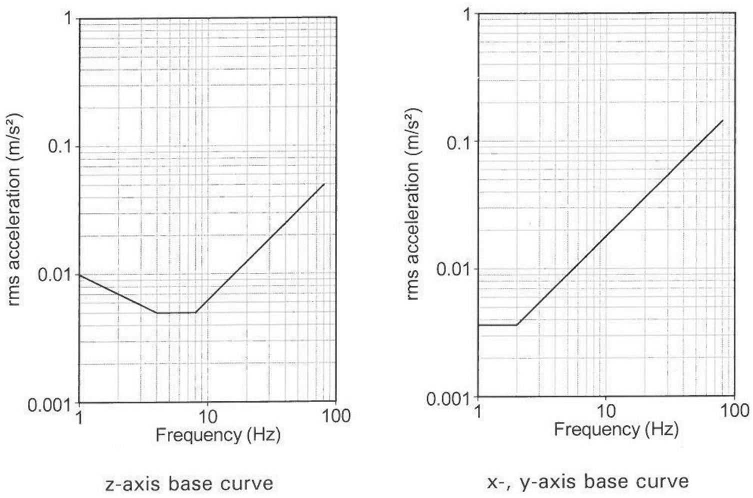

Figure 6. Base Curves for Perception of Vibration, taken from BS 6472[4]

5.2 Adopted Acceptance Criteria

The following tables indicate the proposed acceptance criteria that were established through consultation with the Client and User Groups, and rationalisation based on testing carried out in occupied spaces. This criterion has been established to attract a 'low probability' of adverse comment during use of the various spaces in the building. Vibration sensitive machines have been positioned on stiffer parts of the floor, and may have independent isolators, to prevent adverse effect. Mechanical plant that could cause adverse excitation will be isolated and/or positioned in the basement or plant levels to minimise effects.

Description of Use / Occupancy of Area BBN Curve [Note 1]	Suggested "Target" Response factor "R"	Suggested Theoretical predicted "R" (Max peak) [Note 2]
Mechanical Plant Space / Plantroom	**8**	**10**
Public Circulation Area (no long term seating)	**6**	**7.5**
Atrium Meeting / Break-out Spaces. Seating with nearby walking movements	**5**	**6.5**
Academic Office	**4**	**5**
PGR Office / Write-up Space	**4**	**5**
Computer Laboratory / Teaching Space	**4**	**5**
General Post-Grad Research Laboratory Space	**4**	**5**
"Sensitive locations" within building e.g. Sensitive equipment zones in Research Laboratory Space	**2**	**2.5**

Notes:

1. BBN Classification from “The Control of Vibration in Buildings” – BBN Laboratories, Cambridge MA, 1988 by C.Gordon.
2. Beca estimate of “target” for Max. Peak values predicted by OASYS GSA Finite Element Program (assumed 25% increase on ISO2631 criteria).

Table 2. University of Auckland Science Centre Adopted Vibration Criteria

6. Vibration Analysis of B302

6.1 Footfall Induced Vibration Modelling used on B302 Science Centre

Dynamic response of the floor structure was highlighted as an issue at the early stages of the project, due to the grid spacing of columns and lightweight structure proposed. As the design progressed it became apparent that dynamic response was going to significantly influence the design of the gravity floor support system. A greater degree of certainty of performance and level of analysis was therefore required.

Preliminary design of the structure was first analysed using the proprietary Fabsec and CellBeam software programs. This was verified using the Hera NZ Floor Vibration Analysis Program version 2 Microsoft Excel Spreadsheet and a hand-check using the guidance of SCI P354[1]. This confirmed that a more in-depth analysis was required, and a Finite Element (FE) model was created using Oasys GSA[9] Software, to model the floor plates in 3D.

Vibration analysis was completed under the guidance of SCI Publication P354, 2007. Two different methods of analysis were evaluated, with the first being a conservative hand-calculation estimate. It was found that the peak response of the floor system was in excess of the prescribed maximum for the given workspace.

The P354 refined approach is to assess the floor system using Finite Element (FE) modelling. FE modelling takes a continuous structure and breaks it up into a number of discrete elements. The relationship between these elements are then determined using methods for multi-degree-of-freedom discrete systems. Oasys GSA software[9], developed by Arup, was used to model the floor system. Three typical levels of the Science Centre Tower were assessed; Levels 2, 5 and 7 (the other floors are similar in nature to these). Floor vibration was measured in terms of a Response Factor, R. Response evaluated in Oasys GSA reported values were then evaluated as peak, average and point values. The peak value represents the absolute maximum response factor of the floor given its chosen parameters. The average response factor represents a mean peak value across the floor. The point value evaluates a chosen point on the floor which is the same location for each output, used to compare the response to the variables evaluated.

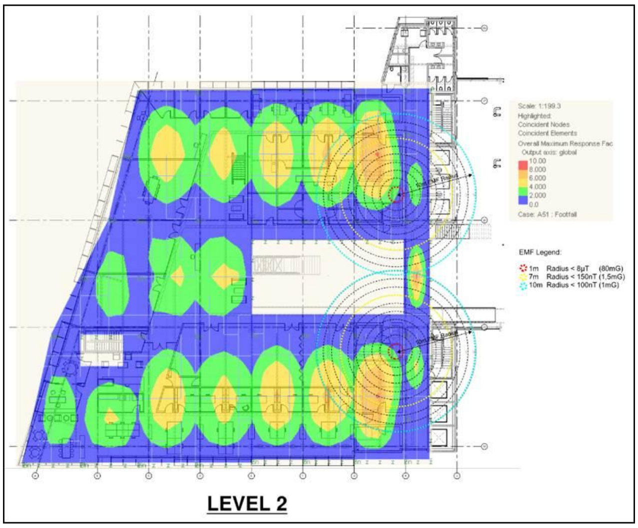

Figure 7. Typical Base case plot for Level 2

6.2 Variables used during modelling and their effect

A ‘Base Case’ was established for each floor, which had an assumed “worst-case” damping value of 4% for a bare floor. The 4% comprised a 2% allowance for the floor system itself (reinforced concrete, reinforced steel deck system, and steel beams) with no partitions or furniture, and 2% accounting for the *Resotec* visco-elastic damping layer provided. As outlined in Section 4.4, façade restraint to the perimeter of the structure and balustrade restraint to the atrium areas was applied. From this base case, a number of independent and concurrent variables were examined to determine their effect on vibration performance.

The following variables were assessed:

6.2.1 Floor Beam Stiffeners

Tertiary 200UB floor stiffeners were placed perpendicular to the castellated beams at mid-span, to mobilise more mass at the location of maximum response. This had a positive effect on reducing the floor response by an R factor of about 0.3 to 0.4. This solution was incorporated into the design to provide acceptable response at atrium areas.

6.2.2 Increased Damping

An increased level of damping of 5% and 6% was analysed to evaluate the effectiveness of an inaccuracy in the estimate of the actual damping available. The level of damping that may be available could increase in a number of ways, including, the actual inherent damping from the floor system, from furnishings, fixtures and services, or from superior performance from the visco-elastic material (Resotec) to that assumed.

From test results from the AUT-WG building (which has a floor system similar to the proposed new structure), it was found that the damping from a bare floor was 2.2%. This provided validation to the estimated 2%. From the proposed architectural layouts, furnishings are indicated in all areas, and there is no current requirement for whole-floor open plan spaces. The presence of fixtures and furnishings could potentially increase the damping available by 1 to 2% from the minimum 4% base case assumption.

6.2.3 Internal Partition Walls

As noted in Section 4.5, internal partitions can have a positive effect by significantly reducing floor vibration response. Sensitivity analysis led us to model the internal partition walls, by creating an element with the same effective stiffness as a 100mm wide timber stud wall with a single layer of gib-board either side. This was deemed appropriate over a blanket increase in damping value applied to the whole floor. An allowance for doorways was made, by not modelling partitions at these locations. Modelling partition walls reduced the floor response to vibration by a reduction in R factor of 2 to 4, depending on the extent of partition and base level of damping assumed. The Client was advised that this improved response might be lost should open plan office layouts be adopted in the future or the full height corridor walls be removed.

6.2.4 Deeper Secondary Beams

Use of a deeper castellated beam was analysed to determine the cost-effectiveness and change in dynamic response. A 900mm deep member was designed and modelled, in lieu of the 800mm deep sections .It was found that the reduction in response was minor with an R value reduction of only 0.1.

6.2.5 Increased Floor Slab Mass

An increase in modal mass has been proven to reduce floor vibration response. A 140Comflor60 deck was assumed as the 'Base Case' floor system. It was found that by changing the floor slab system to a 140-flat deck profile, a 25% increase in slab mass can be achieved. The increased modal mass reduced the floor vibration response, with a reduction of R=2.6. However, the cost associated with increased floor mass is not just the cost of the concrete itself. The additional demand placed on beams, columns, foundations and lateral bracing system meant that this solution was not deemed acceptable.

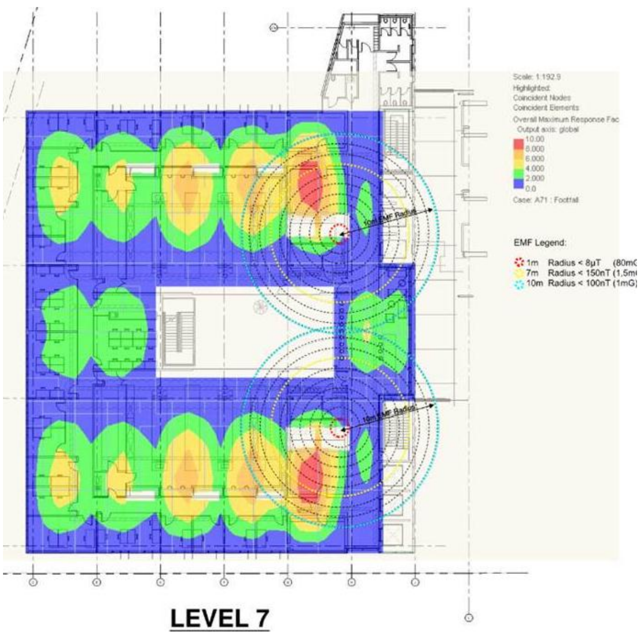

Figure 8. UoA B302 Base Case, No Partitions, Resotec, 4% Damping

Figure 9. UoA B302 Partitions Modeled, Resotec, 4% Damping

6.2.6 Other factors

Other factors to be considered include:

Location of excitation has been assumed to be in the worst place for a receiver placed anywhere on the floor. There are defined walking paths, dictated by the corridors and furniture layouts, and this beneficial effect has not been taken account of in the general analysis, but was used when considering the performance of localised specialist areas.

The nature of footfall induced vibration is that the excitation is intermittent. In the FE models created, excitation has been considered as continuous, and therefore the maximum response experienced by a receiver would be sporadic, rather than constant. This may affect the users perception of vibration, and as a result, the users may be more accepting of occasional higher vibration response.

6.3 Viscoelastic Damping Layer

As noted above the use of viscoelastic materials is a simple method of increasing the damping properties of a slab at the time of construction. *Resotec* is an example of a commercially available product. The Resotec system improves the dynamic performance of composite floors by dissipating energy through shearing of the viscoelastic damping layer during low-level vibrations[10]. Viscoelastic materials used in this application are up to 3mm thick, consisting of the polymer sandwiched in between two thin steel plates. At the location of application, composite connection is lost between the steel beam and reinforced concrete, as there can be no direct connection between the two surfaces to allow the viscoelastic layer to undergo shear deformation.

6.4 Vibration Dose Values [VDV's]

The nature of footfall induced floor vibration is that the excitation is not likely to be continuous, but rather, intermittent[11]. A cumulative measure of this intermittent response can be calculated and benchmarked against the acceptable tolerance level. The Vibration Dose Value (VDV) measures the level of human perception due to specified occasional vibrations for short durations e.g. a person or a group of people walking down a hallway.

The analysis of VDV for the Science Centre assumed a peak response factor for continuous vibration of R=9.4, which is the highest resulting response factor from the analysed 'Base Case'. The analysis results showed that in order to achieve a low probability of adverse comment, any hallway in the building should not be traversed more than 111 times in an hour by an individual person, or group of people. Given the current architectural layout and building usage, this is unlikely to occur.

7. On-Site Testing and Validation of Theoretical Analysis of University of Auckland Projects

To determine floor vibration acceptance criteria and to validate the theoretical analysis of the new floors, it was decided to test and analyse several existing floors which were either; of the same construction as the proposed new floor system, or, were floors housing similar users to the intended use. The purpose of the testing was for the Client to be able to physically experience the vibration response of various floors so they could have a physical understanding of the different "R" values.

Nine floors across four buildings were tested, providing a representative sample for the proposed structure and end use of the new Science Centre and Engineering School buildings. The four buildings tested were:

- The existing B301 Chemistry Research Building, occupied by staff and students that would end up in the new B302 building. This provided an ability to benchmark the vibration response and damping achieved in their existing work areas. The structure is a reinforced concrete frame supporting precast concrete floors. Floor spans and frame centres at 6m to 8m are considerablyu less than the new B302 building.
- The UoA School of Engineering Buildings 403/404, again, occupied by staff and students that would end up in the new building extension. The existing structure is reinforced concrete frames supporting precast concrete floors, which has a different vibration response to the proposed new steel frame structure.
- The UoA Property Services Building which is a 1980's era building constructed from steel beams and composite metal decking. The Client occupies this building and considers the floors to be "fairly lively". The purpose of testing was to compare the actual performance of these existing floors to the predicted performance of the B302 Science Centre which has significantly larger floor spans.
- The Auckland University of Technology WG Building, which has a structural layout similar to the proposed new buildings. These similarities include: steel beam spans, composite floor construction, steel beam spacing and the use of cellular beams. This building has a mixed office and circulation type usage, which is similar to some areas of the proposed Science Centre building. Due to the similar nature of the structure this provided the Client the ability to see and feel what a similar end product could potentially be like. Testing was aimed at analyzing the level of vibrations felt, and damping achieved on a floor with

similar structure to the proposed new buildings. Different levels of fit-out and furnishing on each of the three levels gave a representative result of the different damping that is achievable.

7.1 Vibration Testing and Data Logging

Vibration testing was undertaken to provide information in relation to the dynamic performance of each slab, to quantify the modal properties of the structure, and to measure the response of the slab to a person walking on the floor. These properties were required to assess the inherent properties of the structure, to understand the environment that the Users are currently used to, to establish the actual amount of damping that may be achieved out of the structure, and to give the Client the ability to quantify what a physical floor vibration and proposed acceptance limit response value actually correspond to.

Each floor was subject to a combination of up to three different types of tests, depending on the desired results:

- Accelerations under normal operating conditions
- Accelerations under controlled walking
- Dynamic testing, in order to determine the level of damping and their natural frequencies

Damping of the modes, modal frequencies, and critical walking frequencies likely to induce resonance were calculated. A controlled walking test was undertaken, using a metronome to set the gait and an accelerometer to record the time history of the walk. Where required, vibration data loggers were placed for a period of 48 hours, to measure accelerations experienced under normal operating conditions. The data was extracted and plotted, and a response factor for the given use of the space was calculated.

7.2 Theoretical vs. Measured Floor Vibration Results

An FE model of the AUT-WG floor plates tested was created to determine the correlation between analytical prediction and measured floor vibration results.

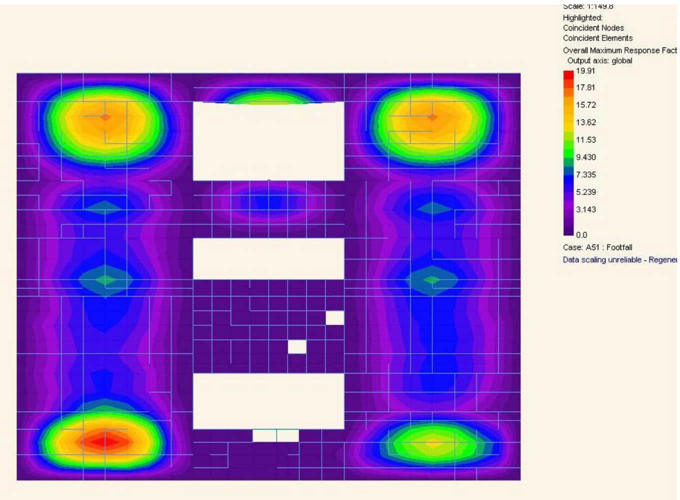

Figure 10. AUT-WG FE Model output

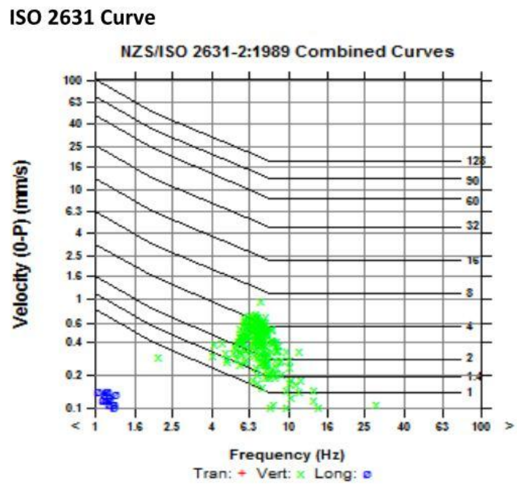

Figure 11. AUT-WG Testing Response output

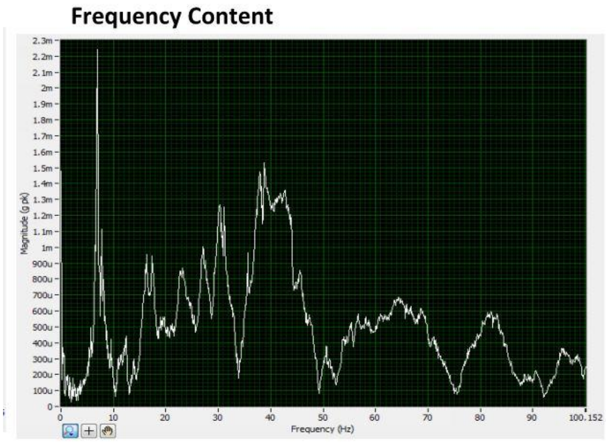

Figure 11. AUT-WG Testing Frequency output

Figure 12. AUT-WG Measurement location photo

Assumptions made in the OASYS GSA model included columns and walls fixed at mid-height between the floor of concern and the floor above and below. Major penetrations modeled, including penetrations for lifts, stairs, escalators and service risers. Restraints for façades, balustrades and atrium walls have been used and all other items have been considered as variables. The variables which were found to provide the greatest amount of effect on the overall response of the floor is the provision of full-height and partial-height partitions, and floor damping.

The OASYS GSA analytical models of AUT indicated a maximum vibration response value of R=19.9. This compares to measured response values in the range of R= 10 to R = 6. There is a poor correlation between the measured response values and the analytical prediction.

The discrepancy between analytical and measured results can be attributed to a variety of factors, including;

- Variations in analytical modeling assumptions such as "effective" span of floor beams, effect of partitions, damping, restraint conditions, stiffness assumptions of supporting elements, variation between analytical 76kg walker excitation force and pace frequency compared to actual etc.
- Excitation of the slab during on site testing may not have the receiver in the worst place for the given excitation, but rather a convenient location for testing. Oasys GSA excites the slab from all locations across the floor plate and provides a contour plot of response values, which gives the maximum response value for each receiver location with the excitation (walker) in the worst place. The analytical model therefore provides a floor response corresponding to a worst case location for the receiver (occupant) at each location for the worst case walking path in the critical location. The site measured walking path and position of receiver may not correspond to the above "worst" case.
- Damping reported by site measurements is specific to a mode, while Oasys GSA evaluates all modes of vibration.
- Various levels of construction material were scattered over the floors during on-site measurement, which may affect the mode shapes and provide varied levels of damping during testing.

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