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Footfall vibration analysis of a high precision manufacturing facility

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ABSTRACT

High tech manufacturing facilities often have specific requirements regarding vibration of floor structures to ensure precision manufacturing is not compromised by vibration induced displacement of components. This paper outlines the design methodology used to mitigate footfall-induced vibration in one such proposed facility. The vibration design process involved an on-site assessment of a similar existing building within the facility to determine the response of typical spans (elevated or on grade) to footfall excitation. Finite element modelling and analyses of proposed constructions were then conducted. The results of this study allowed for floor constructions meeting the specified ASHRAE Vibration Criteria to be accurately determined and priced during the concept stage of the project.

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1. INTRODUCTION

This paper outlines the experimental and numerical modelling methodology used to mitigate footfall vibration in a proposed high precision manufacturing facility. The project brief for the facility required specific vibration design and costing options. A vibration survey of a similar existing facility was undertaken to assess the impact of multiple vibration sources, including external vehicular movements, HVAC plant, and footfall. In order to facilitate structural design for vibration mitigation and costing, finite element modelling was conducting using the General Structural Analysis (GSA) package. Dynamic analysis was performed, including footfall excitation analysis, using the methodology outlined by The Concrete Centre (4). Several structural configurations meeting various vibration criteria were designed and costed, with the final structural design incorporating ground stiffness obtained from geotechnical survey and modelling.

1.1 Project Summary

The project involved construction of a new manufacturing facility to produce high precision electronic components. The proposed 3-storey manufacturing facility included a floor area of approximately 42,000 m^2, with manufacturing spaces and clean rooms on all floors. The proposed site was close to an existing manufacturing facility of the same function.

The project brief required a cost study to be conducted on various structural configurations, with each floor meeting specific vibration criteria, selected from the ASHRAE Vibration Criteria (VC) (1) as shown in Table 1.

Table 1 – Project brief ASHRAE Vibration Criteria options

	Configuration			
	1	2	3	4
Ground floor	VC-D	VC-D	VC-D	VC-D
1st floor	VC-D	VC-D	VC-D	VC-C
2nd floor	VC-D	VC-D	VC-C	VC-B
3rd floor	VC-D	VC-C	VC-B	VC-B

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2. VIBRATION CRITERIA

Common vibration criteria for sensitive equipment and human perception specify vibration limits in terms of Root Mean Square (RMS) velocity. Table 2 presents the ASHRAE Vibration Criteria (1) which outline vibration limits for sensitive equipment. The ISO 2631 (2) Operating Theatre (Base Curve) criterion has also been included. The various criteria curves can be described by the response factor, R, which is a multiplication factor of the ISO Base Curve (R=1).

Table 2 – Vibration criteria and descriptions (4)

Criterion Curve	Max Level µm/s, RMS*	Detail size microns**	Description of Use
Operating theatre (ISO) Base Curve R=1	100	25	Vibration not perceptible. Suitable for sensitive sleep areas. Suitable in most instances for microscopes to 100X and for other equipment of low sensitivity.
VC-A (ASHRAE) R=0.5	50	8	Adequate in most instances for optical microscopes to 400X, microbalances, optical balances, proximity and projection aligners, etc.
VC-B (ASHRAE) R=0.25	25	3	An appropriate standard for optical microscopes to 1000X, inspection and lithography equipment (including steppers) to 3 micron line widths.
VC-C (ASHRAE) R=0.125	12.5	1	Standard for most lithography and inspection equipment to 1 micron detail size.
VC-D (ASHRAE) R=0.0625	6	0.3	Suitable in most instances for the most demanding equipment including electron microscopes (TEMs and SEMs) and E-Beam systems, operating to the limits of their capability.
VC-E (ASHRAE) R=0.03125	3	0.1	A difficult criterion to achieve in most instances. Assumed to be adequate for the most demanding of sensitive systems including long path, laser-based, small target systems and other systems requiring extraordinary dynamic stability

*As measured in one-third octave bands of frequency over the frequency range 8 to 100 Hz

**The detail size refers to the line widths for microelectronics fabrication, the particle (cell) size for medical and pharmaceutical research, etc. The values given take into account the observation that the vibration requirements of many items depend upon the detail size of the process

3. VIBRATION SURVEY

A vibration survey was conducted on areas of the existing manufacturing facility adjacent to the proposed facility site. The existing facility served a similar purpose to the proposed facility, containing manufacturing areas and clean rooms across multiple levels. All likely sources of vibration, including footfall, plant, lab equipment, and nearby vehicular traffic were considered as part of the vibration survey.

3.1 Characterising vibration

In order to characterise the existing vibration conditions of the proposed development site, measurements of ambient vibration were performed. High-sensitivity accelerometers and a portable spectrum analyser were used to carry out the measurements. Baseline outdoor ambient ground vibrations due to nearby road traffic movements (heavy vehicle pass-bys etc.) and background conditions (i.e. without traffic pass-by) were recorded. The ambient vibration survey was used to evaluate site suitability and preferred setbacks for the facility from a planning perspective.

Vibration sources inside the facility were next considered, with HVAC systems and footfall identified as the major sources of vibration. To assess the vibration impact of HVAC systems, ambient indoor facility-wide vibration measurements were undertaken with major base-building HVAC systems operating. Testing locations were carefully inspected and selected such that they were representative of typical zones within the building. Similarly, footfall vibration was characterized through as-built walk-by tests of operational clean room facilities. For these tests, the vibration response at workstations close to mid-span was simultaneously measured with the slab response. The walk-by tests provided a rapid method of assessing footfall vibration within the sensitive areas of the facility.

The results of the vibration survey identified the sources of the vibration in existing facility and allowed comparison between the existing as-built floor response performance against the design brief requirements of the new facility. Footfall excitation was identified as the primary cause of vibration in the existing facility, with all other sources of vibration negligible relative to the brief vibration requirements.

3.2 Footfall vibration survey

The footfall vibration survey of the existing facility was conducted at two critical areas. The first area (Area A) was on the Ground Floor, in a vacant area normally used for manufacturing. This area was critical as VC-D was required for the Ground Floor of the proposed facility. The second area (Area B) was located on the top (3rd) floor, again in an unused manufacturing area. Measurements at this location provided the opportunity to test a typical span. The structure in each of these critical areas is described in Table 3.

Table 3 – Structural configuration of areas surveyed

Area	Span, m	Slab thickness, mm	Primary beam, mm	Primary beam spacing, mm	Secondary beam, mm	Secondary beam spacing, mm
A	7 x 14	300	600 x 1,000	3,500	500 x ,1000	7,000
B	7 x 14	250	500 x 1,200	7,000	300 x 700	14,000

For footfall tests, the accelerometer was positioned at the center of the floor span, and floor vibration measurements were recorded with footfall excitation at different pacing frequencies in a straight line across the span and close to the position of the accelerometer. The footfall vibration survey indicated that the Area A construction comfortably met VC-E (7% exceedance of VC-F), and the Area B construction met the ISO Operating Theatre criterion, noting that Area B exceeded VC-A by 14%. Typical results of the vibration survey are presented in Table 4, with the typical response with frequency shown in Figure 1.

Table 4 – Footfall vibration survey results

Area	Floor	Vibration Criterion achieved
A	Ground floor	VC-E (exceeds VC-F by 7%)
B	Fourth floor	ISO Operating Theatre (exceeds VC-A by 14%)

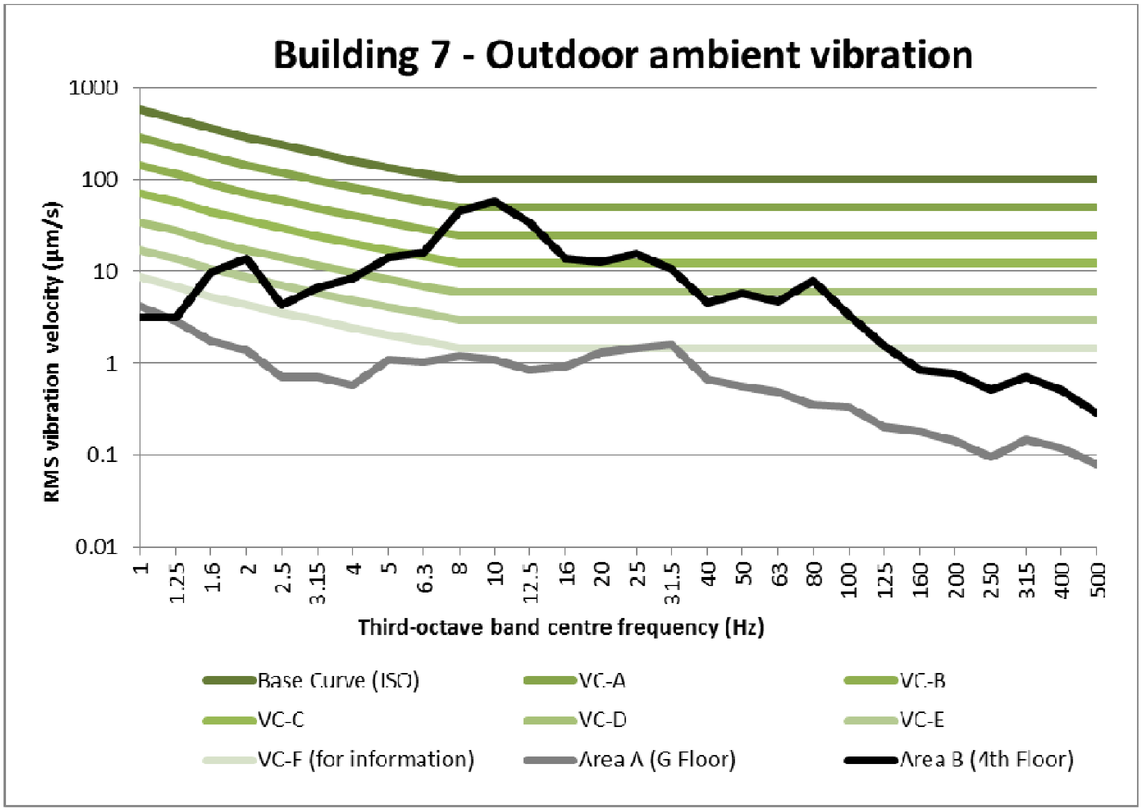

Figure 1 – Typical frequency content of footfall vibration response

As the design brief required a minimum of VC-B for the upper floors, the existing structural configuration could not be used for the proposed building. The response of the Ground Floor indicated that the existing construction was overdesigned, indicating potential cost savings in the construction of the proposed Ground Floor slab.

4. FINITE ELEMENT MODELLING

In order to assess and cost various structural configurations, Finite Element (FE) modelling was used. This methodology allowed a number of structural configurations to be assessed within the programme and budget of the conceptual design phase of the project.

4.1 Software Description

Footfall response modelling was undertaken using the FE package GSA. This package uses the finite element method, with the concrete slab represented by plate elements and two-dimensional members (columns, beams) represented by beam elements. Generation of the numerical mesh was performed manually by element subdivision.

GSA features an eigenvalue solver, allowing for dynamic analysis of structures to be carried out. The resultant natural frequencies and mode shapes are necessary for the calculation of response to dynamic loads, including footfall. GSA also features a footfall response solver based on the Concrete Centre methodology (4), as discussed in Section 4.1.1. This solver automates the response calculation process, producing response factors which may then be visualized across the structure.

4.1.1 GSA Methodology

GSA separates footfall response into harmonic (resonant) response and impulse response methods. A common feature of both of these methods is the use of empirically determined footfall load factors. The Concrete Institute measured a number of footfall time traces, which were non-dimensionalised by the person's static weight to produce a Dynamic Load Factor (DLF). The design DLF used in the GSA method is the 75th percentile, or DLF with a 25% chance of exceedance. Refer to (4) for a detailed outline of the GSA calculation method, noting that a number of footfall calculation methods are offered within the GSA solver suite.

The acceleration response to harmonic footfall excitation at any location is weighted by the mode shape at both the excitation and response points. There is also an empirical correction factor (with a value of 0 to 1) which accounts for the number of footsteps taken to cross the span, assuming that the walker crosses the span in a straight line through the centre. The calculated accelerations are then normalized by the acceleration of the base curve to calculate a response factor. The response factors are summed for each harmonic of the walking frequency, to produce a total response factor for that walking frequency. Calculations are carried out for several walking frequencies, to identify the maximum response factor.

As aforementioned, GSA uses empirically determined footfall loads. The impulse loads are related to the walking frequency and the natural frequency of the structure. As with harmonic footfall excitation, the response is weighted by the mode shape at both the excitation and response points. The RMS response across all the modes is summed, and normalized by the velocity at the base curve to calculate a response factor.

4.2 Finite Element Model of the Existing Facility

The structural configuration measured in Area B was modelled in GSA, in order to validate the accuracy of GSA and the Concrete Centre footfall methodology. An image of the finite element model (excluding the slab plate elements) is presented in Figure 2, with a contour of the footfall response factor over the slab presented in Figure 3. The maximum calculated response factor was within 25% of the measured value. This level of error was considered suitable for preliminary design and costing purposes.

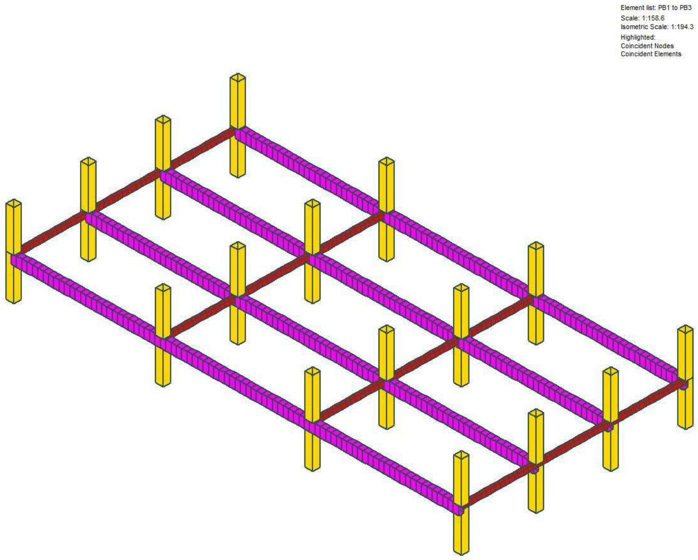

Figure 2 – FE model of existing facility (plate elements not shown)

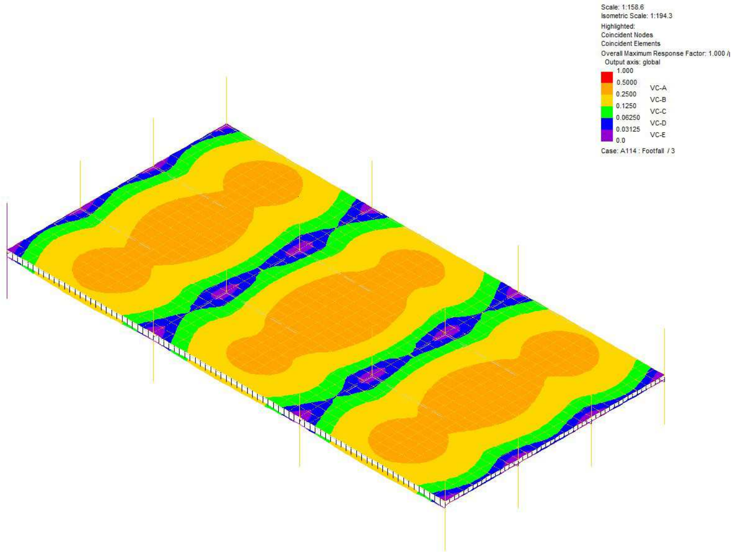

Figure 3 – Footfall response of existing facility

5. APPLICATION TO DESIGN

5.1 Study and Costing of Proposed Structures

The objective of the survey and FE modelling was to provide design and costing advice for the proposed facility at a very early stage. To aid in this process, a number of structural configurations were proposed to the client, each meeting a different ASHRAE Vibration Criterion.

These benchmark structures had a different span than found on the existing building, as such the structural design had to be modelled. A live load of 15 kPa was applied to the entire slab face, representing the weight of manufacturing equipment. This live load was advised in the project brief. A typical FE model of the benchmark structures (excluding the slab) is shown in Figure 4. The benchmark structures included 3 beams, B3 (red), B2 (yellow) and B1 (purple). The mode shape (including plate elements) with the highest mass participation and the footfall response for the below structure are shown in Figure 5 and Figure 6 respectively. The structural configuration of each Vibration Criterion design is presented in Table 5.

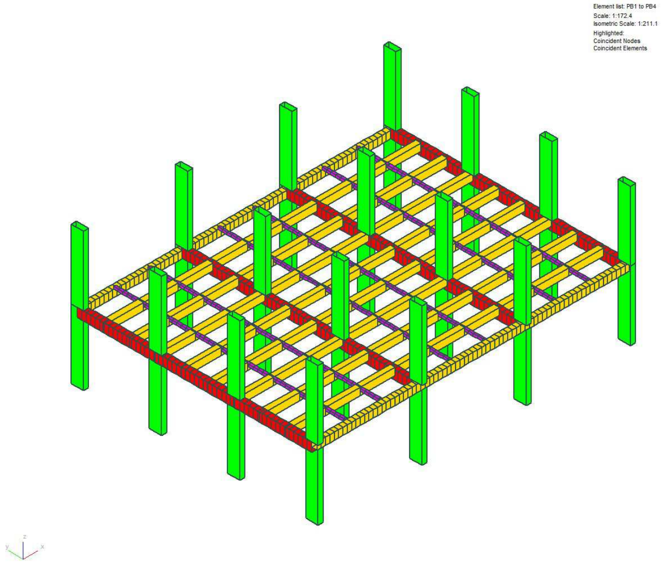

Figure 4 – FE model of typical structure (plate elements not shown)

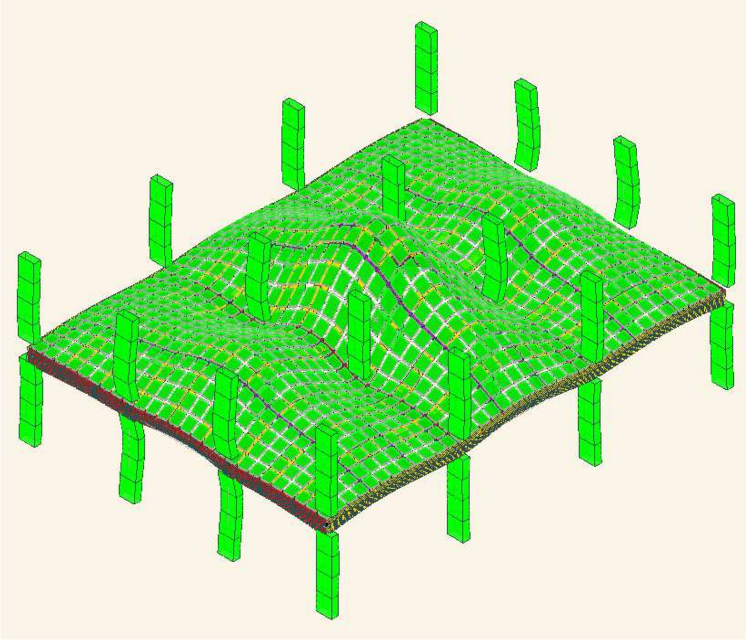

Figure 5 – Typical mode shape (highest mass participation)

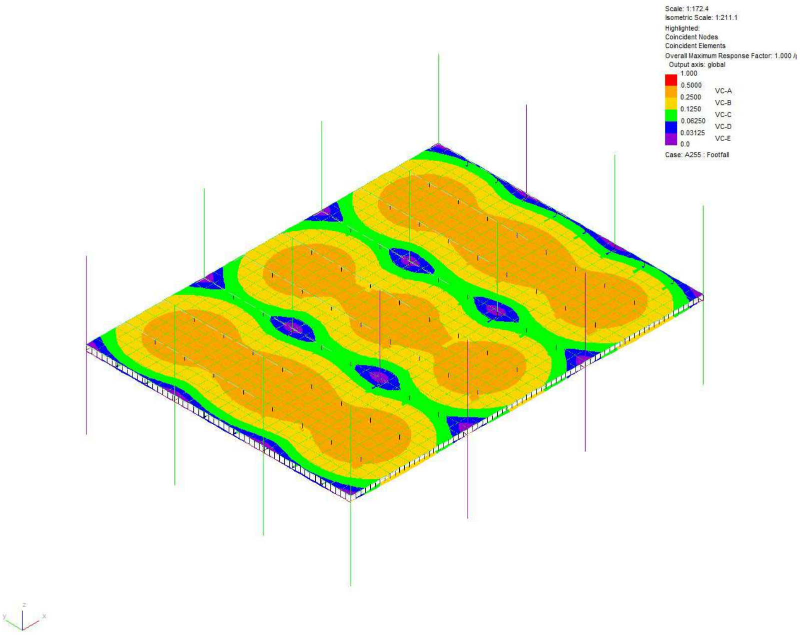

Figure 6 – Footfall response of typical structure

Table 5 – Structural configurations for ASHRAE VC (note that beam depths given are measured from the top of the slab)

Model	Span, m	Slab thickness, mm	B3, mm	B3 spacing, mm	B2, mm	B2 spacing, mm	B1, mm	B1 spacing, mm	Column, mm
VC-A	9 x 12	175	600 x 1,200	1,200	600 x 1,000	3,000	250 x 450	4,000	600 x 1,400
VC-B		300							
VC-C		350			600 x 1,550		250 x 1,175		
VC-D					600 x 1,850	1,500			

From the FE model, preliminary costing of each structural configuration was calculated as presented in Table 6.

Table 6 – Estimated cost of ASHRAE VC compliant structures

Vibration Criterion (9 m x 12 m span)	Cost Ratio
VC-A	1
VC-B	1.15
VC-C	1.33
VC-D	1.52

5.2 Final Design

Based on data detailing the weight of manufacturing equipment it was recommended that the live load be revised down to 10 kPa. The design brief also changed from Structures 1 to 4 as detailed in Table 1 to VC-E for the ground floor and VC-C for all upper floors. Further FE modelling of the proposed designs was therefore necessary.

The FE model of the ground floor required translational and rotational stiffness of the soil to be accounted for. Based on extensive geotechnical investigations on site detailing soil type, properties, and depth, a model of the geotechnical environment was created. This allowed for equivalent soil spring stiffness to be calculated. The properties of the soil are detailed in Table 7. As there was considerable variation in height of the sandy clay layer across the site, the soil stiffness calculations were based on the area with the thickest clay layer after the site cut. This resulted in a conservative stiffness result. Details of the final brief compliant design are provided in Table 8.

Table 7 – Soil properties used for geotechnical modelling

Depth, m	Soil Description	Young's Modulus, MPa	Poisson's Ratio
0 to 2.0	Compacted fill	150	0.5
2.0 to 6.0	Soft to firm sandy clay	7.5	0.5
Below 6.0	Decomposed siltstone/sandstone	Considered incompressible	-

Table 8 – Final structural configuration

Model	Span, m	Slab thickness, mm	B3, mm	B3 spacing, mm	B2, mm	B2 spacing, mm	B1, mm	B1 spacing, mm	Column, mm
VC-C	9 x 12	300	600 x 1,125	12	600 x 1,500	3,000	250 x 1,125	4	600 x 1400
VC-E	9 x 12	300	None. Stiffness provided by ground support.						

6. CONCLUSION

Using experimental and numerical methods, the strict vibration criteria for a proposed high precision manufacturing facility were achieved and costed at an early stage in the design process. A footfall survey was carried out in an existing facility of similar purpose, in order to assess the impact of various vibration sources, including vehicular movements, HVAC plant, and footfall. As footfall was determined to be the vibration source with the highest response, a separate footfall vibration survey was carried out in the existing facility. The finite element package GSA was used, with the Concrete Cnstitute footfall methodology used to assess footfall response of various structural configurations. This methodology allowed for a number of structures to be designed and costed, each meeting a certain ASHRAE Vibration Criterion. The final structural design addressed a change to the project brief, and incorporated ground stiffness obtained through geotechnical survey and modelling.

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