Consultant Advice Note

Job Number:	14934
Project Title:	Victoria Warehouse, Balcony Check
Purpose of Note:	Assessment of Balcony Structure for Vibration
Date:	04 October 2023
Revision:	Rev B.

1 Introduction:

Booth King Partnership Limited have been asked to assess the dynamic behaviour of the balcony at Victoria Warehouse following previous confirmation of its strength and serviceability (refer to BKPL report '*Consultant Advice Note - 230817 Victoria Warehouse balcony check*'.

The balcony structure consists of a simple strut-and-tie cantilever arrangement, with intermediate beams and purlins, and an 8mm checker-plate deck. The balcony provides access to a 'mezzanine' floor with a bar. As defined to BKPL by AMG, the maximum operating capacity of the bar area and balcony is 660 people, with only 250 of these having access to the balcony at any time.

BKPL have not had the benefit of long-term monitoring of the structure, so cannot comment in this regard.

2 Loading

Self-weight of the structure is determined by the FE software (SCIA Engineer 22.1).

The structure has previously been checked for Limit States according to uniform imposed action Sub-category C51 (assembly areas without fixed seating, concert halls, bars and places of worship) of 5.0kN/m^2, specified in Table NA.2 of NA to BS EN 1991-1-1:2002.

For the dynamic analysis, a more representative imposed action is taken from the guidance in SCI P354 (Design of Floors for Vibration: A New Approach).

Section 3.1.3 (Synchronised crowd activities) prescribes an applied loading density of 2.00 persons/m^2 for social dancing activities.

> ***Applied loading density***
>
> It is recommended by Bachmann and Ammann[16] that the crowd density for rhythmic activities should be taken to be:
>
> Aerobic and gymnasium activities = 0.25 persons/m^2
>
> Social dancing activities = 2.00 persons/m^2

Figure 1 – Extract from Section 3.1.3 (SCI P354) Applied Load Density

This equates to 1.492kN/m^2 (with the weight of an average jumper taken as 746N – 12 stone).

Note, this is the closest available approximation as SCI P354 does not prescribe loading for grandstand/stadia – it is, however, very close to the maximum permissible loading on the structure derived from the maximum no. of people allowed on the balcony (250 x 0.746 / 24 / 4 = 1.942kN/m^2).

From a fire safety perspective, Approved Document B of Building Regulations offers a 'Floor Space factor (m^2/person) in Table D.1:

Table D1 Floor space factors[1]

Type of accommodation[2][3]	Floor space factor (m^2/person)
1. Standing spectator areas, bar areas (within 2m of serving point), similar refreshment areas	0.3
2. Amusement arcade, assembly hall (including a general purpose place of assembly), bingo hall, club, crush hall, dance floor or hall, venue for pop concerts and similar events and bar areas without fixed seating	0.5
3. Concourse or queuing area[4]	0.7
4. Committee room, common room, conference room, dining room, licensed betting office (public area), lounge or bar (other than in (1) above), meeting room, reading room, restaurant, staff room or waiting room[5]	1.0
5. Exhibition hall or studio (film, radio, television, recording)	1.5
6. Skating rink	2.0
7. Shop sales area[6]	2.0
8. Art gallery, dormitory, factory production area, museum or workshop	5.0
9. Office	6.0
10. Shop sales area[7]	7.0
11. Kitchen or library	7.0
12. Bedroom or study-bedroom	8.0
13. Bed-sitting room, billiards or snooker room or hall	10.0
14. Storage and warehousing	30.0
15. Car park	Two persons per parking space

NOTES:

1. As an alternative to using the values in the table, the floor space factor may be determined by reference to actual data taken from similar premises. Where appropriate, the data should reflect the average occupant density at a peak trading time of year.
2. Where accommodation is not directly covered by the descriptions given, a reasonable value based on a similar use may be selected.
3. Where any part of the building is to be used for more than one type of accommodation, the most onerous factor(s) should be applied. Where the building contains different types of accommodation, the occupancy of each different area should be calculated using the relevant space factor.
4. For detailed guidance on appropriate floor space factors for concourses in sports grounds refer to *Concourses* published by the Football Licensing Authority.
5. Alternatively the occupant number may be taken as the number of fixed seats provided, if the occupants will normally be seated.
6. Shops excluding those under item 10, but including: supermarkets and department stores (main sales areas), shops for personal services, such as hairdressing, and shops for the delivery or collection of goods for cleaning, repair or other treatment or for members of the public themselves carrying out such cleaning, repair or other treatment.
7. Shops (excluding those in covered shopping complexes but including department stores) trading predominantly in furniture, floor coverings, cycles, prams, large domestic appliances or other bulky goods, or trading on a wholesale self-selection basis (cash and carry).

Items 1. and 2. most correspond to the anticipated loadings for the mezzanine (0.3 and 0.5), with the latter (0.5) corresponding to the anticipated loading of the balcony as prescribed by SCI P354 (2.0 person/m^2 → 0.5 m^2/person) – anything less than this would not allow for exciting the structure due to restricted crowd movement.

The structure is considered restrained horizontally (on the back-span of the cantilever and on either side), therefore horizontal effects are ignored here.

3 Modelling

A full model of the structure is created in SCIA Engineer 22.1, with connections treated as prescribed by SCI P354 for Finite Element models (beam-to-beam/column rigid, column-to-concrete rigid, beam-to-masonry rigid, plate-to-beam pinned).

- All connections should be assumed to be rigid (although joints are designed at ULS to be pinned, in vibration the strains are not large enough to overcome the friction and so pinned joints may be treated as fixed).
- Column sections should be provided and pinned at their theoretical inflexion points (typically located at mid-height between floors for multi-storey construction).
- Continuous cladding provided around façades may be assumed to provide full vertical restraint to perimeter beams. The edges of clad buildings should therefore be modelled as free in rotation but restrained in direction for all three directions of freedom (i.e. pinned).
- Core walls may also be assumed to give vertical restraint. However, at cores the connection of the floor is normally stiff enough to be taken as rigid. The interfaces at cores should therefore be modelled as fully restrained.
- The mass of the floor should be equivalent to the self-weight and other permanent loads, plus a proportion of the imposed loads which might be reasonably expected to be permanent, as described in Section 4.1.2.
- Movement joints may be considered to be rotationally free, though fixed in location. For greater accuracy, the exact transfer of stiffness through the joint may be allowed for by consideration of the deflected form. However, as such transfer is small, it is often inefficient to allow for such detail.

Figure 2 – Extract from Section 6.1.1 (SCI P354) Implementation suggestions (for finite element modelling)

Although a portion of the structure is demarcated as for disabled users, for simplicity, crowd loading is treated as uniform over the extent of the structure.

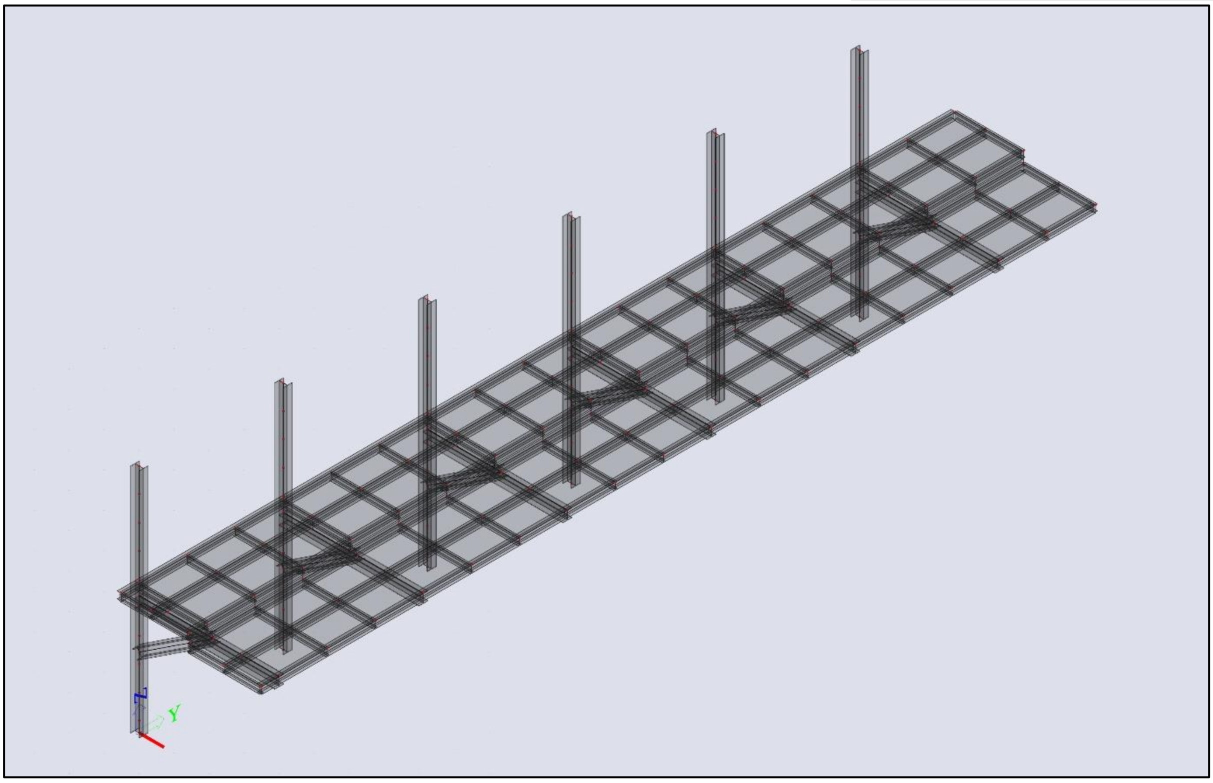

Figure 3 – Cantilever balcony structure (Isometric View)

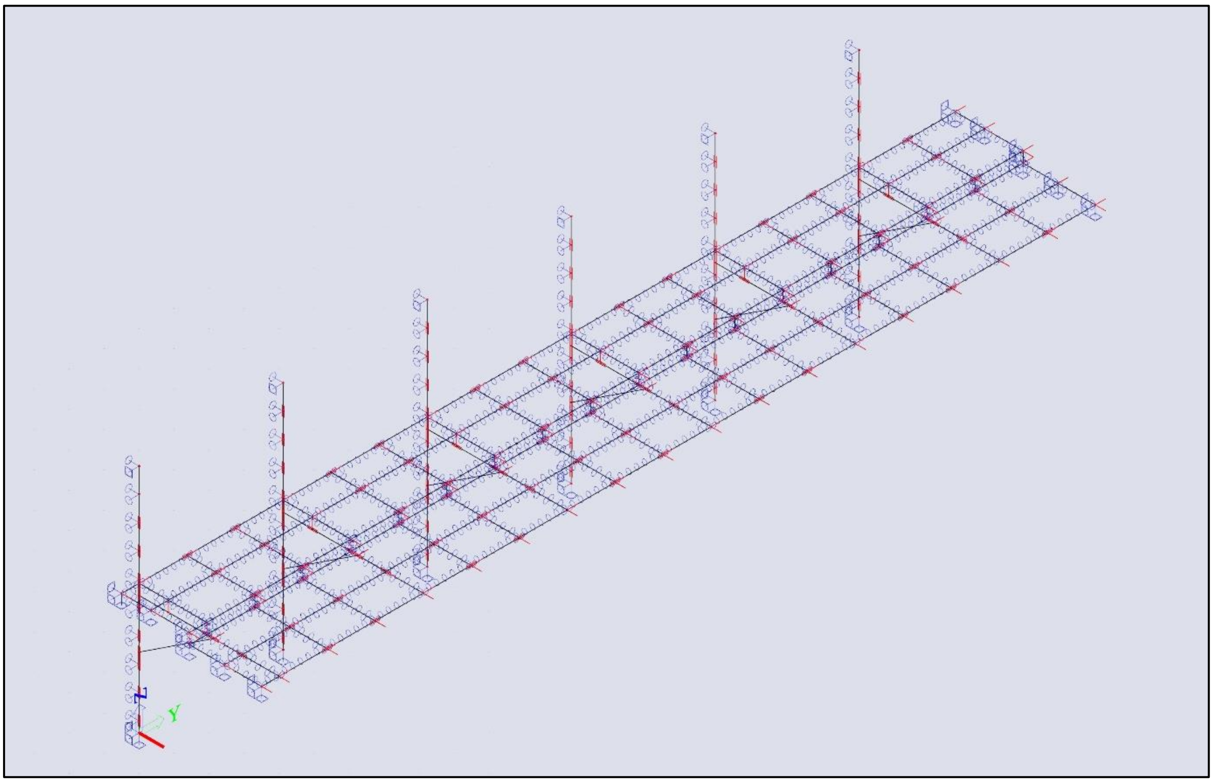

Figure 4 – Cantilever balcony structure (restraints and releases)

4 Analysis

4.1 Dynamic Analysis - Empty Stand

4.1.1. Guidance

Section 3.2 of the IStructE's 'Dynamic performance requirements for permanent grandstands subject to crowd action' identifies the extent of the harmonics to be considered:

3.2 Description of rhythmic loading due to crowd activity

It may be shown that any rhythmic load time history may be represented as the superposition of a number of load components corresponding to integer multiples of the frequency of the basic motion. For example, crowd motion at frequency *f* will lead to load components at *f* (first harmonic, or fundamental frequency), 2*f* (second harmonic), 3*f* (third harmonic) etc. The magnitudes of the components decrease as the harmonic order increases, i.e. the first harmonic (or fundamental) is the largest.

For an individual, the magnitude of the different harmonics increases with the intensity of dynamic activity and whether it involves an 'impacting' motion such as jumping. Rhythmic jumping leads to the highest loads, which include significant components from the third and fourth harmonics[13]. This pattern of loading is somewhat modified when a large number of individuals attempt to jump simultaneously, even when accompanied with a musical beat.

When a group of people moves rhythmically, imperfect co-ordination between the load time histories associated with each person leads to some attenuation of the dynamic load generated by the group. This reduction, in average load per person, is greater for the higher harmonic components so that the third and fourth load harmonics become far less significant for crowd loading than for jumping by an isolated person or a small well-synchronised group. However, it must still be recognised that the ability of a group to act in a co-ordinated manner improves in the presence of an external stimulus of increasing strength, be it aural and/or visual.

Thus, the importance of the higher harmonic load components is believed to increase as the event scenario progresses to increased levels of likely crowd dynamic participation and as the nature of the motion progresses from 'non-impacting' to 'impacting', for example,

- Spectator event with no singing or music played; first harmonic dominant.
- Event with singing, but without musical accompaniment; some influence of second harmonic.
- Event with some audience participation with singing to musical accompaniment but without impacting motion; first and second harmonics significant.
- Dedicated pop or rock concert with audience participation and likelihood of jumping; first and second harmonics very important with the third harmonic becoming influential only if the audience reaction were unusually well synchronised.

Figure 5 – Extract from Section 3.2 (IStructE) Description of rhythmic loading due to crowd activity

The document also further expands on the limiting criteria for determining if a structure provides adequate levels of comfort by determining the natural frequency for the empty stand.

4.3 Pop concerts and their requirements

For structures used for pop concerts and similar events the aim is to avoid resonant excitation at the second harmonic frequency of crowd movement. This is because a strong musical beat will be present so causing crowd action to be both co-ordinated and livelier than if the crowd were to act merely as a collection of quiescent spectators. If the lowest vertical natural frequency is above 6Hz for an empty stand it will be outside the range that can be excited significantly at resonance by the second harmonic loading component. In setting this limit it is considered that higher load harmonics can be disregarded due to the difficulties of achieving sufficient synchronisation of the crowd loading. Besides providing safety from collapse and the onset of panic, grandstands with vertical natural frequencies greater than 6Hz should provide adequate levels of comfort for all but the most extreme pop-concert style excitation.

Figure 6 - Extract from Section 4.3 (IStructE) Pop concerts and their requirements

4.1.2. Modal Analysis

The fundamental frequency for the unloaded balcony is determined using the Modal Analysis function of the Scia software:

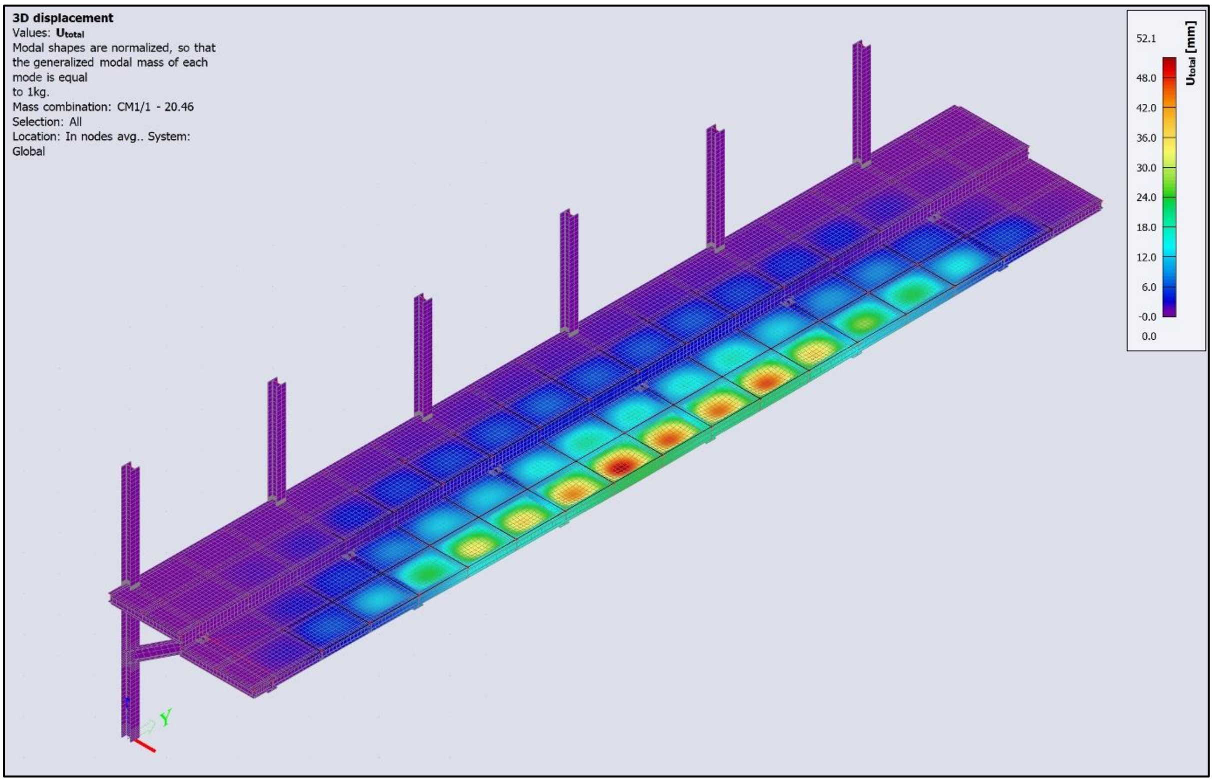

Figure 7 – 3D Deformation of empty structure (First Eigenmode)

Eigen frequencies

N	f [Hz]	ω [1/s]	ω^2 [1/s²]	T [s]
Mass combination : CM1				
1	20.46	128.54	16522.28	0.05
2	21.10	132.60	17582.77	0.05
3	22.09	138.78	19260.46	0.05
4	23.22	145.92	21292.37	0.04
5	24.50	153.94	23696.79	0.04
6	26.04	163.60	26765.91	0.04
7	26.05	163.70	26797.82	0.04
8	26.07	163.80	26830.97	0.04
9	26.08	163.88	26855.58	0.04
10	26.14	164.24	26973.99	0.04

Figure 8 – Eigenfrequencies of empty structure

AT 20.46Hz, the fundamental frequency is well outside the 6Hz value as prescribed by the guidance, therefore the structure exhibits adequate levels of comfort.

4.1.3. Actions

Figures 1 & 2 of the IStructE guidance document also provide a visual guide to determining frequency criteria for assessment and design, and actions required to be taken by management:

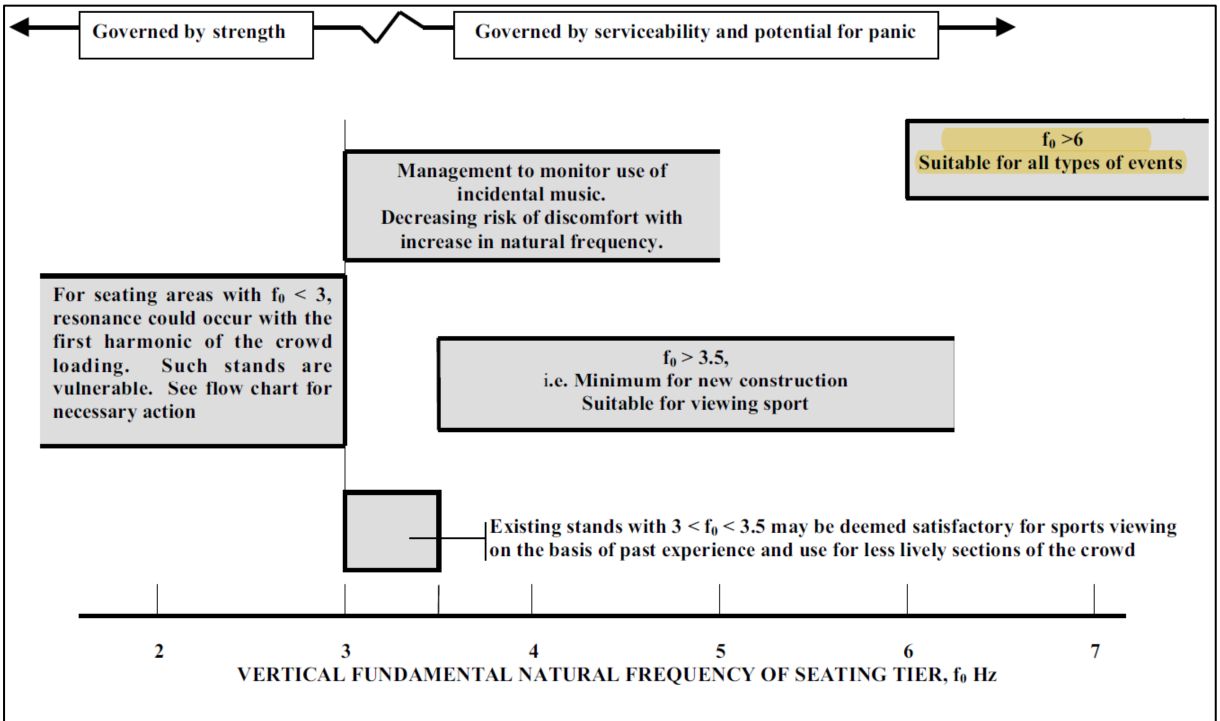

Figure 1 Frequency criteria for assessment and design

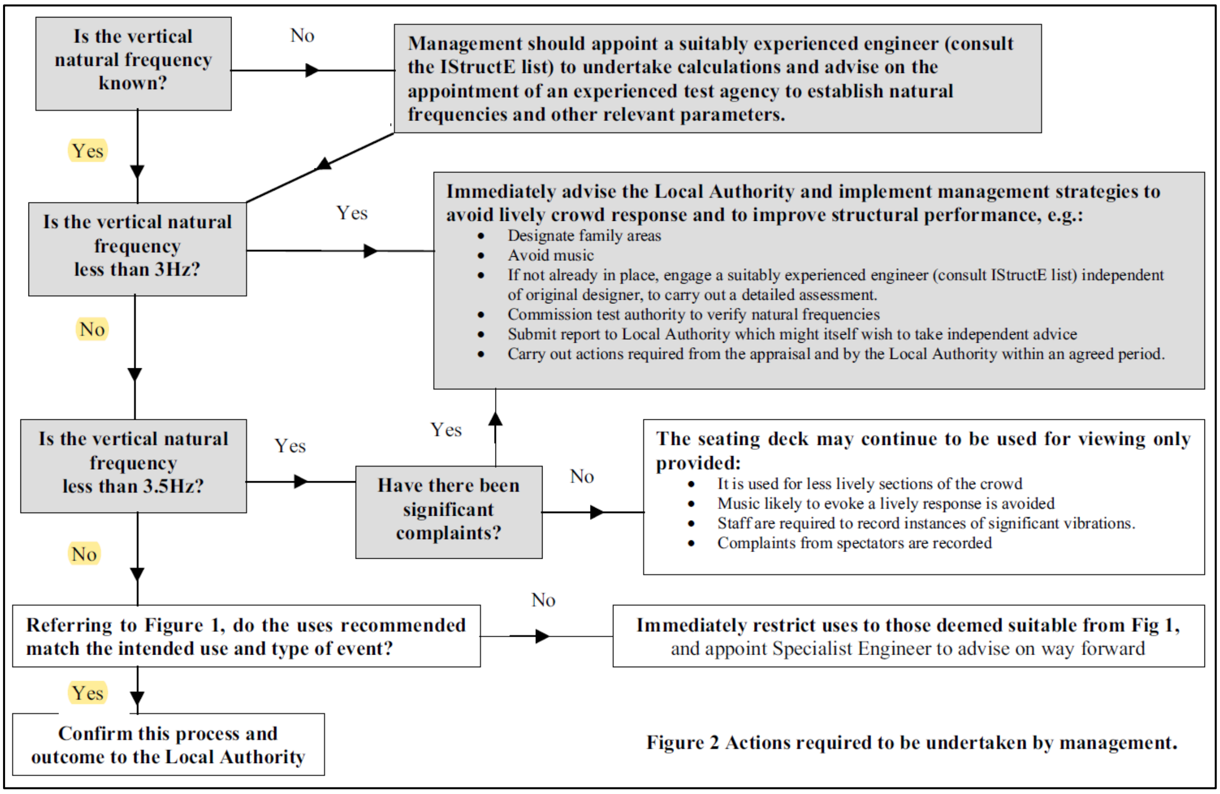

Figure 2 Actions required to be undertaken by management.

4.2 Response Calculation

4.2.1. Guidance

While the modal analysis indicates the compliance of the global structure, an adapted footfall analysis is carried out to determine the response factor as the floor frequency is less than 24Hz.

8.1.3 Floor response

For serviceability considerations, the first six harmonic components given in Table 3.3 should be used to estimate the floor accelerations. If the floor frequency is greater than 24 Hz, then the floor may be considered to be unresponsive for serviceability conditions.

Figure 9 – Extract from Section 8.1.3 (SCI P354) – Floor response

The SCI P354 guidance indicates that consideration is made for both 'steady-state' and 'transient' responses:

6.3 Response analysis

To find the peak response, the following analyses will need to be performed for a range of floor frequencies within the range of walking frequencies (see Section 3.1.1), and the maximum response taken. It should be noted that these methods assume that the force is applied at the most responsive location on the floor even though the walking path will only pass across this point briefly. However, this is a conservative assumption and an analysis based on walking paths, rather than individual points may be taken; this leads to an increased level of complexity. For low frequency floors (where the fundamental frequency is lower than the values given in Table 6.1), both the steady-state response (given in Section 6.3.2) and the transient response (given in Section 6.3.3) need to be checked, as the higher frequencies of the floor may result in the transient response being greater than the steady-state. For high frequency floors only the transient response needs to be checked.

Table 6.1 *Low frequency floor to high frequency floor cut-off*

Floor type	Low to high frequency cut-off
General floors, open plan offices etc.	10Hz
Enclosed spaces, e.g. operating theatre, residential	8Hz
Staircases	12Hz
Floors subject to rhythmic activities	24Hz

Figure 10 – Extract from Section 6.3 (SCI P354) – Response analysis

However, only the steady-state is generally considered for a floor with rhythmic activity.

Although the general response limit for 'floors subject to rhythmic activities' (and the default setting used in the software) is 69.4, there is an amount of interpretation to be considered in the guidance:

> **5.3.4 Rhythmic activities and stadia**
>
> Dynamic crowd loads are generated by the movement of people. The largest loads are produced by synchronised rhythmic movements which mainly arise from people dancing or jumping, usually in response to music. A crowd of people jumping rhythmically can generate large loads and this may be of concern for both safety and serviceability evaluations.
>
> There is no generally agreed acceptance criterion for structures of this type. Guidance is offered by the AISC[34] which recommends that 4 to 7% gravity is a recommended peak acceleration limit for vibration due to rhythmic activities; this is equivalent to a multiplying factor of 55 to 97. Recent test evidence suggests that a response factor of 120 is acceptable for dance floors in nightclubs, where the loud music and low lighting will reduce the perception and vision. From tests on grandstands[22], this level of response has been described as 'disturbing' (see Table 5.5). However, it should be noted that the values in Table 5.5 were derived from tests where less extreme levels of sound and light were imposed on the crowd.

Figure 11 - Extract from Section 5.3.4 (SCI P354) – Rhythmic activities and stadia

Although the ensuing line discusses grandstands, it should be noted that the corresponding benchmark tests were carried out at 'less extreme levels of sound and light' – therefore a response limit of 120 may be considered as acceptable for this particular case.

4.2.2. Modal Analysis

Vertical imposed action is taken as noted in section 2 Loading.

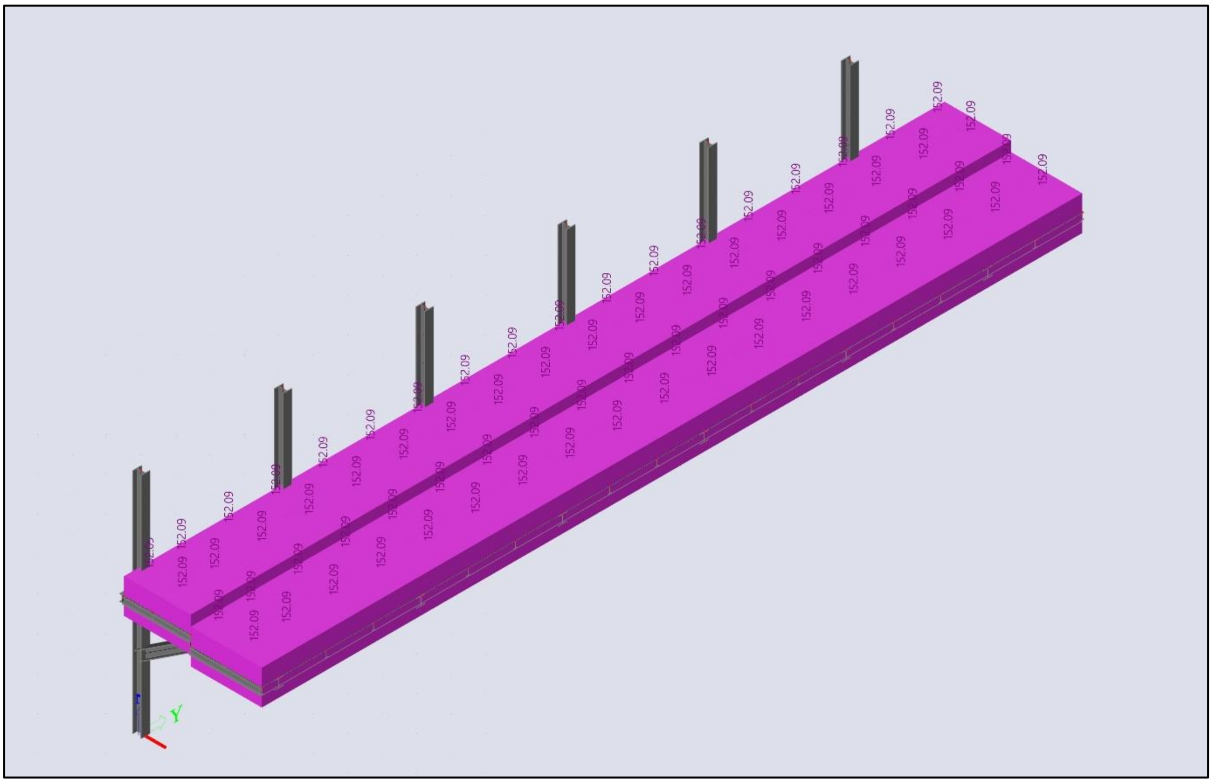

Figure 12 – Loaded structure (152.09kg/m^2)

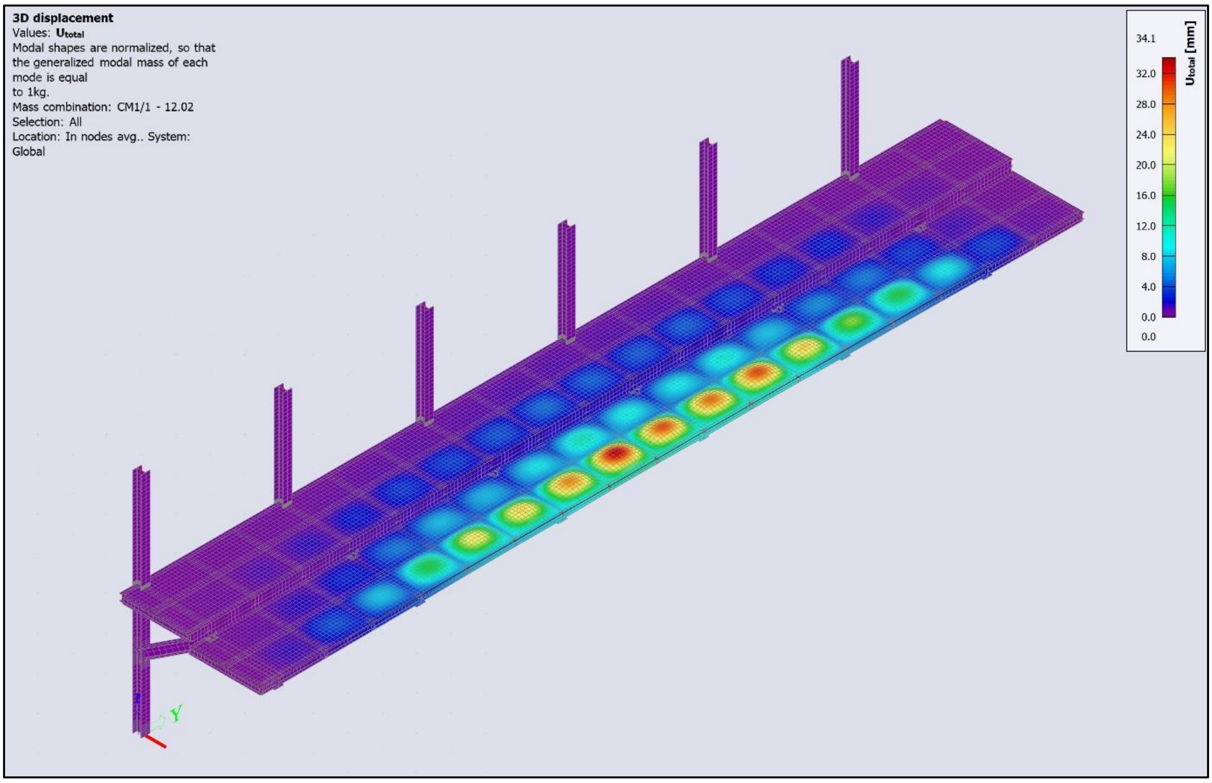

Figure 13 - 3D Deformation of loaded structure (First Eigenmode)

Eigen frequencies

N	f [Hz]	ω [1/s]	ω^2 [1/s²]	T [s]
Mass combination : CM1				
1	12.02	75.53	5704.90	0.08
2	12.28	77.14	5949.93	0.08
3	12.65	79.50	6319.59	0.08
4	13.07	82.12	6744.31	0.08
5	13.55	85.16	7252.52	0.07
6	14.10	88.62	7852.83	0.07
7	14.11	88.67	7861.75	0.07
8	14.12	88.72	7871.15	0.07
9	14.13	88.76	7878.20	0.07
10	14.15	88.91	7905.72	0.07

Figure 14 - Eigenfrequencies of loaded structure

There is notable reduction in the fundamental frequency of the structure with the applied imposed action, however, still within the prescribed limits.

4.2.3. Footfall Analysis

The model analysis model is post-processed using CADS Footfall Analysis with the following parameters:

- The floor type is considered as 'subject to rhythmic activities'
- Activity considered is 'jumping'.

Table 3.3 *Fourier coefficients and phase lags for different contact ratios*

			Fourier coefficient and phase lag for h^{th} harmonic					
			$h = 1$	$h = 2$	$h = 3$	$h = 4$	$h = 5$	$h = 6$
$\alpha_c = 2/3$	Low impact aerobics	α_h	9/7	9/55	2/15	9/247	9/391	2/36
		ϕ_h	-π/6	-5π/6	-π/2	-π/6	-5π/6	-π/2
$\alpha_c = 1/2$	High impact aerobics	α_h	π/2	2/3	0	2/15	0	2/35
		ϕ_h	0	-π/2	0	-π/2	0	-π/2
$\alpha_c = 1/3$	Normal jumping	α_h	9/5	9/7	2/3	9/55	9/91	2/15
		ϕ_h	π/6	-π/6	-π/2	-5π/6	-π/6	-π/2

Figure 15 - Table 3.3 (SCI P354) - Fourier coefficients and phase lags for different contact ratios

- 'Rhythmic activities: groups' is considered for the range of applicable frequencies (1.5 – 2.8 Hz).

3.1.3 Synchronised crowd activities

This Section is intended to give guidance for dance and aerobic areas. Detailed guidance for stadia can be found in a forthcoming publication from The Institution of Structural Engineers.

Activity frequencies

Where floors are likely to be subject to rhythmic activities characterised by synchronised movement of multiple participants (e.g. dancing, aerobics, etc.), Ji and Ellis[21] recommend that the anticipated dynamic loading should be calculated for the following activity frequency ranges:

Individuals = 1.5 – 3.5 Hz

Groups = 1.5 – 2.8 Hz

Figure 16 – Extract from Section 3.1.3 (SCI P354) - Activity frequencies

- Damping factor is taken as 1.1%, corresponding to completely bare floors, as given in Table 4.1 of SCI P354

Table 4.1 *Critical damping ratios for various floor types*

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).

Figure 17 – Table 4.1 (SCI P354) Critical damping ratios for various floor types

- 'Stride length' is not necessarily an applicable parameter here as there is no walking path, so 0.5m is assumed as the space between 2 persons in a $1m^2$ area.
- Structural span length is the length between two cantilever frames.
- Only 'resonant' outputs are calculated.

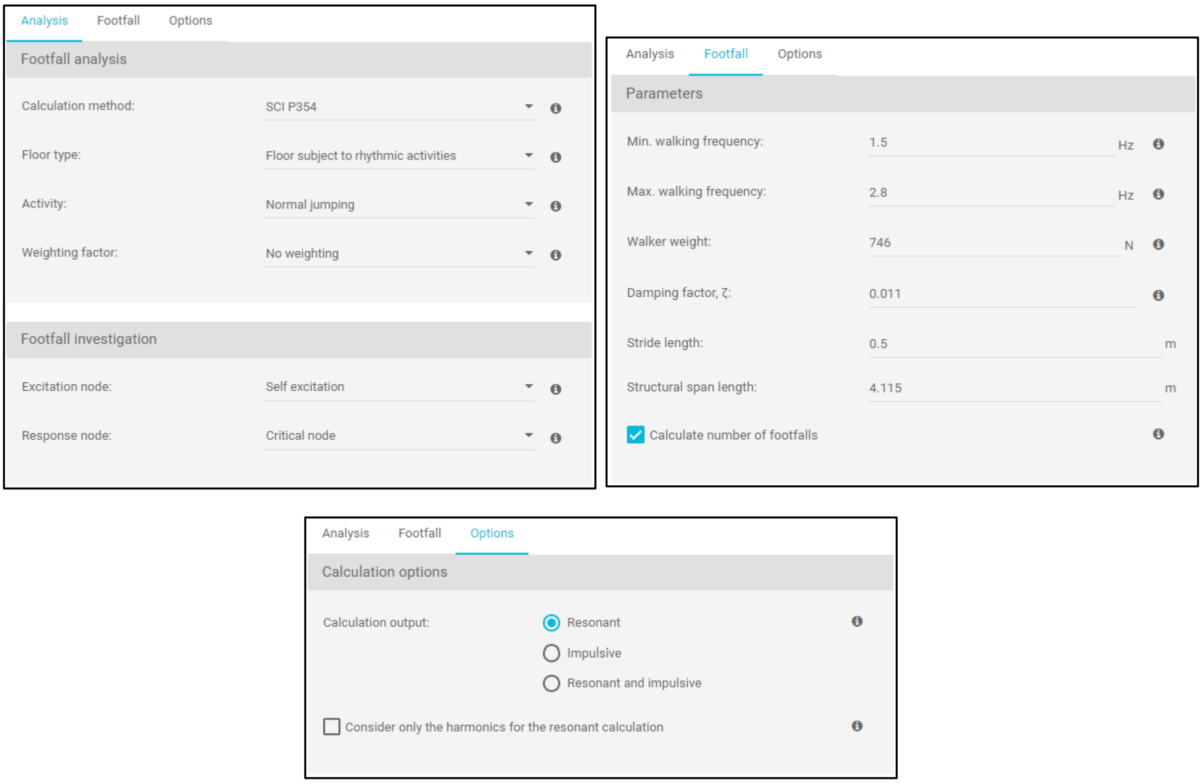

Figure 18 - Footfall analysis input parameters

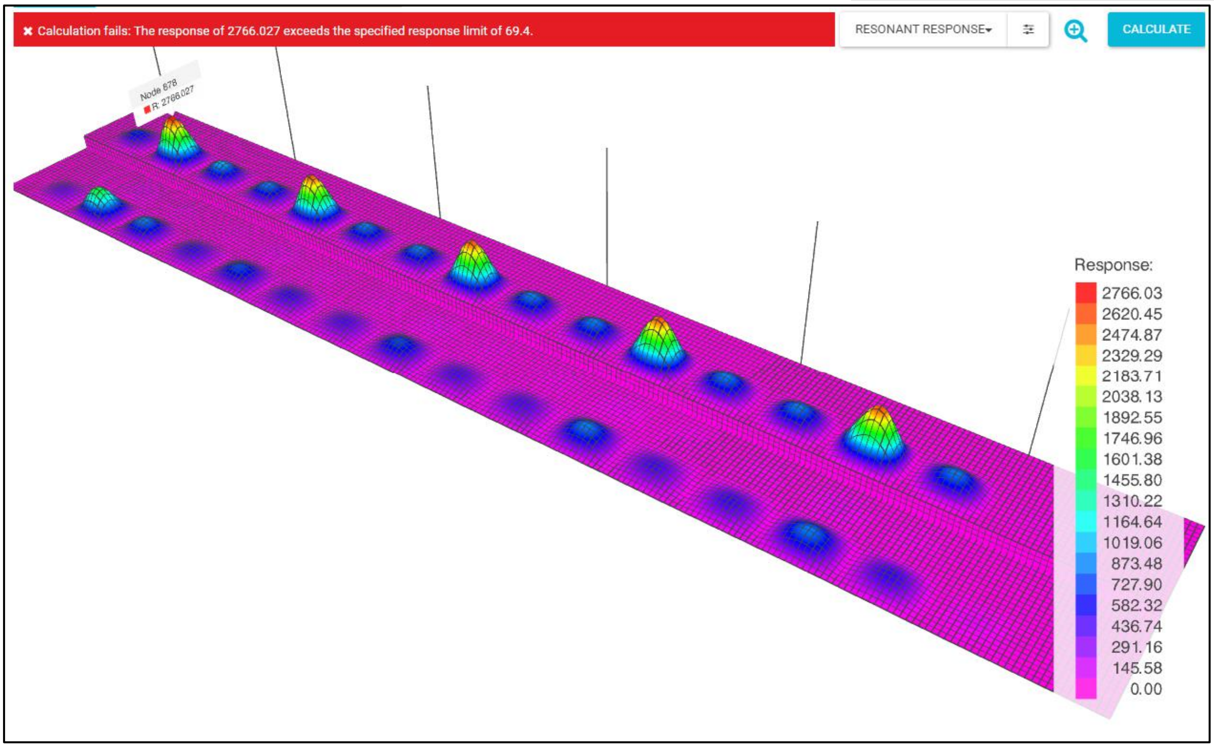

Figure 19 - Response Spectra for loaded structure

The output indicates an uncharacteristically high response, however, these are concentrated at the centre of the checker plate panels – the areas corresponding to lines of structure are much lower, and within the determined limit of 120 (see previous).

The high outputs on the plates are likely due to the inability to accurately model a connection representative of the fixings used - a fully pinned connection will not capture the bearing width. This is also a known issue with modelling relatively thin plated decking elements, with results that are not necessarily representative of the actual phenomena. Consideration could be made for dampening the floor, or adding stiffness to the plates if there are sufficient user complaints; BKPL are not aware of any such comment.

5 Conclusion

According to the IStructE guidance document, the frequency of the structure is proved to be within the specified limit for maintaining adequate levels of comfort, **and no further actions are required**.

However, for completeness, a footfall analysis was carried out with conservative assumptions, and the primary structure is deemed within the prescribed levels of comfort – **BKPL do not recommend further action**. Additional stiffening / vibration dampening to the underside of plates could be implemented if further comfort was required.