SECED 2015 Conference: Earthquake Risk and Engineering towards a Resilient World
9-10 July 2015, Cambridge UK

HUMAN INDUCED VIBRATION ASSESSMENTS CHALLENGES AND LIMITATIONS

Giovanna Caracciolo[1]

Abstract: In the last few decades Clients demand evermore functional, cost effective and aesthetically pleasing solutions, whether it is for a building, a sport venue, a bridge or a staircase. These slender structures are susceptible to dynamic vibration induced by pedestrian and crowds. Over the years, human induced vibration on structures has been extensively investigated within university research programmes, sometimes in collaboration with private and public organisations. Hence, a large number of publications are available to structural engineers when assessing structures for the effects of human induced vibration.
Commercial projects often demand comprehensive analyses within the constraints of programme, resource and budget. Hence, when embarking on a human induced vibration assessment, the structural engineer faces the challenge of choosing an appropriate approach, with sufficient rigour, whilst still meeting the Client's expectations within programme and budget.

Introduction

Clients are demanding evermore functional and cost effective solutions. These high expectations often translate into buildings with long span, shallow floor slabs, sports and music venues with high seating capacities and large open spaces, bridges spanning further and floating staircases with low visual impact. These design solutions are more susceptible to what would be second order effects in their more robust counterparts, e.g. dynamic behaviour induced by pedestrian and crowds resulting in vibrations, potentially causing adverse comments, discomfort or even panic.

Over the years, the impact of human induced vibration on structures has been extensively investigated within university research programmes, sometimes in collaboration with private and public organisations. This has led to a large number of publications being available to structural engineers to guide and support their assessment of structures for the effects of human induced vibration.

Commercial projects often demand comprehensive analyses within the practical constraints of programme, resource and budget. These constraints impose limitations on the options available in terms of approach, types of analyses and the opportunity to refine results and so force a level of conservatism.

[1]Senior Structural Engineer, Mott MacDonald Limited, London, giovanna.caracciolo@mottmac.com

Hence, when embarking on a human induced vibration assessment, the structural engineer faces the challenge of choosing the most appropriate approach, with sufficient rigour, whilst still delivering the Client's functional expectations within programme and budget.

This paper presents examples of commercial projects where structures have been assessed for human induced vibration. A brief overview of each project is presented in terms of scope, type of analysis and results. More focus is placed on identifying the challenges that the design team have to overcome and on evaluating how certain decisions made by the structural engineer can impact on the success of the project.

Design Challenges and Project Constraints

The investigation of human induced vibration on structures carried out within a commercial project can be particularly challenging. In particular, there are constraints and limitations which the design team have to overcome and work through, such as for example programme and budget. Three projects examples are presented in which, Mott MacDonald (MML) have assessed the effects of human induced vibrations.

For each of the projects a general overview of the structure, the scope of the study and key results are first presented. We then focus on identifying those aspects of carrying out these investigations within a commercial project which can be quite challenging, especially when considering project constraints such as budget and programme.

Four key aspects ("challenges") to which the structural engineer has to pay particular attention and make important decisions on, in order to ensure a successful outcome, are here identified. In parallel to these, four typical "constraints" imposed on the design team of a commercial project are also recognized. Both challenges and constraints are shown in Figure 1a.

The project challenges impose on the design team the necessity to make key, important decisions. These will inevitably have an impact on the outcome of the study, and in particular, how the team manage to respect and satisfy the project constraints. The level of impact is analysed for each of the case studies presented and it is measured using the colour coded scale shown in Figure 1b.

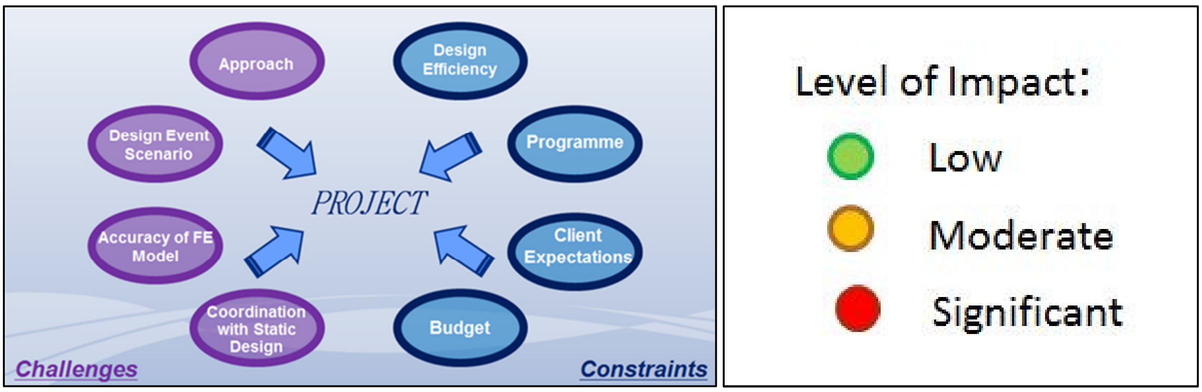

Figure 1: (a) "Challenges" and "constraints" typical of human induced vibration assessments within commercial projects / (b) level of impact colour coded scale

Case study 1 - Crowd Loading Effects on a sports venue

This project involved the investigation of the response of a sport venue structure to crowd loading, as part of a CAT III check.

The main dimensions of the venue footprint are 140m by 130m circa and it can host up to 6000 spectators. The typical main supporting structure, repeated at each grid line, is shown in Figure 2a.

The roof panels are supported by a tension cable net which covers the whole building. At the rear, the roof connects into the main rib trusses which support the tier spectator areas. The main rib trusses sit on reinforced concrete piers which connect into the deep foundations via reinforced concrete pile caps.

The structure was assessed for crowd induced vibration according to the IStructE guide for permanent grandstands [1]. A finite element model of the whole structure (3D model) was generated and this is shown in figure 2b.

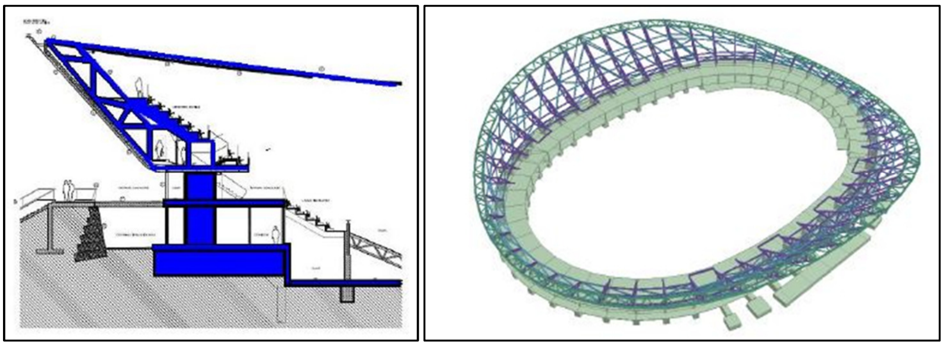

Figure 2: (a) Typical Section at main supporting structure / (b) 3D finite element model

The finite element model was generated using ADINA, a finite element software package; ~5000 structural elements were used and the crowd was modelled with 1500 body units.

The dynamic properties of the structure were calculated by analysing the natural frequencies and mode shapes; some of these are shown in Figure 3.

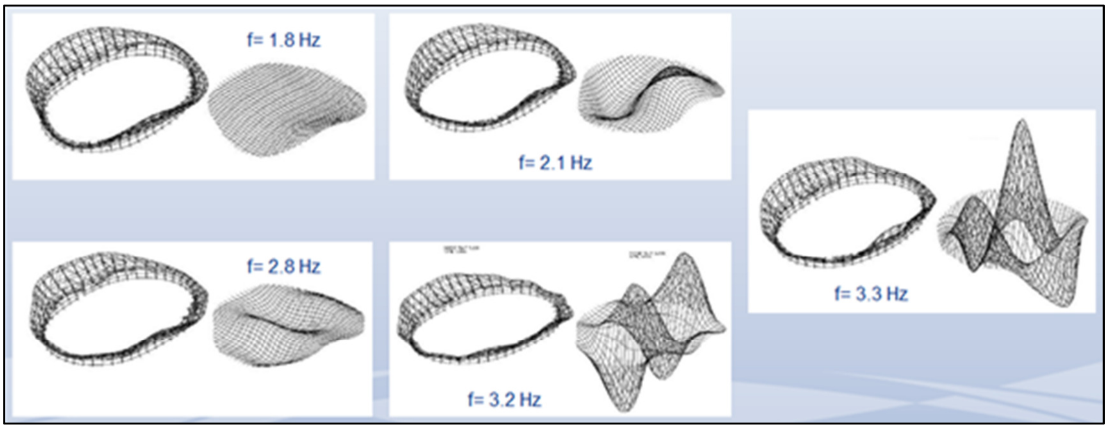

Figure 3: Structure’s first five mode of vibration

The ADINA model was analysed under many different load configurations together with sensitivity checks on critical input parameters, such as the structural damping, the participating mass and stiffness from non-structural elements and the stiffness of connections. Some results are shown in Figure 4 in terms of rms acceleration spectra, extracted from the ADINA model.

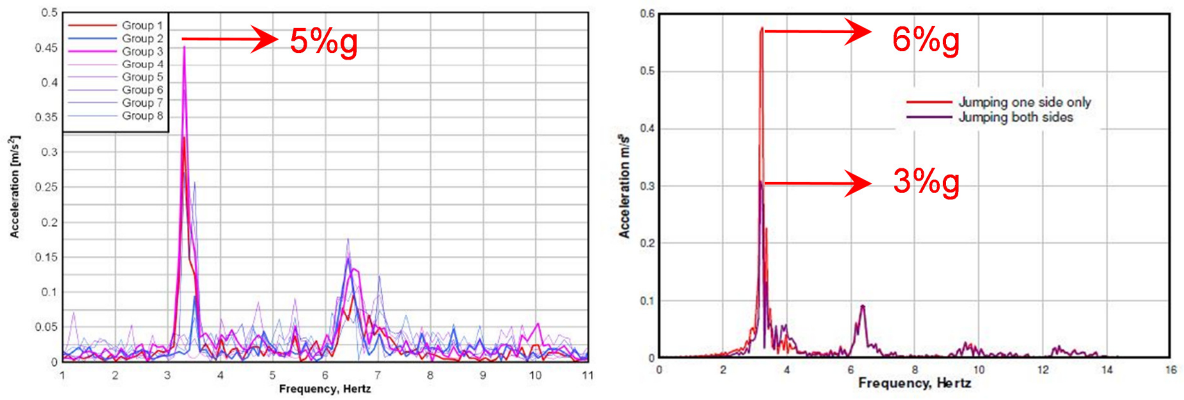

Figure 4: (a) response acceleration spectra of the structure subjected to crowd loads modelled in accordance to three harmonics loads on the left side / (b) and to real measurements on an existing venue on the right side

Let us now look at how a methodology, such as the one described above and the decisions involved in the process, can affect the quality of the outcome of the study. In particular, Figure 5 presents, for each "challenge" identified, the level of impact on each of the project's "constraints"; the impact is indicated using the colour code shown in Figure 1b.

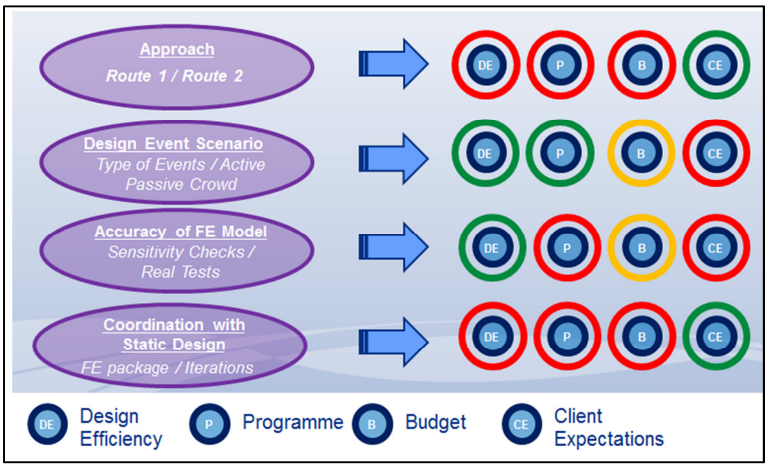

Figure 5: Crowd loading on grandstands - Identified level of impact of "challenges" versus "constraints"

Selection of approach: The IStructE guide [1] suggests two possible approaches for the assessment of grandstands to the effect of crowd loading, route 1 and route 2. These two approaches differ significantly. Route 1 is based on a criterion which limits the lowest natural frequency of the structure, depending on the type of scenario foreseen for the venue. Route 2 prescribes the analysis of the structure response to the crowd loading in terms of induced accelerations. The amount of work and calculations involved in the second approach is significantly more onerous than the first one, yet considerably less conservative. The choice of one of the approaches over the other one has generally a remarkable impact on design efficiency, programme and budget.
Design event scenario: Nowadays, sports venues are often used to host music events, as well as sportive matches, and this aspect needs to be considered at design stage as the crowd behaviour is different and dynamically more onerous. Even among music events, the induced loads are different depending on the type of music and audience. For this reason the IStructE guide provides four typical scenarios for which the venue can be designed. The selection of the design scenario is extremely important as it needs to reflect the potential future use of the venue without imposing too onerous and unnecessary requirements on the

design. Discussion with the client and understanding his expectations are crucial when selecting the design event scenario.

Finite element model accuracy: One of the biggest challenges of this type of work is the ability of the structural engineer to build a finite element model which provides reliable and realistic results. The number of parameters to which the results are sensitive to and which are difficult to assess, are too many and therefore the need for sensitivity checks cannot be ignored. Tight programmes often make this part of the process extremely challenging as analyses are time consuming and the sensitivity checks on the input parameters can be exhausting if not sensibly thought out and properly planned. Failure to ensure the reliability of the finite element model can result in the real structure performing differently from that predicted, imposing the need for un-planned tests and inevitably causing the client to lose confidence.

Coordination of static and dynamic design: Structural engineers have the luxury of a wide range of choice when selecting software for finite element modelling. It is often true that the ideal software to carry out the static analysis is not the best choice for the dynamic analysis and vice versa. Moreover, static and dynamic analysis may be carried out by different teams based in separate offices sometimes located in different countries. These aspects make the coordination of the static and the dynamic design a challenging exercise which, if not sufficiently thought through, can impact significantly on the efficiency of the design, the programme and the budget.

Case study 2 - Pedestrian Induced Vibration on long span structure

The second project presented is an assessment of floor vibration induced by pedestrians on a long span floor structure.

A typical layout of the slab structure analysed is shown in Figure 6. A 130 mm thick composite metal deck slab spans in between 12m long composite steel beams.

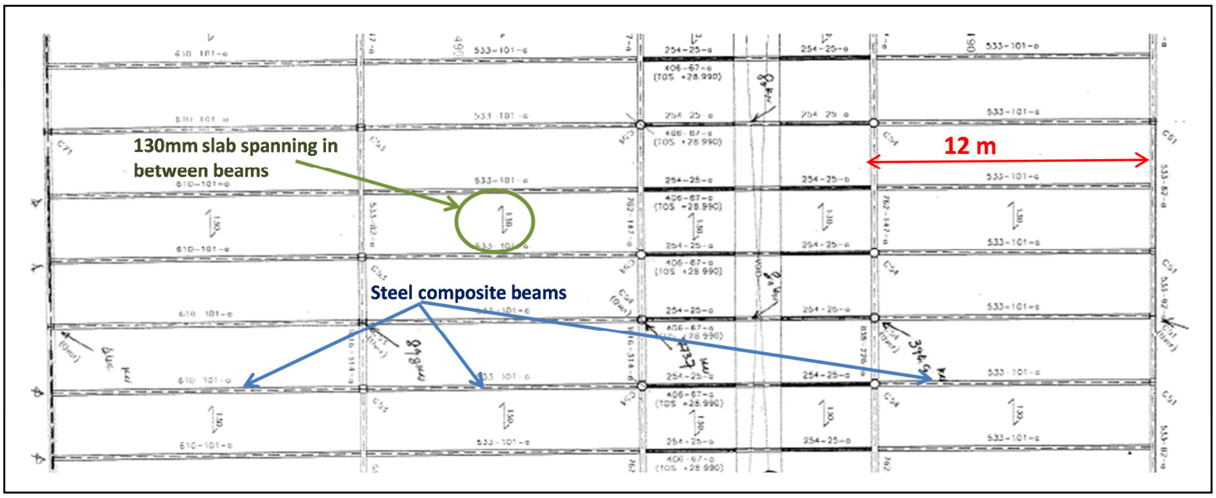

Figure 6: Typical slab structure layout

The assessment was carried out in accordance with SCI Publication 354 [2]. The project vibration criterion was proposed by the client to be a response factor of 4. A model was generated using LUSAS (a finite element modelling package) as shown in Figure 7.

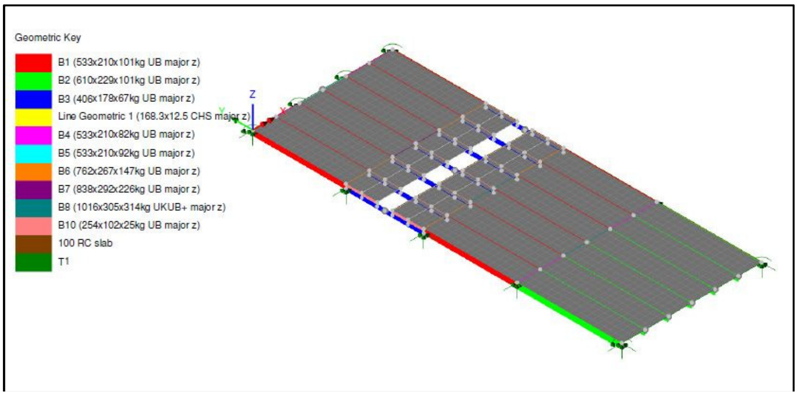

Figure 7: Finite Element Model of slab structure analysed

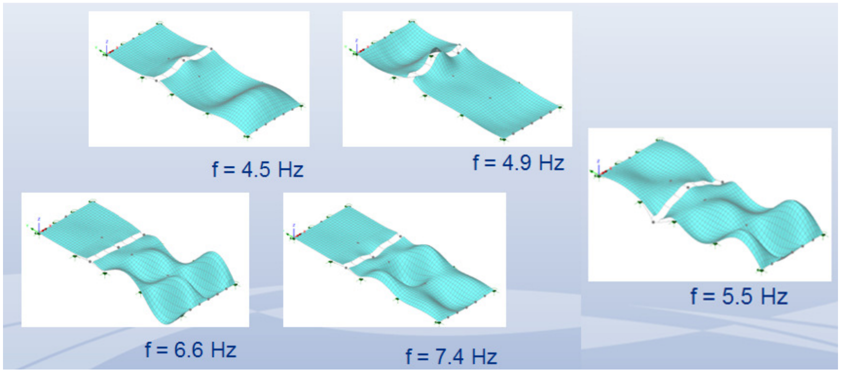

Figure 8: Finite Element Model of slab structure analysed

Figure 8 shows a few of the fundamental modes of vibration of the portion of the slab analysed. The natural frequencies range between 4.5Hz and 7.4Hz, suggesting the structure will be prone to resonate under the effect of the second harmonic component of pedestrian loading rather than the first one.

The structure modes of vibration were input to MML in-house software MABEL which performs dynamic analysis of structures under moving harmonic loads. A few examples of time history results, at a few locations across the floor, are shown in Figure 9.

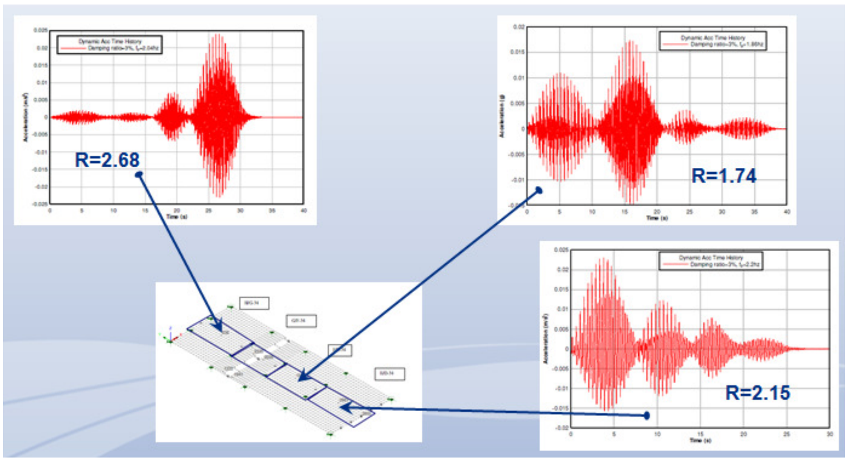

Figure 9: Example of dynamic analysis results in terms of acceleration time histories and relative response factors

Let us now look at how a methodology, such as the one described above and the decisions involved in the process, can affect the quality of the outcome of the study. In particular, Figure 10 presents, for each "challenge" identified, the level of impact on each of the project's "constraints"; the impact is indicated using the colour code shown in Figure 1b.

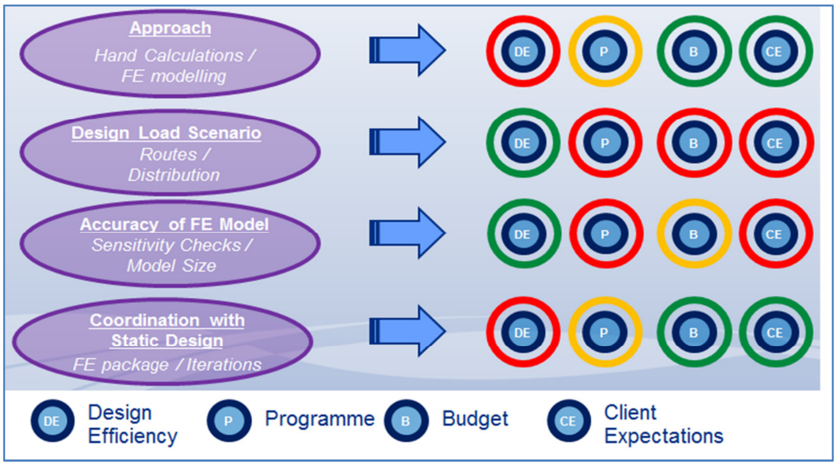

Figure 10: Long span floor structure - Identified level of impact of "challenges" versus "constraints"

Selection of approach**:** Guidance available in literature provides good support to the design engineer by offering different options to carry out the assessment which do not necessarily involve excessively complex and time consuming finite element analyses. Even when finite element analyses are used, these are relatively rapid when compared to more complex analyses such as those described in the previous case study; therefore the level of impact on the programme contains a moderate level of risk. The choice of the approach is therefore more driven by the desired level of the design efficiency.

Design event scenario**:** Large floor areas with multiple long span bays are often characterised by many different modes of vibration, all potentially susceptible to pedestrian induced vibrations. It is therefore crucial to identify the most sensitive areas and to select the pedestrian paths to be analysed so that the worst case can be captured. On the other hand, this could turn into an excessive and time consuming number of load cases. Failing to identify the worse scenario can lead to poor performance of the built floor, disappointing the client; in parallel the number of cases analysed need to be controlled to respect programme and budget.

Finite element model accuracy: As mentioned for the previous project presented, the finite element model needs to be validated through a number of sensitivity checks. In addition, multi bay floor areas can sometimes require very large models if all the bays are included; hence, where possible, the complexity of the model is often significantly reduced by modelling a portion of the floor area only. This simplification is reasonable as long as enough thought is given to the boundary conditions specified in the smaller model. Failing to identify possible simplification of the model can lead to very time consuming analysis and risk to the programme; on the other hand, a too simplistic model could cause the underestimation of the structure dynamic response, with negative consequences to the robustness of the design and hence client satisfaction.

Coordination of static and dynamic design: The coordination of the static and the dynamic design is relatively more manageable for this type of assessments when compared to the analysis of grandstands, however still constitutes a potential risk on the efficiency of the design if not planned properly. Hence, the level of impact can be high on the design efficiency and moderate on programme.

Case study 3 - Design of mitigation solutions for a lightweight steel staircase

The third and last study involves an investigation of mitigation options for an existing lightweight long span staircase, which, in service, showed excessive response to footfall excitation. For confidentiality reasons, pictures of the real staircase could not be presented in this paper; however some similar ones are shown in Figure 11 below.

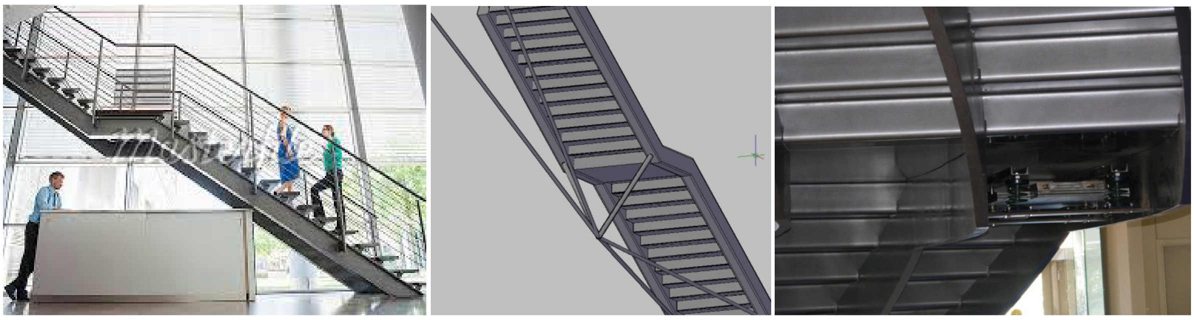

Figure 11: representative concept for lightweight long span staircase

Different possibilities were explored in consideration of mitigation options and a tuned mass damper (TMD) turned out to be the most effective solution.

The study comprised measurements on the real structure from which the modes of vibration were calculated and the response to different type of footfall excitation was also recorded. The data from the site measurements were used to calibrate the finite element models to be analysed. In particular, a single degree of freedom (schematically represented in Figure 12a below), representing the most susceptible mode of vibration, was generated for initial time effective tuning of the TMD. A second 3D model (Figure 12b) was then generated for a more accurate analysis and refinement of the TMD.

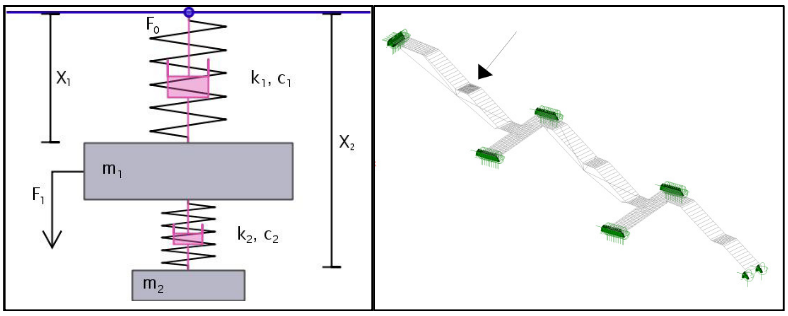

Figure 12: (a) 1 DOF FE model / (b) 3D FE model

Some examples of the calculated dynamic response of the structure to footfall are presented in Figure 13.

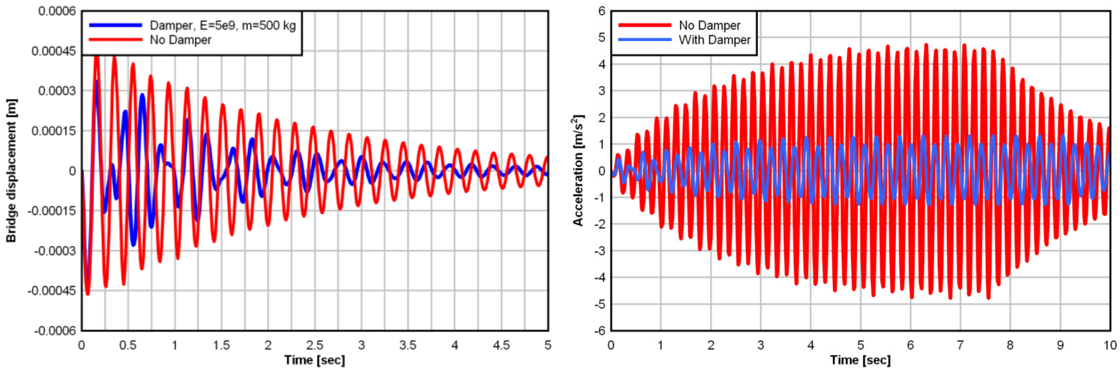

Figure 13: Example of calculated response (a) to impulsive load / (b) to resonating jumping loads

Let us now look at how a methodology, such as the one described above and the decisions involved in the process, can affect the quality of the outcome of the study. In particular, Figure 14 presents, for each “challenge” identified the level of impact on each of the project’s “constraints”; the impact is indicated using the colour code shown in Figure 1b.

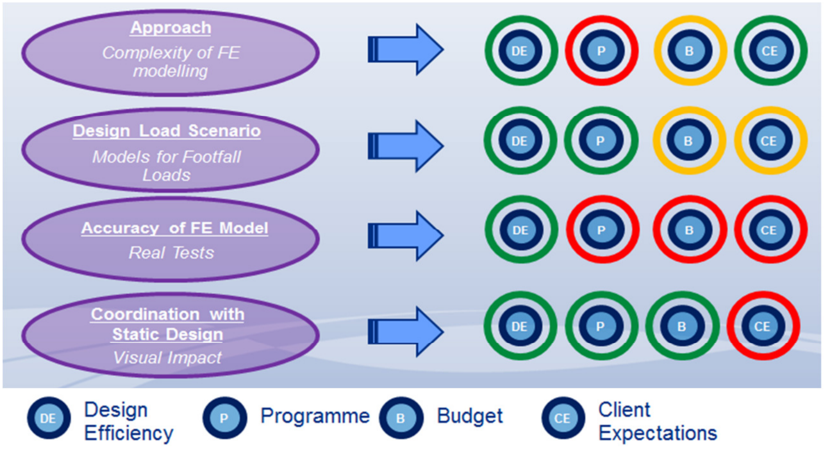

Figure 14: Lightweight staircase - Identified level of impact of “challenges” versus “constraints”

Selection of the approach: The case study presented is an example of how the selection of the right approach can lead to faster and more time effective analysis. The real measurements were tailored so that the specific sensitive mode of vibration could be identified at an early stage. This allowed the use of a single degree of freedom model to quickly generate a first pass solution which was then refined in the 3D model. A different choice could have led to a longer and slower process for the TMD tuning with a significant impact on the programme.

Design load scenario: Models for footfall loads on stairs are relatively well known, and available in literature, hence the choice of the loading scenario, in this case, has a lower level of impact on the outcome of the project.

Finite element models: For an existing structure, the use of real measurements to calibrate the FE model is often an obvious choice. However, tests need to be thoroughly planned ahead, especially when carried out by sub-contractors which do not necessarily always have a comprehensive understanding of the project. Inappropriate tests may produce inadequate data for the purpose of the study and may need to be repeated; this can impact hard on programme, costs and client expectation.

Coordination of static and dynamic design: For an existing structure, the static design is already completed at the time of the assessment. However it is important for the design engineer to understand the intent of the original design; for example, mitigation devices can have a significant aesthetical impact on the structure and a negative effect on client expectation.

Impact of design challenges on project constraints – an overview

The levels of impact (Figures 5, 10 and 14) of the design team “challenges” on the project “constraints” identified for the three case studies presented, are summarised in Figure 15 below.

Figure 15 shows how the selection of the approach and the coordination with static design, tend to have more impact on deign efficiency and programme. The design loading scenario and the accuracy of the FE model, are mainly affecting the programme, budget and client expectation. However, overall, there is no specific pattern in Figure 15, and this suggests that every case is different and needs to be treated individually.

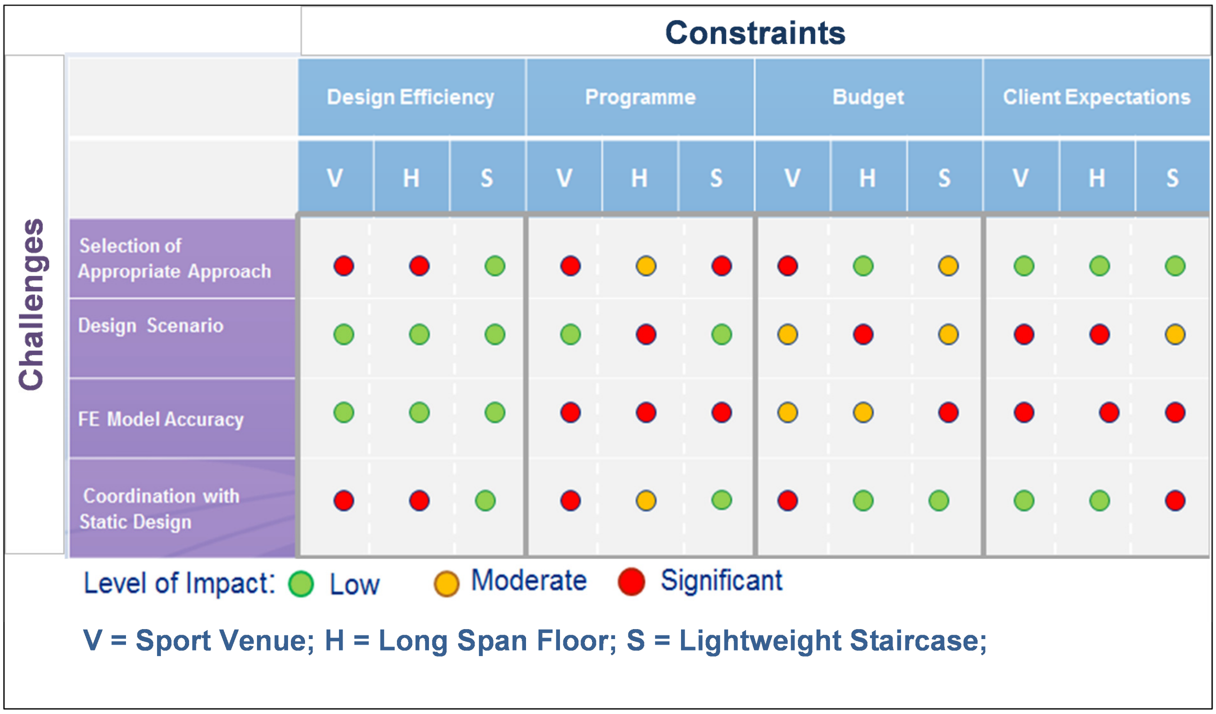

Figure 15: Identified level of impact of “challenges” versus “constraints”

Conclusions and general considerations

This paper highlights the importance of the design team’s key decisions when carrying out structural assessments to human induced vibrations and how these decisions can affect the success of the project, not just technically but also on wider commercial aspects.

In particular, four specific aspects (“challenges”) were identified: selection of approach, the design scenario, the accuracy of the FE model and the coordination of dynamic and static designs. The paper highlights the importance of these aspects being thoroughly considered at a very early stage of the project as otherwise the consequences will impact on the success of the project; measured here with four indicators: efficiency of the design, compliance with programme and budget and client satisfaction.

The paper illustrates how each assessment can be very different. There is no standard way to approach these types of investigation; the best way is to consider each case on its own merit and make the best choice accordingly, without taking any aspect for granted. Moreover, each client can be different in terms of expectations, understanding of dynamic investigations and ways of communicating. A two way clear dialogue between the project team and the client is necessary to ensure that the team comprehend the client’s broader drivers and so that the client appreciate the challenges and limitations of the work.

REFERENCES

[1] Institution of Structural Engineers, Department for Communities and Local Government and Department for Culture, Media and Sport. *Dynamic performance requirements for permanent grandstands subject to crowd action: Recommendations for management, design and assessment*. London: IStructE, 2008.

[2] Smith, A.L., Hicks, S.J., Devine P.J., Design of floor vibration: A New Approach (SCI Publication 354). Ascot, UK: SCI, 2009.