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# RESULTS OF ISTRUCTE 2015 SURVEY OF PRACTITIONERS ON VIBRATION SERVICEABILITY

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**Abstract**: *In 2015 IStructE conducted a survey of structural engineering practitioners about their experience with designing structures to have satisfactory vibration serviceability. This is the first international survey of this kind known to the author. Over 100 responses were received from around the world. Almost a quarter of respondents had experienced problems with human comfort in designs which were code compliant and over 40% stated that they had experienced limitations in design code guidance/requirements. These and responses to the other 8 questions, as well as free text comments, are analysed and presented, with some recommendations as to the way forward for the profession considering the outcomes of this survey. Key areas of concern identified by the survey are: (1) generally low level of competence of structural engineers when dealing with vibration serviceability; (2) poor code and design guideline provision to cope with a plethora of vibration serviceability scenarios in modern lightweight structures; (3) aspects of client-engineer relationship preventing full engagement of the client in specifying vibration serviceability requirements; and (4) unreliable or unworkable vibration limits proposed in the standards.*

## Introduction

Vibration serviceability is becoming the governing design criterion for many long, tall and slender civil engineering structures. This means that structural vibration rather than strength dictates the size and shape of modern structures. As construction materials and techniques improve, yielding stronger but lighter structures, and architectural drive continues towards open plan, slender and transparent designs, modern structures – although strong and robust – increasingly feature considerably reduced mass, stiffness and damping. Therefore, basic laws of physics dictate livelier behaviour of such structures compared with their counterparts a few decades ago.

Vibration serviceability problems are often caused by human-induced vibration due to walking or jumping, such as for footbridges or grandstands. At the beginning of this century, the 13th Report of the Standing Committee on Structural Safety (2001) devoted the whole of Section 3 of the report to vibration serviceability problems. This was prompted by then well-publicised and known vibration serviceability problems experienced with the Millennium Bridge in London and Millennium Stadium in Cardiff. In both cases, these were related to crowd dynamic loading, but – considering that both structures were brand new designs – SCOSS (2001) also reflected on the overall ability of the profession to cope with design governed by structural dynamics and vibration by stating:

> *"There appears to be a trend in structural engineering towards the use of more slender and larger structures. The trend is a result of society seeking more elegant and exciting solutions and clients seeking greater economy in meeting increasingly onerous structural performance requirements. Today structural engineers are therefore much more likely to be required to design dynamically responsive structures than in earlier decades. The ability to identify dynamically sensitive structures has therefore become a necessary part of a structural engineer's skills. Often the emphasis in engineer's education is however on 'static' design based on computer analysis.*
>
> *The design of dynamically responsive structures for safety and to meet performance requirements for acceleration and frequency is a relatively complex subject. It is perhaps not sufficiently well covered as a matter of course in the education and formation of civil and structural engineers. Today these engineers should, it is suggested, learn the principles of the subject as undergraduates. There may also be a need for more post-*

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*graduate courses specialising in structural dynamics. In addition, practising engineers should perhaps have more opportunity to develop their skills in identifying and designing dynamically responsive structures as part of their continuing professional development. In summary, there is doubt in the Committee as to whether the balance in the education and formation of civil and structural engineers gives sufficient emphasis to developing understanding and skills of visualising structural behaviour under dynamic loads."*

## IStructE Survey questionnaire

That was in 2001. Almost 20 years later, it can be reported that the trend towards slender structures continued unabated, whilst our understanding of the vibration serviceability behaviour of such structures has generally struggled to keep pace. For example, building floors in open plan offices and major public buildings such as schools or hospitals, could nowadays boldly be designed to be as light as 100-150kg/m$^2$ and made of lightweight concrete, cold formed steel (CFS) or cross laminated timber (CLT). However, current floor vibration serviceability design guidelines used in the UK published by the Concrete Society, Concrete Centre and Steel Construction Institute were not calibrated to work with such novel structural solutions. Therefore, it is not surprising that there is a general feeling of increasing frequency of vibration serviceability problems in modern civil structural design. These problems tend not to be public knowledge due to legal and commercial sensitivities, but they cross the desk of the author of this paper with increasing regularity.

Prompted by anecdotal evidence of such problems in 2015 the IStructE launched a global survey of design practitioners on the vibration serviceability of structures. This paper is the first publication of the results of this survey.

The survey had nine questions:

1. Q1 Have you experienced vibration serviceability problems with any of the following structural types[3]:
    a. Steel
    b. Concrete
    c. Composite
    d. Timber
    e. Spans less than 10m
    f. Spans more than 10m
2. Q2 If you answered yes to any of the above please describe critical causes of any such issues[4].
3. Q3 Have you experienced serviceability problems with any of the following issues:
    a. Complaints over human comfort on code compliant designs
    b. Equipment performance problems with code compliant designs
    c. Limitations in design code guidance/requirements
4. Q4 If you have answered yes to the above question, please describe critical causes of any such issues[5].
5. Q5 Do you have difficulty understanding the difference between natural frequency and response factors?
    a. Yes
    b. No

[3] Select one or more answers: No; Yes, during design; Yes, during construction; Yes, whilst in service.
[4] Answers were provided as free text comments.
[5] Answers were provided as free text comments.

6. Q6 During your career, have you encountered many issues with vibration?
    a. Yes
    b. No
7. Q7 What level of guidance would best support you in the design of vibration serviceability design of[6]:
    a. Steel Structures
    b. Concrete Structures
    c. Timber Structures
8. Q8 Which country are you based in?
9. Q9 If you wish to submit any further comments about vibration serviceability do so here[7].

The worldwide survey took place between August and November 2015. A total of 122 practitioners from 10 countries participated in the survey. Not all questions were answered.

## Survey results

This section presents the initial results of the survey. These are, in the author's opinion as an experienced structural engineering educator as well as a vibration serviceability practitioner, quite enlightening when judging the state of the profession as to practical vibration serviceability design.

*Q1 and Q2 responses: Have you experience vibration serviceability problems?*

Table 1 contains summary of answers to Q1.

*Table 1: Responses to Q1: Have you experienced vibration serviceability problems with any of the following structural types?*

| | No | Yes, during design | Yes, during construction | Yes, whilst in-service | Total Respondents |
|---|---|---|---|---|---|
| Steel | **33.04%**<br>38 | **40.00%**<br>46 | **21.74%**<br>25 | **36.52%**<br>42 | 115 |
| Concrete | **56.99%**<br>53 | **31.18%**<br>29 | **8.60%**<br>8 | **12.90%**<br>12 | 93 |
| Composite | **54.95%**<br>50 | **31.87%**<br>29 | **10.99%**<br>10 | **16.48%**<br>15 | 91 |
| Timber | **61.11%**<br>55 | **15.56%**<br>14 | **2.22%**<br>2 | **28.89%**<br>26 | 90 |
| Spans less than 10m | **55.91%**<br>52 | **25.81%**<br>24 | **6.45%**<br>6 | **24.73%**<br>23 | 93 |
| Spans more than 10m | **42.00%**<br>42 | **41.00%**<br>41 | **17.00%**<br>17 | **25.00%**<br>25 | 100 |

Perhaps not surprisingly, based on what is written in the relevant literature, steel was the structural material with which two thirds of responding practitioners experienced problems. What is surprising and somewhat concerning, however, is that over a third of them experienced problems "whilst in service".

Looking at the free text comments given when answering Q2 to elaborate on the data in Q1, some answers are also quite revealing:

> *"Encountered a mezzanine floor within a sports hall. Was intended for use as weights area, but area 'bounced'."*
>
> *"Footfall induced vibration causing concerns to building users on a 16.50m span composite cellular beam in an office accommodation. The area have minimal finishes with open plan arrangement. The beams were designed to minimum 4Hz natural frequency and a response factor of 8. Actual footfall dynamic testing was carried out on the structure and the results were satisfactory with recorded damping of 2.5% and maximum response factor of 6.5."*

[6] Select one answer: Basic; Intermediate; Advanced
[7] Answers were provided as free text comments.

*“Lack of mass in the floor plate being supported caused high response factors at design stage.”*

*“Selecting an appropriate vibration response factors damping coefficients during design isn't always straight forward depending on the use of the building. For example most of the occupants in a primary school are much lighter than an average adult. During construction, where floors are often bare, vibration issues may be perceived by the client or their agent.”*

*“Serviceability problems normally happen to lightweight and long-span structures. As a design, serviceability limit state criteria normally control the design for these structures; as a user, you can feel the serviceability problems during the service, like vibrations and large deflections.”*

*“Office floor vibration in Steel multi-storey Structure initiated by passing traffic - large vehicles Timber floor vibration - multi-storey timber frame construction from doors slamming”*

*“Long span slender structures driven by architectural demands”*

*“Working on hospital buildings dynamic response factors require additional design to ensure performance is obtained as set out in the compliance guidance.”*

*“Human response of floors in service - vibration and deflection limits for domestic conditions or light commercial (hotels, student accommodation) - can be a mine field. The Structural Timber Association are working on a technical paper on domestic floor vibration to EN1995-1-1 - may be good to talk to them on this.”*

*“Long span lightly loaded steel beams in situations where a response factor of 4 or better is expected. The floor plate had to be designed to meet this response factor.”*

*“During design: vibration not checked at appropriate time.”*

*“Lack of awareness of the problem, use of outdated design guidelines, inconsistent design guidelines, lack of basic knowledge of structural dynamics and principles of vibration engineering, oversimplification, design cost-cutting, absolutely huge and disproportionate consequences if something goes wrong with vibration serviceability.”*

*Q3 responses: What kind of problems?*

Data in Table 2 reveals another very worrying trend.

*Table 2: Responses to Q3: Have you experienced vibration serviceability problems with any of the following issues?*

| | Yes | No | Total |
|---|---|---|---|
| Complaints over human comfort on code compliant designs | **23.30%**<br>24 | **76.70%**<br>79 | 103 |
| Equipment performance problems with code compliant designs | **14.14%**<br>14 | **85.86%**<br>85 | 99 |
| Limitations in design code guidance/requirements | **43.81%**<br>46 | **56.19%**<br>59 | 105 |

Almost a quarter of respondents experienced problems with code compliant structures whereas well over 40% believe that there are limitations in design code guidance/requirements. These two answers could indicate unacceptably high levels of risk when using the current guidelines to design for vibration serviceability.

Some anonymous free text comments elaborating on responses in Table 2 are also quite enlightening. They are presented below in their original unedited form:

*“There is a huge problem with the calibration of R=8 as acceptable for 'busy offices'. There is very little or in fact no research worldwide justifying using R=8 for offices, and it's still featuring in various guidelines.”*

*“In all cases, there is more prevalence of codes/standards to cover issues concerning requirements with statements like "... must consult the client...". However, except for a few large clients with in-house expertise, the clients typically have no idea about SLS, what they want or what they should have, even when it is explained to them. Very frequently,*

*the engineer makes a decision on the client's behalf and such decisions risk being poorly informed by the client's needs."*

*"Whilst design guidance is becoming more prevalent/easier to understand, when I first came across this issue, I personally found it a bit difficult and even now it takes a bit of getting my head around it all."*

*"Design guidance for vibration performance of lightweight floors does not appear to be consistent with the assessment methods used for heavier weight construction (concrete or composite floors)"*

*"Issues with identifying appropriate response factors for scientific equipment. Clients don't understand what the want or need. Clients don't understand what they already have in existing buildings. Clients specify unnecessary onerous requirements which can't be achieved easily."*

*"We were asked to review a stair design where the vibrations were proving uncomfortable. We could find no flaw in the design in relation to the Codes. The codes are in our opinion deficient in terms of vibration allowances and deflection limitations in certain conditions, particularly where the loads are cyclical."*

*"Where to start? Footbridge (designed to local BS5400) getting complaints, vibration sensitive facility producing defective product, although design was for VCs not by codes, codes are too simplistic."*

*"The codes is not a sufficiently detailed document to allow for these matters to be resolved. We generally need to look beyond code guidance to design our buildings"*

*"Some codes are silent on vibration requirements. The guidance is poor."*

*"SCI and CC guides give different response factor limits for commercial office space."*

*"For pedestrians: open area shopping malls and open offices have history of inadequate damping. Equipment problems often a result of structural designer not accounting for dynamics at all."*

*Summary of responses to other questions*

Interestingly and worryingly again, over a third of respondents reported difficulty in understanding the difference between natural frequency and response factors. Furthermore, almost half of the respondents report that they have encountered many issues with vibration during their career. Finally, half of the respondents believe that an advanced level of guidance is needed for designing steel structures to have satisfactory vibration serviceability whereas that figure is 39% for concrete structures and 30% for timber structures.

The final set of anonymous free text comments on vibration serviceability had 32 responses and some of them are presented here:

*"I have experience of vibration assessments for footfall induced vibration in both steel and concrete structures, and also grandstand design under crowd loading. With relation to footfall induced vibration - I feel clients do not fully understand the problem and see the response factors as a definitive 'pass/fail' criteria - often the use of Vibration Dose Values is difficult to apply as the usage of a structure and number of pass in a given period of time can be difficult to quantify for different types of facility. Maybe some guidance on likely use per hour of typical offices/busy offices/hospitals/corridors etc. may be useful"*

*"When/If I have to carry out designs relating to vibration I usually end up understanding (more or less) how to do the design, but, they checks are not 'standard' ones that we would do by hand so am not always confident that the number I get at the end is correct. For Eurocode calculations I would normally let Tedds (or other software) carry out the analysis."*

*"Detailed dynamic analysis is generally an iterative and time consuming process (even with the use of sophisticated software). This is not appreciated by many Engineers and clients. An initiative to raise awareness can only be a good thing. Structural dynamics is a poorly understood subject amongst members. The influence of soil properties should also be included in any awareness initiative."*

*"It seems to me that vibration issues 'slip through the net' far too often. The trouble is once the issue exists it is very difficult to rectify so it really needs to be captured during the design phase."*

*"An institution guide that included good annotated drawings and / or figures such as the recent Stability Guides would go a long way to ensure the design team, the contractor and the client have an industry guide to lead them through the design process. This could also cover Mitigation Strategies and Details"*

*"Clients or project managers with experience (or at least awareness) generally help: hospitals or high-end laboratory space is generally right first time because they recognise it's a fundamental requirement of the design. Vibration analysis is typically a complex, time/processor-hungry, analysis carried out by FEA to allow for highly irregular floorplates (few people ever get to design simple regular floorplates like SCI/CC use in examples!); clients need to expect to pay extra or it and not expect it be part of a list of 'run-of-the-mill' services."*

*"I really like the idea of the "Vibrate It" smartphone app by Expedition Engineering, to allow engineers to close the loop on an area of design where there is a gap between there complicated design theory and the very subjective performance requirements. Some further development of this app and it's uses will be very interesting."*

*"Most problems are with buildings but pedestrian bridge vibrations can be problematic as well."*

## Discussion

Every vibration serviceability problem can be rationalised into three elements: vibration source, vibration path (i.e. mass, stiffness and damping of the structure) and vibration receiver (i.e. assessment of vibration levels for human receivers or sensitive processes). A cursory look at the responses indicates a growing gap between the increasing ambition of modern structural schemes and the ability of structural designers to deliver satisfactory vibration serviceability performance of such schemes. The free text comments indicate the existence of an amazing plethora of structural design scenarios featuring various aspects of vibration serviceability with which practitioners need to deal daily. However, it is clear that many of them are not equipped with the knowledge, skills and tools to tackle the problems they are facing. In the 18 years since the 13$^{th}$ SCOSS report, a new generation of floor, grandstand and footbridge vibration serviceability design guidelines have been developed and utilised, but the drive for ever more slender and lighter structures is outpacing the research effort to understand the behaviour of such structures.

Key areas of concern identified by the survey are:

1. Lower than desirable level of knowledge, skill, training and competence of structural engineers when dealing with vibration serviceability;
2. Inadequacy of code and design guideline provision to cope with the plethora of vibration serviceability scenarios in modern lightweight structures, and
3. Aspects of client-engineer relationship preventing full engagement of the client in specifying vibration serviceability requirements.

Particularly worrying are that there are so many code compliant structures which do not have satisfactory vibration serviceability performance after construction. Among other reasons, the crucial question of what is an acceptable vibration level seems to be still unresolved and may be the key culprit in this situation. This should not be surprising, as the vibration receiver is by far the least researched element of the vibration serviceability problem.

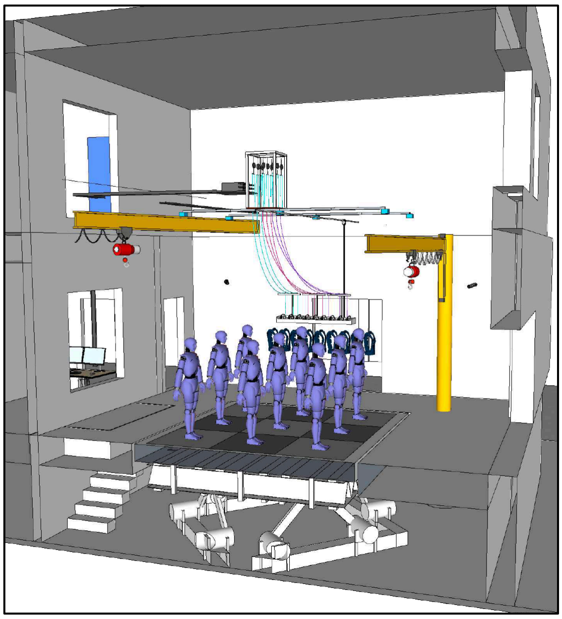

*Figure 1: VSimulator facility at the University of Exeter.*

To address this issue, the EPSRC is currently funding multi-million-pound split-site research facilities at the Universities of Exeter and Bath, supported by key UK consultants and other universities with interest in this area, to address acceptable levels of vibration in the built environment for humans and sensitive processes. For example, the facilities in Exeter (Figure 1) and Bath will be able to simulate vibro-acoustic environmental conditions in tall buildings, building floors, footbridges, grandstands (Figure 2) and many other environments by utilising motion simulators, virtual reality and an environmental chamber. This is the only facility of this kind in the world which recognises continuing UK leadership in this area. The facility will be fully operational in early 2020.

*Figure 2: VSimulator in 'stadium mode' using virtual reality and controlled motion of the 4mx4m instrumented platform.*

One of the key novel ideas for industry is to use the VSimulator facility to start developing customised (rather than standardised) vibration serviceability design guidelines for major projects, taking into account their specifics via motion, virtual reality and other environmental simulations using a statistically reliable number of human test subjects. This could address the issue of the plethora of design scenarios and currently inadequate design guidelines based on inadequate standards, which are unable to cater for all relevant design scenarios.

## Conclusions

The 2015 IStructE survey of vibration serviceability practitioners revealed a mismatch between the growing demand for slender, light and transparent structures and the ability of civil structural engineers to design them satisfactorily.

A quarter of respondents experienced problems with code compliant structures which is an unacceptably high proportion. Key other areas of concern identified by the survey are:

1. Generally low level of competence of structural engineers when dealing with vibration serviceability;
2. Poor standards, code and design guideline provision to cope with the plethora of vibration serviceability scenarios in modern lightweight structures;
3. Aspects of client-engineer relationship preventing full engagement of the client in specifying vibration serviceability requirements, and
4. Unreliable or unworkable vibration limits proposed in the standards.

## Acknowledgements

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## References

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