Institution: University of Sheffield

Unit of Assessment: 14 - Civil and Construction Engineering

Title of case study: Managing full scale dynamic performance of civil infrastructure

1. Summary of the impact

Research in the Department of Civil and Structural Engineering at the University of Sheffield on dynamic performance and vibration serviceability has contributed to internationally applied guidance on building serviceability for floors, buildings, stadia and other structures and has led to the spin-out Full Scale Dynamics Ltd (FSDL). Based on our research FSDL provides applied research and consultancy services, and has delivered projects approaching £1m since 2008. FSDL has demonstrated significant reach through its work with blue chip clients nationally and internationally. Our research has impacted on leading national sport infrastructure (such as Premiership Football stadia and notably the Olympic 2012 Velodrome) and public companies to deliver economic benefits by providing evidence based compliance, demonstrating that stadia, hospitals, manufacturing plants and other public structures comply with safety and vibration serviceability standards. Interventions based on our research and implemented via FSDL have, on numerous occasions, avoided potentially serious economic and safety consequences due to the poor vibration performance of structures.

2. Underpinning research

Underpinning research in the field of vibration performance of civil engineering structures was initiated by Pavic (Professor, joined Sheffield 1996) with the formation of VES (Vibration Engineering Section) at The University of Sheffield, focussing on vibration serviceability of structures. Reynolds (Professor, joined Sheffield 1998) extended this research to dynamic performance of grandstands and developed active vibration control systems. Brownjohn (Professor, joined Sheffield 2005) brought in expertise on dynamic performance of tall and long structures over wide ranges of time and length scales. In 2008 Pavic, Reynolds and Brownjohn founded the Sheffield University spinout company Full Scale Dynamics Ltd (FSDL) as a delivery mechanism for impact of the research. Racic (Lecturer, joined Sheffield 2011) added expertise in experimental characterisation and mathematical modelling of dynamic loading of structures induced by active individuals, groups and crowds of people.

Our research led to novel approaches to management, design and in-situ dynamic performance assessment of large civil infrastructure with respect to fitness for purpose with complimentary attention to safety, comfort and economy. Our research was partly funded via the award of an EPSRC platform grant in 2009 (EPSRC EP/G061130/1), the first of its kind for this area of civil and structural engineering research in the UK.

Our researchers capitalised on technology and methodologies for modal testing typically applied to mechanical and aerospace structures, such as ground vibration testing and finite element model updating of prototype aircraft and transferred it to civil structure applications [R1]. Civil structures differ substantially from mechanical structures in materials and scale as well as in level and nature of vibrations. What worked well in controlled laboratories had to be adapted through a series of research projects (GR/L68742/01, GR/S14924/01) to work in open space environments with challenging environmental and operational conditions and unusual signal to noise ratios. Within these research projects we developed systems-engineered tools and procedures that combine artificial forcing and ambient excitation and linked simulations to assess fitness for purpose of grandstands, floors [R1], bridges and vibration-sensitive facilities worldwide. Due to this research and application of knowledge to real-world issues and applications, we generated the world's largest database of operational performance of floors, stadia and footbridges. Since 2005, we adapted capability for ambient vibration measurements with applications to 'operational modal analysis' and assessment of extreme low vibration environments [R2]. These unique experimental capabilities have formed the core that links design, analysis, simulation and evaluation of performance in commercial (FSDL) projects e.g. for Yorkon and Stoke Mandeville hospital retrofit.

We developed motion capture and force measurement facilities and used them to create the world's largest database of ground reaction force and to develop new models of jumping and walking [R3]. This was necessary to address deficiencies in the existing human dynamic load

models used in standard design practice. Our research (in collaboration with University of Manchester) has also provided valuable data on the effects of perceptible structural vibrations on loads generated by spectators bobbing on grandstands [R4]. This research was used to validate our contributions to design guidance, and by FSDL to predict performance for pedestrian and crowd-loaded structures.

Based on our research, we created bespoke software, Vibration Serviceability Assessment Tools (VSATs) [R5], now used by industry in performance-based design and assessment of footbridges, floors and grandstands. VSATs links experimentally and numerically derived structural dynamic properties and applies a range of loading from design guides and our research is now heavily relied upon by FSDL as a primary tool for structure serviceability evaluation.

We developed capabilities for remote structural monitoring of grandstands, long span bridges and buildings incorporating automated operational modal analysis for the first time in any Civil structure. The rollout of this technology led to the Tamar Bridge prototype system in 2006, whereby modal property data was broadcast in real time by internet, and has been used as a prototype for two safety-critical commercial applications**.**

Most recently in collaboration with University Castilla La Mancha (Spain), we developed unique capabilities for active vibration control of floors. The system has been evaluated in service in the office of an industry partner (WSP) [R6] and featured in subsequent FSDL proposals for high profile structures.

The criticality of our research is exemplified by our contribution to interventions to address the type of problems that occurred in the London Millennium Bridge and regularly occurs in a range of structures that are rendered unfit for purpose (unserviceable) by lack of understanding of the source (load) –path (structure) –receiver (use/occupant) chain.

3. References to the research [**denotes best indicators of quality of underpinning research]

R1. **Pavic A & Reynolds P (1999). Experimental Assessment of Vibration Serviceability of Existing Office Floors under Human-Induced Excitation, *Experimental Techniques*, Vol. 23, No. 5, 41-45. doi: 10.1111/j.1747-1567.1999.tb01305.x

R2. Brownjohn JMW, Pavic A (2006) 'Vibration control of ultra-sensitive facilities'. Proceedings ICE Structures and Buildings 159, 295-306. doi: 10.1680/stbu.2006.159.5.295

R3. Racic V & Brownjohn JMW (2011) Stochastic model of near periodic vertical loads due to humans walking. *Advanced Engineering Informatics* 25(2) 259-275. doi: 10.1016/j.aei.2010.07.004

R4. **Yao S, Wright JR, Pavic A, Reynolds P (2006). Experimental study of human-induced forces due to jumping on a perceptibly moving structure. Journal of Sound and Vibration 296(1-2). doi: 10.1016/j.jsv.2006.02.018

R5. **Zivanovic S, Pavic A (2009) Probabilistic modelling of walking excitation for building floors. ASCE Journal of Performance of Constructed Facilities 23(1). 132-143. doi: 10.1061/(ASCE)CF.1943-5509.0000005

R6. Reynolds P & Diaz IM, (2010) On-off nonlinear active control of floor vibration. *Mechanical systems and signal processing* 24(6) 1711-1726. doi: 10.1016/j.ymssp.2010.02.011

4. Details of the impact

The impact demonstrated by our activities and research, driven by our desire to apply our knowledge and exploit our expertise and specialised equipment, has been primarily achieved through:

1. VES engagement with standardisation committees and learned societies to develop industry guidance (codes and standards) and
2. FSDL focusing on commercial activities leading to economic and safety impact

Impacts on practitioners and professional services: codes and standards

Our research has contributed to a number of guidance documents/standards. These are used internationally and have legal status in civil court actions that can result from poor serviceability.

1. *The Institution of Structural Engineers (2008), "Dynamic performance requirements for permanent grandstands subject to crowd action. Recommendations for management,*

design and assessment": This is recognised as the international state of the art (adopted worldwide) and directly applies outcomes of our research [R1, R4] on stadia performance and human structure interaction.

2. *Structural Engineering Institute, American Society of Civil Engineers (2013). A State-of-the-Art Report by ASCE SEI Committee on Structural Identification of Constructed Systems:* This presents the measurement technology developed through our research and an industry application of active vibration control. Our research [R1, R3, R6] formed one of the six chapters and one of the 18 case studies.
3. *British Standards Institution (2008) Guide to evaluation of human exposure to vibration in buildings. Part 1: Vibration sources other than blasting. (BS6472-1:2008):* Our academics are long-term members of the BSI technical committee, contributing to the development and establishment of these standards.
4. *The Steel Construction Institute (2009) Design of Floors for Vibration: A new Approach (Revised Edition, February 2009, particularly Appendix C):* Our research [R1, R4, R5] formed the basis of the appendix on dynamic testing of building floors.

Economic impacts: Spin-out: Full Scale Dynamics Ltd (FSDL).

Our researchers have been engaged in consulting activities in this field since 1996. In 2008, due to the large volume of commercial activity, FSDL was incorporated. No inward investment was sought and cumulative FSDL turnover to date is around £1m. FSDL is directed by academics and has seconded six postdoctoral and PhD students to UK and overseas projects, equipping them with high-level professional skills. Clients include:

- UK companies e.g. Expedition Engineering [S1], Arup, Gifford, Balfour Beatty, Jacobs, Flint & Neill and Yorkon [S4]
- Overseas clients e.g. Intelligent Engineering (Canada), Seagate (USA) [S2], Land Transport Authority, (Singapore) and Centroprojekt (Russia)
- National stadium operators such as Premier League/Championship football clubs (Middlesbrough, Sunderland)
- Public organisations e.g. [text removed for publication] [S3] and [text removed for publication]

FSDL undertakes and completes approximately 15 high profile projects annually. The following is a brief digest of the FSDL impact on industry (economic and safety) grouped by structure type.

Stadia:

Post-Hillsborough, UK football clubs have a legal obligation to ensure spectator safety, which includes avoiding excessive vibration and consequent crowd panic. Using the testing, simulation and design tools developed in our research projects since 1998, FSDL has enabled UK stadia operators and overseas clients to comply with regulations ensuring safety and fitness for purpose. As an example, for the London 2012 Olympic Velodrome [S1] (on behalf of Expedition Engineering, 2009) FSDL used VSATS and applied the new, at the time untested in practice, stadia design guidance [R1]. This independent assessment enabled a saving of 400 tonnes of steel and was essential for the purposes of Category 3 performance based design compliance due to the inherent low natural frequency of the stands [S1].

"using this approach allowed us to have confidence in a solution which saved 400 tonnes of steel over using traditional design methods" [S1]

"without the involvement of FSDL and the fundamental research undertaken by your research group..., the dynamic performance of the lightweight seating deck would have been much more difficult to justify" [S1]

Floors:

In 2011 FSDL applied our research [R1, R2, R5] based ambient vibration testing technology to identify modal properties and vibration environment being experienced in the multi-$bn Seagate disk drive production facility in Singapore (opened 2007). [text removed for publication]. This novel data collected by FSDL was used to validate modelling of the facility that had previously been undertaken by VES. These simulations predicted the behaviour observed and provided the operator with a clear understanding of how to tackle the problem. Based on Seagate's annual

turnover of $12bn and figures and opinion of the Seagate specialist [S2] annual production loss of the order $10m appears to have been mitigated by the interventions.

"Brownjohn's vibration work allowed the Seagate engineering staff to be ahead of the production juggernaut (for once), and not underneath the beast" [S2]

"to this day we are still building on Prof. Brownjohn's original modelling and have made detailed plans for some structural reinforcements in the specific areas of greatest sensitivity ... we owe a great debt to this theoretical work apparently all done before one pile was bored for this building"[S2]

"if production delays are experienced, that if measured in days, would result in the loss of revenue measured in tens of millions of dollars" [S2]

From 2005 we applied our research [R2] based expertise to diagnose and assess extreme low vibration performance of the foundation systems for the new Orion high power laser facility at the [text removed for publication]. Successful operation of the £100m facility relies on minute positional tolerances for multiple laser reflections; our vibration measurements (conducted 2009) showed these were not exceeded. The facility has now been successfully commissioned [S3].

In a sequence of R&D projects between 2009 and 2013, FSDL was engaged by Yorkon, the leading UK off-site construction specialist, to apply research [e.g. R1, R3, R4, R5] and resolve a key problem of liveliness of their ultra-light building flooring systems under pedestrian-induced dynamic loading. As a result of this 4-year work, Yorkon's new Pioneer modular building system was developed featuring an order of magnitude lower dynamic responses of its floors. This was achieved by discovering and exploiting the beneficial effects of the novel pre-installed lightweight concrete floor and vertical partitions. With the Pioneer system, Yorkon moved decisively into quality public buildings market, such as schools and hospitals. After investing [text removed for publication] into this R&D, a significant proportion of Portakabin Group annual sales (£30m) are now featuring the Pioneer flooring [S4].

Industrial Chimneys:

In 2008, the flue gas exhaust stack (chimney) at Rugeley Power Station was suffering enhanced vortex shedding due to up-wind construction of a replacement chimney. As the wind-induced sway (predicted by the operator) could have resulted in structural failure and collapse, FSDL were commissioned to monitor the performance of the old chimney and its tuned mass damper. The damper was designed by Multitech (France) to reduce the vibration to levels that would not compromise operation of the power station. Remote monitoring technology developed in our research on the Tamar Bridge study was adapted to track the performance of the chimney/damper system to the power station staff in real time. The monitoring system clearly demonstrated that the damper worked and removed any safety concerns [S5]**.** Since 2009, FSDL has operated a more sophisticated monitoring system on a chimney at the Sellafield Nuclear facility. The system enables the site operator to comply with stringent safety requirements avoiding the need to interrupt site operation.

5. Sources to corroborate the impact

S1. Letter from Director of Expedition Engineering corroborating impact of our intervention and the subsequent economic benefit.

S2. Letter from Sr. Staff Engineer at Seagate Technology corroborates impact of our research to resolve vibration related disturbance of high value manufacturing and economic benefit.

S3. [text removed for publication].

S4. Letter from Principal Engineer at Yorkon (Portakabin Ltd) corroborating the application of our research and the financial impact associated with our activities.

S5. Chief Engineer at Bierrum International can corroborate the implementation of our monitoring system and the safety and on-going operation at Rugeley power station.