Dynamic assessment of the Malaysia Square Pedestrian Bridge, Battersea Power Station transformation

SYNOPSIS

In this article, Artur Soczawa-Stronczyk discusses his work on a project to assess the dynamic characteristics of the Malaysia Square Pedestrian Bridge – a structure built as part of the transformation of the former Battersea Power Station site in London. The project drew on Artur's MSc and doctoral research into pedestrian-induced vibration to establish that additional damping measures were not required for the bridge. The case study was highly commended in the IStructE's 2022 Research into Practice Case Study competition.

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Challenge

Modern architectural trends seek to produce sleek and slender futuristic designs, rejecting the heavy structures of the past. Recent advances in lightweight construction materials have allowed for such designs to be realised, leading to cutting-edge, signature structures for our modern era. However, this often comes at a price, since the use of lightweight materials is usually accompanied by reductions in stiffness and damping, introducing engineers to previously unexplored behaviour regimes[1].

Consequently, many of today's structures often struggle to satisfy vibration serviceability criteria for human occupancy[2–14]. Well-known examples of this include the Toda Park Bridge[15,16], Pont de Solférino[17], Pedro e Inês Bridge[8–10], and, most notably, the London Millennium Footbridge (LMFB)[2–5]. The excessive vibrations experienced by the latter during its opening day resulted in its closure for almost 18 months in order to establish the cause. This led to £5M being spent on retrofitting the footbridge with a combination of viscous and passive tuned mass dampers (TMDs)[18], to prevent this from happening in the future.

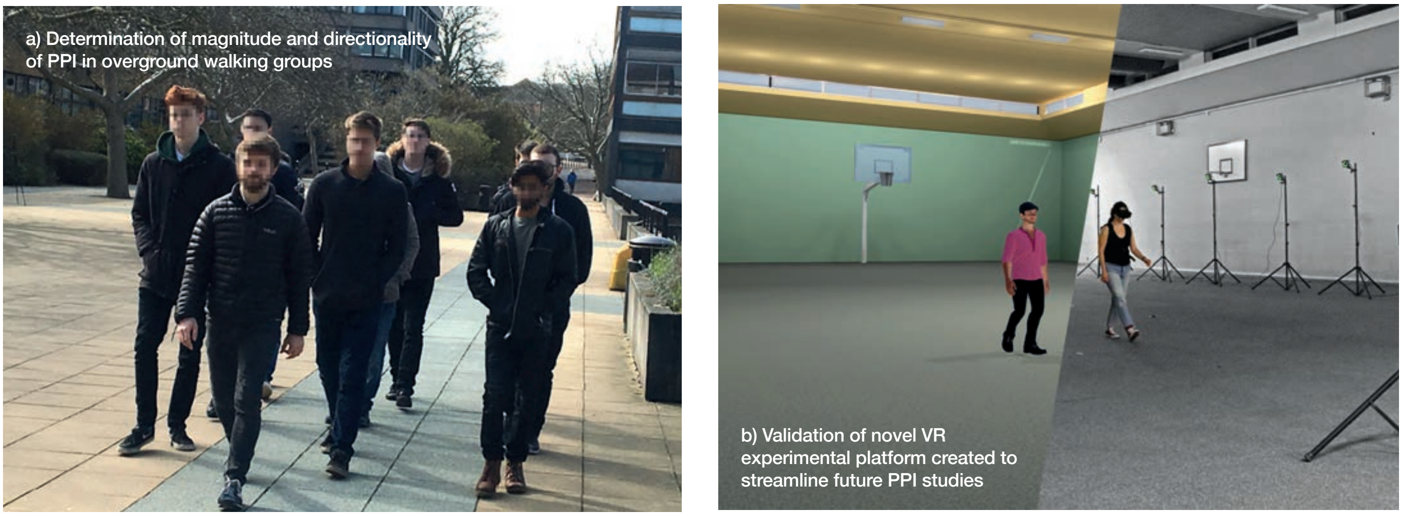
The research efforts sparked by the LMFB's excessive excitation led to the formulation of several novel dynamic behaviour models that attempt to account, during the design stage, for the complex force interaction(s) between pedestrians and structures, known as pedestrian–structure interaction (PSI), as well as the adaptation of pedestrians' stepping mode in the presence other walkers[19–22], known as pedestrian–pedestrian interaction (PPI). Tackling both phenomena necessitates bringing together diverse research fields, including structural engineering, biomechanics, transportation engineering, physics, applied mathematics, cognitive science, and psychology[1].

Research background

To address remaining gaps in relevant knowledge, the author's MSc research project at the University of Leeds, and later doctoral research at the University of Leicester, focused on measuring and reproducing the underlying dynamics of PSI and PPI. This was done in a real-world setting, i.e. outside of a laboratory, and without the presence of PSI **(Figure 1a)**, to isolate and better understand PPI. Through this approach, the magnitude and directionality of PPI in a walking group were quantified, providing empirical data readily applicable to simulating realistic crowd motions.

Furthermore, the connection between various levels of gait synchronisation among pedestrians and the dynamic response of a structure was studied. This was done by performing a series of parametric numerical simulations on a crowd-occupied model bridge, as well as during real bridge tests with coordinated crowds. The structural responses were then assessed against the estimates prescribed in the latest international design guidelines for structural response under pedestrian occupancy.

Finally, to improve the reliability and repeatability of future PPI studies, a novel virtual reality (VR) experimental platform was designed and validated **(Figure 1b)**. The platform allows for the creation and simulation of biomechanically representative virtual walkers and assesses the interaction of real people with them. To achieve this,



a) Determination of magnitude and directionality of PPI in overground walking groups

b) Validation of novel VR experimental platform created to streamline future PPI studies

↑FIGURE 1: Two studies performed as part of doctoral research[23-26]

a fusion of state-of-the-art technology was employed, including motion-capture systems, artificial intelligence, and computer modelling.

Challenge meets research background

Battersea Power Station is a Grade II* listed landmark that was transformed from an industrial relict in the heart of London to an exciting retail, leisure and cultural destination that opened to the public in October 2022[27]. Sitting at the heart of an eight-phase masterplan, the power station is home to over 100 shops, bars, restaurants, 254 apartments, offices, leisure, and event venues.

As part of the site's regeneration, Buro Happold provided multidisciplinary engineering services, and the Bridge Team, along with WilkinsonEyre architects, designed the Malaysia Square Pedestrian Bridge (MSPB). The bridge **(Figure 2)** was subsequently constructed by Hollandia with Mace acting as construction manager.

The footbridge is π-shaped in plan and is located at the south face of the power station. It provides a dual entrance to the building while bridging over the main entrance at the level below. It consists of a trapezoidal box girder made of welded steel plates, supported on spherical bearings at all support locations.

According to the numerical model of the bridge prepared by Buro Happold, the natural frequency of the first vertical vibration mode falls within the critical frequency range for pedestrian excitation, as specified by Eurocode 1. As a result, the design of the bridge called for dual TMDs to control, through supplementary damping, excessive response owing to collective pedestrian-induced excitation.

To confirm the numerical findings, resulting from known limitations of the codified method of dynamic analysis of this as-per-design prospect, Buro Happold, on behalf of Battersea Power Station Development Company, formulated a practical research project encompassing structural monitoring and inverse analysis. The aim of the project was to uncover the real as-built dynamic state of the partly completed and unconventionally-shaped MSPB structure. A team of expert researchers from the Universities of Leeds, Leicester and Wrocław, Poland was formed to boost the effort with state-of-the-art skills and tools in experimental dynamics.

Tracking the dynamic characteristics, particularly modal damping in novel structural designs, is beyond a standard process, and typical artefacts can easily lead to LMFB-type failures which translate to bridge downtime, resulting in major economic and PR ramifications.

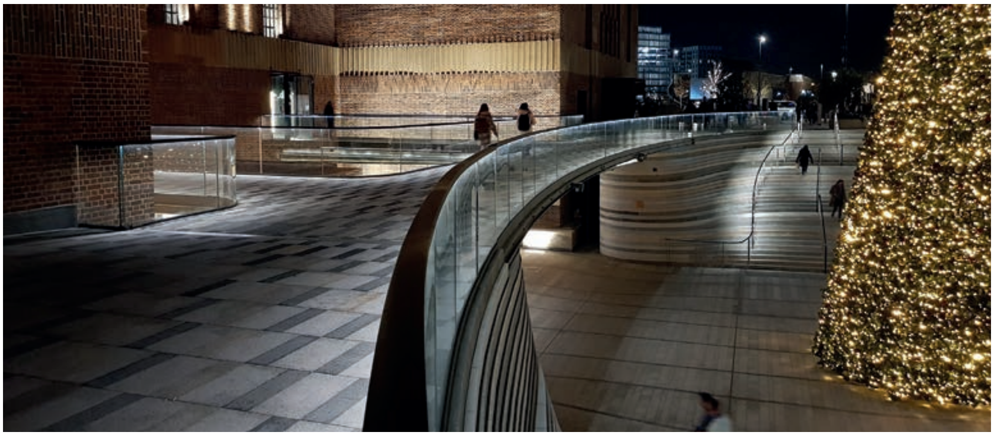
As part of the main experimental campaign, the APS 400 shaker **(Figure 3a)** was roved along the main span to provide controlled vertical energy input. The shaker was accompanied by six ultra-low-noise Kinemetrics EpiSensor ES-U2 force balance uniaxial accelerometers, which measured the distributed structural acceleration response.

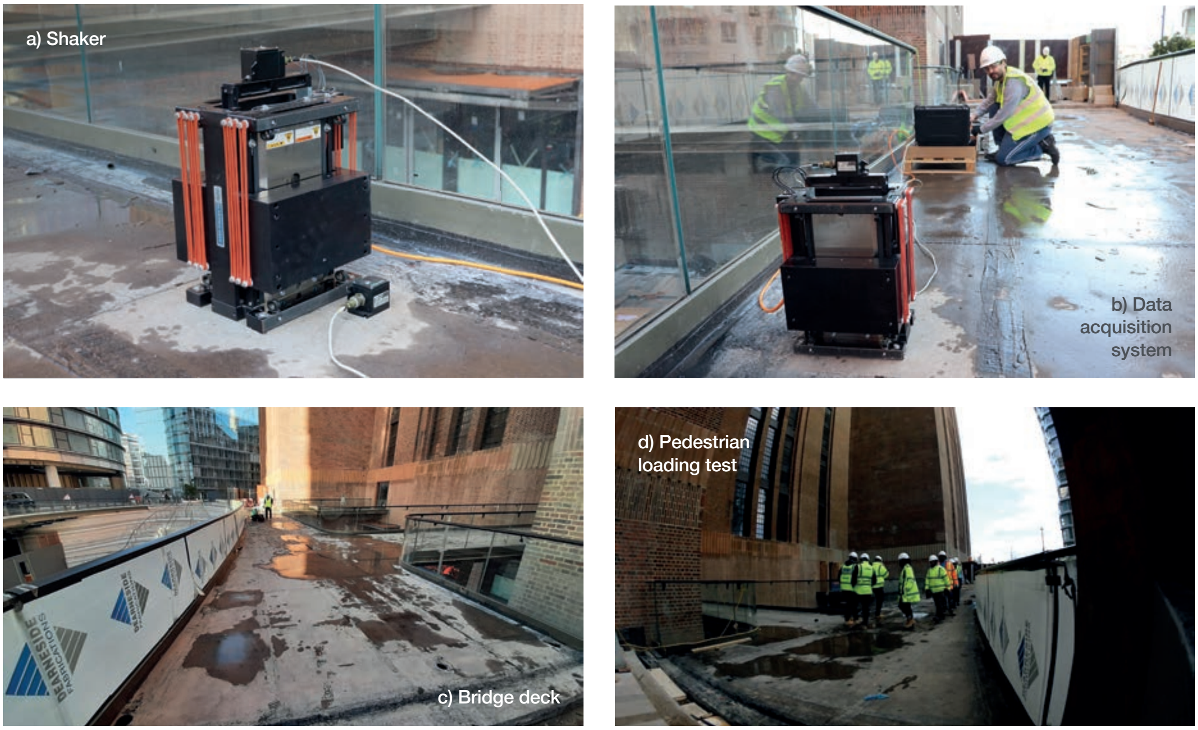
The campaign consisted of a mix of shaker and 'natural' human-induced excitations. The former included sine chirp and white noise signals, whereas the latter included heel drop tests, jumping tests, and a routine of coordinated pedestrian loading tests. During the latter routine, a mixed group of eight pedestrians walked back and forth across the main span, in a front-to-back arrangement (one after another) with a pacemaker **(Figure 3d)**.

The pacemaker, who was always the first in the walking group, was instructed to walk to the beat of a metronome set at frequencies spanning from 1.0Hz to 2.5Hz (i.e. where walking conventionally crosses to running) at 0.1Hz step intervals. All pedestrians walking behind the pacemaker were instructed to synchronise to their best ability with the person immediately in front of them.

The results of the experimental campaign proved that the mode of vibration of concern was well controlled by the inherent structural damping, which was underestimated in the design phase. This was due to the damping effects of relatively heavy

↘FIGURE 2: Malaysia Square Pedestrian Bridge after completion





➔FIGURE 3: Snapshots from testing campaign

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finishes, such as paving and glass parapets, not accounted for in codified analysis methods.

The outcome was that the resulting vertical accelerations fell easily within the comfort criteria outlined in the relevant guidelines, eliminating the need to revert to costly external damping appendices. On more high-end features, MSPB proved to be a very modally 'clean' structure, where all higher pedestrian force harmonics could be clearly recognised, and further PSI effects could be easily quantified and compared with associated design guidance.

Research and practice in unison

As a direct consequence of the study performed on the MSPB, a decision was made not to install TMDs on the bridge, leading to significant cost savings in construction and maintenance. The work highlighted how even the most meticulous and detailed design, based on modern design standards, can prove defective without the invaluable validation of experimental data.

Structural monitoring tools and culture should not be seen as a privilege of the specialist academic community alone, but rather as a practical tool in the hands of designers that can gain confidence and deliver even more economical and efficient designs.

Finally, the organisation and the logistics of the experimental campaign can serve as a blueprint for academic-industrial collaborations. The entire study was organised in under a month and involved the coordination of an international academic group with the structure's owner, managing contractor and engineering designer, costing little but gaining a lot!

Acknowledgements

The author would like to acknowledge Dr Mateusz Bocian for his supervision during the doctoral research and his input in the dynamic testing of the MSBP; Dr Nikolas Nikitas for planning, coordinating and executing the experimental campaign on the MSBP and Mr Wentao Yin for assisting in data collection; and the Buro Happold Bridge Team consisting of Mr Edmund Metters and Mr Thomas Eckhart.

REFERENCES

1) Venuti F. and Bruno L. (2009) 'Crowd-structure interaction in lively footbridges under synchronous lateral excitation: a literature review," *Phys. Life Rev.*, 6 (3), pp. 176–206; https://doi.org/10.1016/j.plrev.2009.07.001

2) Dallard P., Fitzpatrick A.J., Flint A. *et al.* (2001) 'The London Millennium Footbridge', *The Structural Engineer*, 79 (22), pp. 17–33

3) Dallard P., Fitzpatrick A.J., Flint A. *et al.* (2001) 'London Millennium Bridge: pedestrian-induced lateral vibration', *J. Bridg. Eng.*, 6 (6), pp. 412–417; https://doi.org/10.1061/(ASCE)1084-0702(2001)6:6(412)

4) Dallard P. (2005) 'Pedestrian excitation on the London Millennium Footbridge', *Structures Congress 2005: Metropolis and Beyond*, pp. 1–13; https://doi.org/10.1061/40753(171)138

5) Fitzpatrick A., Dallard P., Le Bourva S. *et al.* (2001) *Linking London: the millennium bridge*, London: Royal Academy of Engineering

6) Brownjohn J.M.W., Fok P., Roche M. and Moyo P. (2004) 'Long span steel pedestrian bridge at Singapore Changi Airport - Part 1: Prediction of vibration serviceability problems', *The Structural Engineer,* 82 (16), pp. 21–27

7) Brownjohn J.M.W., Fok P., Roche M. and Omenzetter P. (2004) 'Long span steel pedestrian bridge at Singapore Changi Airport - Part 2: Crowd loading tests and vibration mitigation measures', *The Structural Engineer,* 82 (16), pp. 28–34

8) Butz C., Distl J. and Huber P. (2020) 'Effectiveness of horizontal tuned mass dampers exemplified at the footbridge in Coimbra', Third International Conference on Footbridges, Porto, 2–4 July, In: *Footbridge 2008 – Footbridges for Urban Renewal*, pp. 311–312 [Online] Available at: https://structurae.net/en/literature/conference-paper/effectiveness-of-horizontal-tuned-mass-dampers-exemplified-at-the-footbridge-in-coimbra (Accessed: December 2020)

9) Caetano E., Cunha Á., Moutinho C. and Magalhães F. (2010) 'Studies for controlling human-induced vibration of the Pedro e Inês footbridge, Portugal. Part 2: Implementation of tuned mass dampers', *Eng. Struct.*, 32 (4), pp. 1082–1091; https://doi.org/10.1016/j.engstruct.2009.12.033

10) Caetano E., Cunha Á., Magalhães F. and Moutinho C. (2010) 'Studies for controlling human-induced vibration of the Pedro e Inês footbridge, Portugal. Part 1: Assessment of dynamic behaviour," *Eng. Struct.*, 32 (4), pp. 1069–1081;

https://doi.org/10.1016/j.engstruct.2009.12.034

11) Kawasaki T., Nakamura S. and Ohno K. (2004) 'Field measurement of lateral vibration of a suspension bridge induced by pedestrians', *Doboku Gakkai Ronbunshu*, 2004 (777), pp. 97–107; https://doi.org/10.2208/jscej.2004.777_97

12) Nakamura S.-I. and Kawasaki T. (2006) 'Lateral vibration of footbridges by synchronous walking', *J. Constr. Steel Res.*, 62 (11), pp. 1148–1160; https://doi.org/10.1016/j.jcsr.2006.06.023

13) Hoorpah W., Flamand O. and Cespedes X. (2017) 'The Simone de Beauvoir Footbridge between Bercy Quay and Tolbiac Quay in Paris: Study and measurement of the dynamic behaviour of the structure under pedestrian loads and discussion of corrective modifications', In: Caetano E., Cunha Á., Hoorpah W. and Raoul J. (eds.) *Footbridge Vibration Design* (1st edn.), Leiden: CRC Press/Balkema, p. 202

14) Bocian M., Burn J.F., Macdonald J.H.G. and Brownjohn J.M.W. (2017) 'From phase drift to synchronisation – pedestrian stepping behaviour on laterally oscillating structures and consequences for dynamic stability', *J. Sound Vib.*, 392, pp. 382–399; https://doi.org/10.1016/j.jsv.2016.12.022

15) Fujino Y., Pacheco B.M., Nakamura S.-I. and Warnitchai P. (1993) 'Synchronization of human walking observed during lateral vibration of a congested pedestrian bridge', *Earthq. Eng. Struct. Dyn.*, 22 (9), pp. 741–758; https://doi.org/10.1002/eqe.4290220902

16) Nakamura S.-I. and Fujino Y. (2002) 'Lateral vibration on a pedestrian cable-stayed bridge', *Struct. Eng. Int.*, 12 (4), pp. 295–300; https://doi.org/10.2749/101686602777965162

17) Dziuba P., Grillaud G., Flamand O., Sanquier S. and Tétard Y. (2001) 'La passerelle Solférino. Comportement dynamique', *Bull. Ouvrages Métall.*, 1, pp. 34–57

18) Davies C. (2020) '£5m bill to mend wobbly Millennium Bridge', *The Telegraph* [Online] Available at: www.telegraph.co.uk/news/uknews/1374490/5m-bill-to-mend-wobbly-Millennium-Bridge.html (Accessed: December 2020)

19) Grundmann H., Kreuzinger H. and Schneider M. (1993) 'Dynamic calculation of footbridges', *Bauingenieur*, 68, pp. 215–225

20) Piccardo G. and Tubino F. (2008) 'Parametric resonance of flexible footbridges under crowd-induced lateral excitation', *J. Sound Vib.*, 311 (1–2), pp. 353–371; https://doi.org/10.1016/j.jsv.2007.09.008

21) Newl D.E. (2004) 'Pedestrian excitation of bridges', *Proc. Inst. Mech. Eng. Part C J. Mech. Eng. Sci.*, 218 (5), pp. 477–492; https://doi.org/10.1243/095440604323052274

22) Venuti F., Bruno L. and Napoli P. (2007) 'Pedestrian lateral action on lively footbridges: A new load model', *Struct. Eng. Int.*, 17 (3), pp. 236–241; https://doi.org/10.2749/101686607781645897

23) Soczawa-Stronczyk A.A., Bocian M., Wdowicka H. and Malin J. (2019) 'Topological assessment of gait synchronisation in overground walking groups', *Hum. Mov. Sci.*, 66, pp. 541–553; https://doi.org/10.1016/j.humov.2019.06.007

24) Soczawa-Stronczyk A.A. and Bocian M. (2020) 'Validation of a novel virtual reality platform for investigating pedestrian-pedestrian interaction in the context of structural vibration serviceability', *Proc. 11th International Conference on Structural Dynamics, Eurodyn 2020*, pp. 1777–1790; https://doi.org/10.47964/1120.9143.19028

25) Soczawa-Stronczyk A.A. and Bocian M. (2020) 'Gait coordination in overground walking with a virtual reality avatar', *R. Soc. Open Sci.*, 7 (7), 200622, 10.1098/rsos.200622; https://doi.org/10.1098/rsos.200622

26) Soczawa-Stronczyk A.A. (2021) 'Pedestrian–pedestrian interaction and its effects on vibration serviceability', PhD thesis, University of Leicester [Online] Available at: https://figshare.le.ac.uk/articles/thesis/Pedestrian-pedestrian_interaction_and_its_effects_on_vibration_serviceability/16558281 (Accessed: April 2024)

27) Phillips J., Robert F., Monteith R., Brooks M. and Youdan S. (2023) 'Battersea Power Station – regeneration of an icon', *The Structural Engineer*, 101 (10), pp. 24–33; https://doi.org/10.56330/ZBEO8463