SHAPED BY WALKING:
INNOVATIVE DYNAMIC DESIGN OF CHISWICK PARK FOOTBRIDGE

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Summary (maximum 15 lines)

The Chiswick Park Footbridge will be both a practical link and a sculptural addition to the Rogers Stirk Harbour + Partners business park in Chiswick, London. This paper describes how Expedition Engineering has led the design of this weathering-steel arch footbridge from feasibility stage through to construction, focussing on the performance based approach to pedestrian vibrations and its integration within the general design process. At each stage of the project, tools - ranging from back-of-envelope calculations to stochastic time-history simulations - were used to assess and design for dynamic behaviours not well covered by standard codes. Alongside these methods, appropriate performance criteria and dynamic loading scenarios were developed in a holistic manner.

A design has been developed which is not only shaped by architectural drivers, such as form and aesthetics, but is also shaped by the inherently interlinked engineering of pedestrian vibrations, flow-of-forces, constructability and maintenance. The best ideas and best designs only arise when the process is seamless.

Drawing on the experiences and lessons on this footbridge, performance based approaches dynamics and serviceability are now being researched and developed for future, including different building types and adaptive structures.

Keywords: design process; network arch; structural concepts; material efficiency; dynamics; serviceability; performance-based design

1. Introduction

Engineered structures are increasingly pushing the limits of materials. Whether for reasons of reducing material quantities, for sustainability purposes or just visual slenderness, there is a trend for buildings and bridges with lower stiffness and lower mass. Such structures are more likely to be susceptible to human/pedestrian induced vibrations; hence dynamic performance is likely to be an increasingly important design consideration. We see dynamics as part of central part of the design process not just a check at the end.

Traditional approaches to structural dynamics typically involve specialist study and analysis after many aspects of the design have already been finalised, and working to rigid pass/fail criteria which often do not cover real-world scenarios given that “acceptable” behaviour is subjective. Instead, it is useful to build a fuller picture of how the bridge would behave across a range of different scenarios, to feed into the holistic design process.

Dynamics should be considered at all stages of this design process - alongside aspects such as form development, deflections, and ultimate limit state strength considerations. In part this stems from the widely held view that an engineer’s influence on the design diminishes rapidly as a project progresses over time. The most influential decisions are almost always made during concept and scheme design stages, so considering dynamics sooner give the potential for better decision making and a better final design.

Over a number of years, our experience has evolved over a range of different projects including the Stockton Infinity Footbridge, London 2012 Olympic Velodrome and Chiswick Park footbridge. We have moved from a ‘traditional’ dynamic design approach to a holistic, performance based approach which is integral throughout the whole design process from concept to construction. This paper describes the approach taken for the Chiswick Park footbridge (see Figures 1 and 2). It covers the development of performance based vibration design criteria, and gives an overview of the detailed dynamic design approach. Finally, the paper summarises the benefits that this had on the bridge; how it was Shaped By Walking.

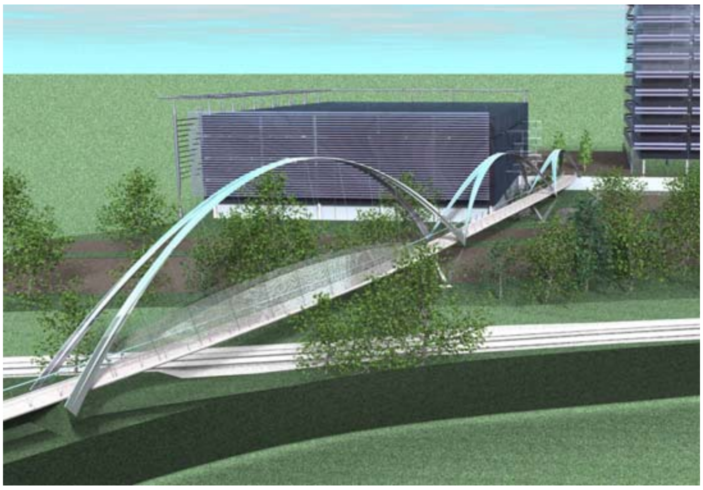


Figure 1: Chiswick Park Footbridge concept image (Expedition)

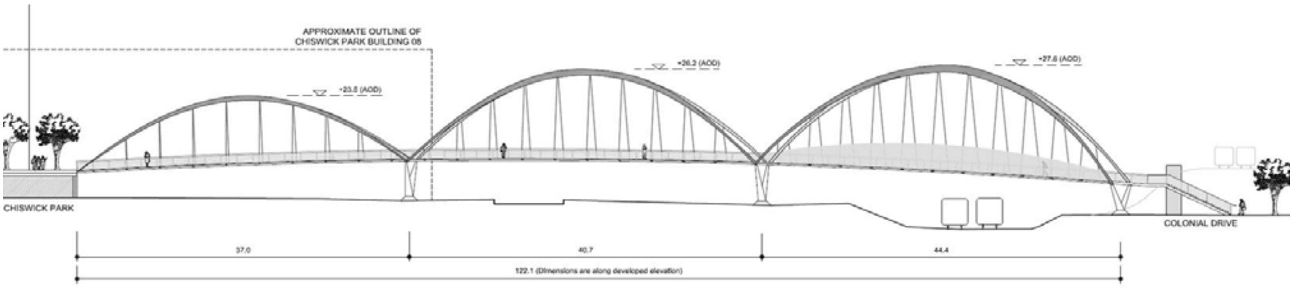


Figure 2: Chiswick Park Footbridge elevation from early in the design process (Expedition)

2. Background

As is well known, the London Millennium Footbridge brought pedestrian-induced vibrations into the public eye, and sparked significant interest and research by the structural engineering profession. Many key research papers were published around this time, including Dallard [1] on lateral synchronisation, Fletcher [2] on this use of time history simulations of serviceability vibrations, and later JRC53442 [3] (a pan-European report on this field). The aim of this paper is not to provide a full review or even a summary of this extensive research field, rather to present our experiences and lessons relating to pedestrian vibrations, from a design practice perspective.

A few years after the turn of the millennium, Expedition was lead designer for a footbridge in West London (not constructed) and then for Stockton Infinity Footbridge. Although drawing on this latest technical research, the design process was relatively conventional for both bridges. Concept design focussed on form finding and statics, with dynamics studied in detail once the project was well advanced. The result for both bridges was use of tuned mass dampers integrated in the deck detailing to give suitable dynamic performance (see Figure 3), rather than adding extra steel or concrete. More details of the Stockton Infinity Footbridge dynamic design are given by McRobie [4], which also derives an extension to the Arup lateral synchronisation criteria for the more complicated lateral vibration modes that are often associated with arch bridges.

Another significant project on which human induced vibrations was a key design consideration was the London 2012 Olympic Velodrome [5]. With the engineering design undertaken by Expedition throughout 2008-2009, it was quickly apparent from the very earliest engineering analysis models of the superstructure that critical natural frequencies would be in the range 2-3Hz; precisely those most excited by a crowd and substantially below the frequencies normally deemed acceptable in stadium design.

One option was to increase steel member sizes to stiffen the structure to meet a strict natural frequency criterion. However, the team felt that increasing steel tonnages for the seating bowl would not be a good design solution and would affect sustainability considerably. Instead the team proposed adoption of a performance-based approach. Aided by a draft version of the Institution of Structural Engineers' stadium dynamics guidance [6], our holistic performance-based approach enabled a 30% reduction in steel tonnage.

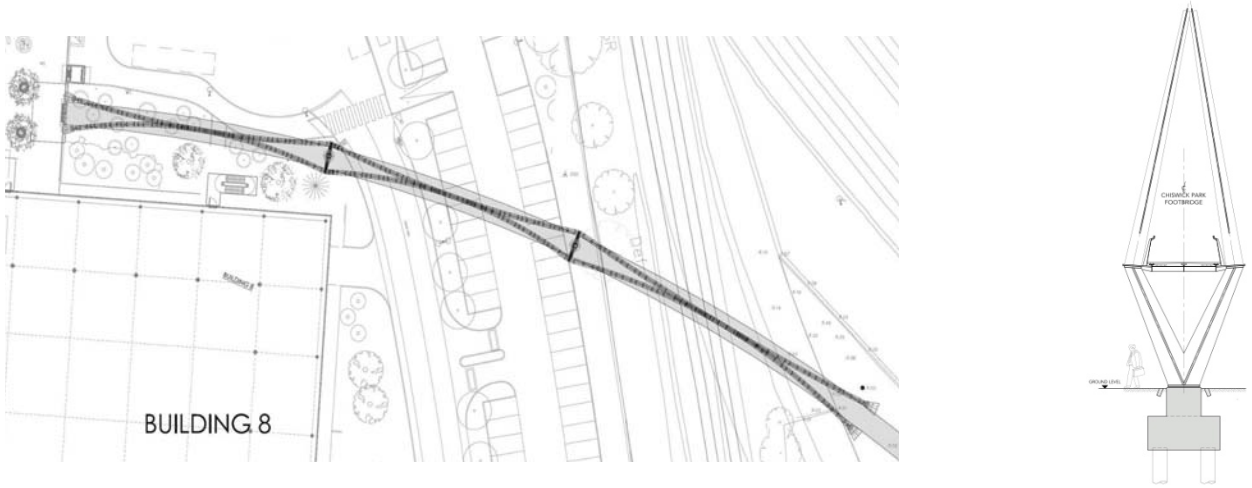
3. Design approach for the Chiswick Park Footbridge

In 2011, Expedition was appointed lead designer for a new footbridge to link Chiswick Park London Underground Station with a recently completed business park (by Arup and Rogers Stirk Harbour & Partner). There were a number of design drivers, including:

- providing a direct route for commuters walking to work
- desire for a slender aesthetic to complement the high-end office development
- a set of tight geometrical constraints on site
- crossing a railway and highway.

An evolution of our approach to structural dynamics was possible, bringing together technical/analytical methods from the Infinity Bridge and the performance based philosophy from the London Velodrome. Initially, it was considered that the recommendations of UK National Annex to EN1991-2 [7] would be directly applicable (and indeed it has proved relevant for a number of simpler bridges designs both before and after). However the shape and configuration of the Chiswick Park Bridge involved some more complicated dynamic behaviour, necessitating a more bespoke approach.

The concept for the bridge is a three-span tied arch bridge with a total length of 120m, with spans of 35 m, 40 m and 45 m. The deck and arch are primarily weathering steel for aesthetic and maintenance reasons. Hanger cables were to be used to suspend the deck, which itself acted to tie the arch thrusts. As can be seen from Figures 2 and 4(a) it is curved in plan and elevation in order to meet tight constraints on foundation positions, pass over Network Rail train lines, over bus routes on Chiswick Park road and stay within appropriate deck gradients for accessibility. To provide an interesting aesthetic in keeping with the business park and fit within the space available for foundations, the support legs and cross section are tapered; see Figure 4(b). The end result could be a bridge with unusual dynamic behaviour, which we tackled using a suite of tools at each stage of the project, summarised in Table 1.



(a) (b)

Figure 4: Chiswick Park Footbridge in (a) Plan and (b) Section (Expedition)

Table 1: Overview of project stages and tools utilised

Project stage	Dynamic Design Tools
Concept	Hand calculations and global assessments
Scheme	Simple spreadsheet for combined V/T/L modes + initial dynamic FE model
Design development	Developed spreadsheet inc. harmonics & combined modes Time-history simulation (Matlab) of key scenarios + dynamic FE model with further validation
Detail/final	Time-history simulations (Matlab) covering multi scenarios + dynamic FE model with sensitivity studies

Even at concept design stage, the engineering analysis models (carried out using Oasys GSA FE software) used for form finding the arches were developed to provide an initial understanding of dynamic behaviour. Figures 5 and 6 show some of the key vibration modes, from which it quickly became apparent were in the frequency range excitable by pedestrians, 0.5 Hz to 5 Hz+. Interestingly, many of the modes were 'mixed'; they contained a combination of vertical, horizontal and torsional movement. This was a result of a bridge curved in plan and in elevation. Dynamically, this was of particular concern because they could be excited by vertical pedestrian forces (which are larger than lateral pedestrian forces) but would also cause lateral movements (the direction in which people are most sensitive). Also, this is an area which is not well covered by code approaches [7] [8] [9].

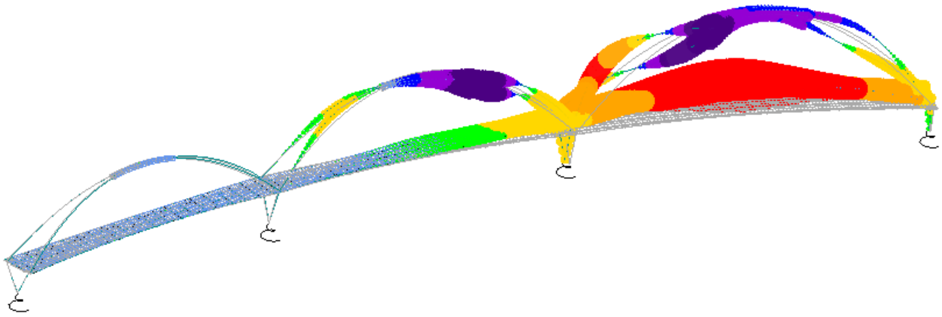


Figure 5: Deck-arch vibration mode with combined vertical, lateral and torsional motion (Expedition)

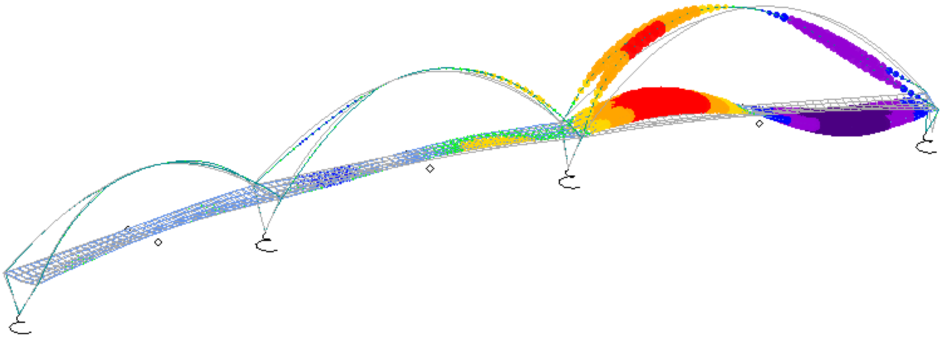


Figure 6: Deck-arch vibration mode at low frequency due to form-found slender arch with low bending stiffness. (Expedition)

When designing many form-found arch footbridges it is quite common to find one or more critical vertical modes. Typically the arch is given a shape effective for resisting static and relatively uniform loads – optimising the shape reduces bending moment in the arch itself and hence designers may wish to derive a form with relatively low bending stiffness. As a direct result, vertical vibration modes then exist at lower frequency. In the case of Chiswick Park footbridge each of the three arches had a first vertical mode in the range 1.5-2.5Hz, which could have easily been excited by pedestrians. Hence this is one of the key areas where the bridge was significantly "shaped by walking" rather than a pure form found arch with members highly refined for strength alone.

For the Chiswick bridge concept design, quick analysis was carried out; not just looking at natural frequencies but also modal masses, in order to get ballpark figures for accelerations induced by dynamic walking/running forces for groups of 8-15 people or a handful of joggers. Bringing together key equations from the EC1 UK National Annex [7], Meirovitch [10], and extensive simulation results from Stockton Infinity Bridge, we based a series of quick initial assessments on:

$$A_{peak} = \frac{F\sqrt{n}}{2\zeta M} \tag{1}$$

Where:
A_{peak} = Estimate of peak acceleration (m/s^2)
F = Dynamic force (Newtons), typically 5%-40% of weight of a walker
n = Number of people walking/jogging on bridge
ζ = Damping (% of critical), taken as 0.5%
M = Mass of dynamic mode under consideration (kg)

This equation was used for initial hand calculations, but additional tools were needed due to the complexities of a real bridge. We developed initial assessment tools by building from this equation, combining effects of different modes and also forcing harmonics, tabulating results from both walkers and joggers.

These initial assessments indicated, even at very early design stages, that dynamics would be a key design driver. Specifically, lateral and vertical serviceability/comfort was seen to be important, although lateral synchronisation was not since no lateral vibration modes fell in the range 0.5-2Hz [1]. Towards the end of the concept design phase the bridge design evolved from a deck conventionally suspended on vertical hangers to a “network arch” bridge with inclined hanger cables; boosting the ‘vertical’ stiffness and thus raising first vertical modal frequencies to 3.5-4.5Hz. The philosophy for the legs also began to evolve, with a shift in cross section shape to provide additional lateral stiffness.

Although these initial assessments were influencing significant design decisions, it was clear that further development of the design would need to be based on a fuller, realistic, set of dynamic criteria for a bridge in this context.

4. Development of design criteria

Broadly, we needed to determine (i) a set of realistic dynamic loading scenarios of differing likelihood and (ii) target criteria for the bridge performance under these scenarios.

The loading scenarios were developed from a series of design team discussions, feeding in estimated usage data from the client for this large business park. For any bridge this is an important early design step because, for example, a specific vibration mode of the bridge may be susceptible to a single runner but not a large crowd. Some key scenarios are given in Table 2.

Table 2: Summary of pedestrian scenarios

SCENARIO	TECHNICAL DETAILS	BASIS OF SCENARIO
Continuous stream of commuters	15 people walking on each span at any one time (not synchronised). Check for comfort and lateral ‘lock-in’.	Code recommendations [7].
Bunched commuters (tube/bus arrival)	85 people walk over bridge once (not synchronised). Check for comfort and lateral ‘lock-in’.	Assessment of client usage requirements and site context.
Runners	3 runners in-step. Check for comfort.	Code recommendations [7].
Jogging club	8 joggers (not synchronised). Check for comfort.	Assessment of site context in Chiswick.
Vandals / deliberate excitation	One or two vandals on ‘sweet spot’. Check for excessive vibrations + comfort in adjacent spans.	Assessment of site context near high end business park.

The first scenario in the table is derived from code recommendations [7], and by considering the Client’s Brief which states the bridge is to accommodate up to 1000 people per hour. Assuming this is spread over a 30 minute period in the morning, commuters walking at 2.2Hz and 2m/s would be spaced 30x60/1000 x 2 = 3.5m apart. This equates to 30-40 people spread over the 120m long bridge at any moment in time. Therefore we will take 15 people per span, replenished, to study the steady state response of the bridge.

The second scenario considers that the eastern end of the bridge is 300 m from a tube station. Taking 1000 people per hour, arriving on tube trains at 5 minute intervals, equates to 1000/(60/5) = 85 people in each group. We assume that this will be spread over a 120m length, and will walk across the bridge with no replenishment.

Target criteria performance criteria were generally expressed in terms of accelerations since humans perceive accelerations as is well established in structural dynamics. However, human perception of vibration is subjective [11]. For a given acceleration level one person might complain vociferously whilst another may have barely noticed the motion. In addition, dynamic forces exerted by pedestrians on a bridge need an element of stochastic modelling; if a given group of people were to walk across the bridge a number of times, the resulting acceleration of the deck would not be identical each time. In some large part this is due to probabilistic variations in the pacing frequency, speed and gait of individuals, and their tendency (or not) to walk partially in step with others from the group.

As a result, although we drew on Eurocode recommended limits of 0.7m/s2 for vertical accelerations and $0.2m/s^2$ for lateral accelerations [1], we also tried to build a fuller picture of how the bridge would behave in unusual and/or exceptional scenarios. For example, should a running club or football team decide to jog across partially in-step (outside UK code requirement) then clearly adherence to 0.7m/s2 would be uneconomic – however holistically we concluded that this would be an unusual case but not exceptional. Thus it was felt that vertical accelerations around 40% greater would still be acceptable c.f. JRC53442 Table 4-4 [3]. A crowd filled bridge was, however, deemed unrealistic and exceptional due to the bridge location – but a minimum level of comfort was deemed necessary to prevent danger or fright – therefore $<2.5m/s^2$ was taken for vertical acceleration. Consultations with the wider project team aided the development of these scenarios and acceptable performance criteria. At each design review or progress meeting, dynamics considerations were carefully communicated.

5. Detailed design

As the bridge design developed, and as the need for certainty over dynamic performance increased, we began more detailed simulation of the bridge behaviour which was based around time-history analysis for the full set of pedestrian loading scenarios. Using our in-house software we invested some time at the beginning of the detailed design stage to set up all the simulations, which enabled quick re-analysis of behaviour of the latest bridge design as it was being developed by the team.

The in-house software, based in Matlab, has inputs including: mode shapes, frequencies and masses from a finite element model, then user inputs of damping and time step size. Additionally, fully bespoke loading scenarios are input which can account for any number of people, moving at a specified speed distribution across/along the bridge, with a specified frequency distribution, and user-input Fourier coefficients for forces (to cover walking, jogging and running, for example see [3] Table 9-1). The software, created initially by Allan McRobie of Cambridge University and then developed over a number of years by Expedition, was enhanced to simulate more complicated and unusual 'combined' modes where the vibration mode is a mixture of vertical, lateral and torsional motion.

As indicated in the section above the input loading is stochastic in nature, which means that running the same scenario twice will not give exactly the same level of vibration. For example, a group of fifteen pedestrians (unsynchronised) will vary slightly in walking frequency, speed and spatial distribution, both in the physical world and in our simulations. Thus each scenario was run a number of times, initially taken as ten. We then took the peak accelerations from these ten scenarios then calculated the mean, standard deviation and the 95% confidence level on bridge performance. Two sample results charts are given in Figures 7 and 8, which can also be related back to the discussion about unusual/exceptional behaviour towards the end of the Development of Design Criteria section above. Our aim was not to say "in scenario X the bridge performance will be precisely Y, which is/isn't acceptable". Rather our aim was to build a picture of likely performance across a range of scenarios, from which the wider team could make holistic decisions and further design choices.

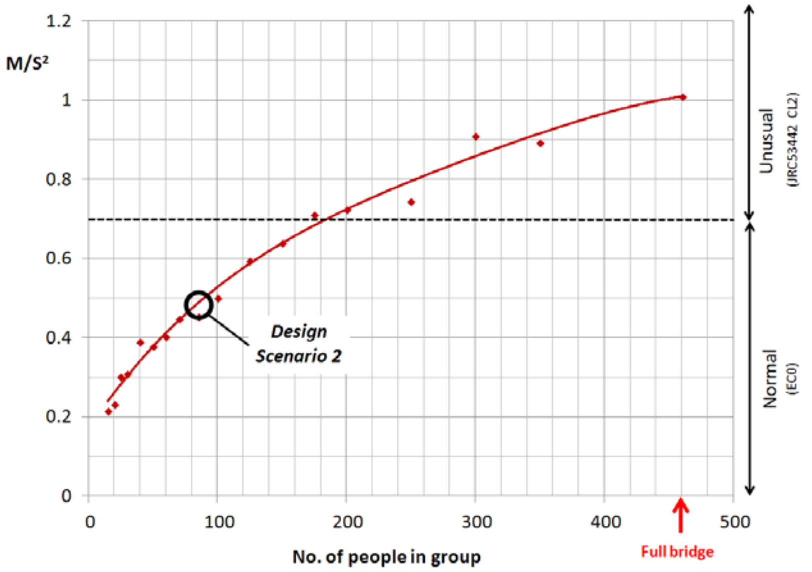


Figure 7: Simulated vertical accelerations due to vertical forces from group of walkers @ 2.2Hz, 95th percentile confidence level (Expedition)

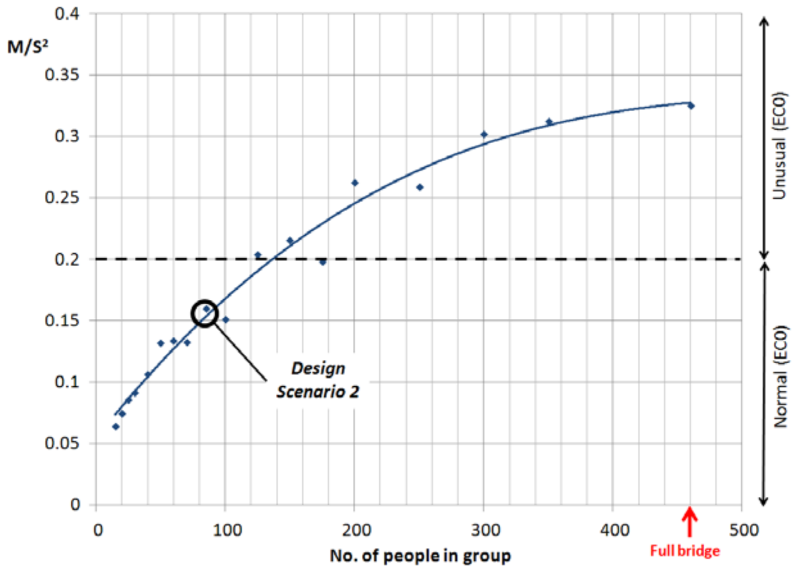


Figure 8: Simulated lateral accelerations due to vertical forces from group of walkers @ 2.2Hz, 95th percentile confidence level (Expedition)

6. Shaped by Walking

The iterative process of quick assessment and then increasingly in-depth simulation allowed the bridge design to develop in a different manner to a traditional design process. Some of the main changes and benefits are highlighted below:

- Initial assessments and calculations allowed the early decision to exchange vertical for inclined hanger cables to improve performance. This single change added approximately 98 cables (with a slight reduction in diameter) but enabled the possibility of no dampers, in keeping with the overall design philosophy of minimum maintenance. It gives the bridge increased robustness and also an interesting aesthetic.
- Refined dynamic analysis at the detailed design stage allowed us to simply explore positions for, and masses of, tuned mass dampers that may be required in the event that the as-built bridge natural frequencies differed from estimates. With very minor refinements to deck stiffener design, at negligible cost, spaces for tuned mass dampers were provided over the largest span with positions access from above the deck. Choice was then given to the client to allow for contingency of procuring dampers at a later date.
- A number of local refinements to the design resulted. The cross section of the legs was optimised, by moving material to provide increased lateral stiffness and slightly reduced longitudinal stiffness. Weathering steel deck stiffeners were influenced in different ways. Laterally, between hanger cables, they were governed by dynamics, affecting vertical natural frequency. Conversely, from a very early stage it was seen that longitudinal stiffeners were governed by strength considerations for the curved deck, not lateral or torsional dynamics.

Understanding and presenting a broader picture on pedestrian induced vibrations, rather than just a pass/fail assessment at the end of the project, has improved many integrated aspects of the design. It gives a tuned balance between deck weight, material usage, maintenance requirements, arch buckling and vibration performance. Overall, the performance based design approach with more integrated dynamics considerations will lead to a better bridge for Chiswick Park.

7. The Future

At the time of writing the bridge is out to tender, with construction scheduled to start towards the end of 2014. Upon completion we will be carrying out on-site testing to validate the dynamic design.

Performance based design approaches are a way for everyone in the team to understand better the impacts of pedestrian dynamics, something that we are increasingly seeing on other projects both as designers and as CATIII checkers. It is also an exciting area for structural engineers to exploit more widely in a resource-conscious society, when rigidly adhering to (often very subjective) serviceability limits can result in significant overuse of material. Expedition is currently constructing a research prototype for a slender adaptive truss, with steel members sized for strength only and strategically placed actuators to cope with serviceability needs. This demonstrator re-thinks traditional design philosophies, and we hope it will be stepping stone for novel performance based design in the future.

Figure 9: ‘Shaped design’ of the Chiswick Park footbridge (Expedition)

8. Acknowledgements

The client for this project was Blackstone and Stanhope the developer. We would like thank Arup, who were CATIII checkers for this footbridge. Thank you also to Allan McRobie of Cambridge University for numerous invaluable thought-provoking discussions. The approaches and methods used for Chiswick bridge built on much of the previous work that Allan did with us on the Stockton Infinity Footbridge a number of years ago.

9. References

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