DAMPER RETROFIT OF THE LONDON MILLENNIUM FOOTBRIDGE – A CASE STUDY IN BIODYNAMIC DESIGN

Douglas P. Taylor
Taylor Devices, Inc.
90 Taylor Drive
North Tonawanda, NY 14120-0748
716-694-0800

ABSTRACT

The Millennium Footbridge was opened to the public on June 10, 2000 – the first new bridge across the River Thames in historic London in more than a century. Nearly 100,000 people used the new bridge in its first day of operation. On June 12, 2000, the Millennium Bridge was ordered closed, due to hazardous deck motions. Seemingly random pedestrian footfalls were causing resonance of the bridge deck, with lateral accelerations measuring up to 0.25 g.

The selected method of retrofit was to add fluid damping to the bridge – and test the structure with groups of up to 2,000 people.

INTRODUCTION

The London Millennium footbridge is sited on the River Thames in London, United Kingdom, between St. Peter’s Hill and St. Paul’s Cathedral on the north bank of the river, and the Borough of Southwark with the nearby Globe Theater and Tate Modern Art Museum on the South. The Millennium Bridge is the first new bridge across the Thames in London in more than a century, and was the result of an intense competitive bid process, with more than 200 competing design entries. Each team consisted of an architect, an engineer, and an artist. The winning team was Foster and Partners (architects), ARUP (engineers), and sculptor Sir Anthony Caro.

As with any modern construction in a historic area, considerations were expected in the final bridge design to accept the latest design codes and local design ordinances, while preserving and protecting the historic context of the site. In this case, the bridge design constraints included a maximum height limitation, so that tourists would be provided an unobstructed view of the area. An additional constraint was the requirement for the bridge design to allow adequate clearance for marine traffic on the River Thames. When these two constraints were applied, only a very small vertical window remained for construction of the bridge itself.

The bridge design team elected to use lateral suspension cables, where the cables are located at the level of the bridge deck. Two piers are located in the river, with a main span of 144 m between piers, and end spans of 81 m on the north and 108 m on the south. The bridge deck is 4 m wide, and uses articulated sliding joints spaced at regular intervals along its length. The architectural design theme for the Millennium Bridge is that of a “Blade of Light”; expressed and exemplified by the slender, ribbon-like cross section of the structure. A photograph of the bridge is provided as Figure 1.

BRIDGE OPENING – JUNE 10, 2000

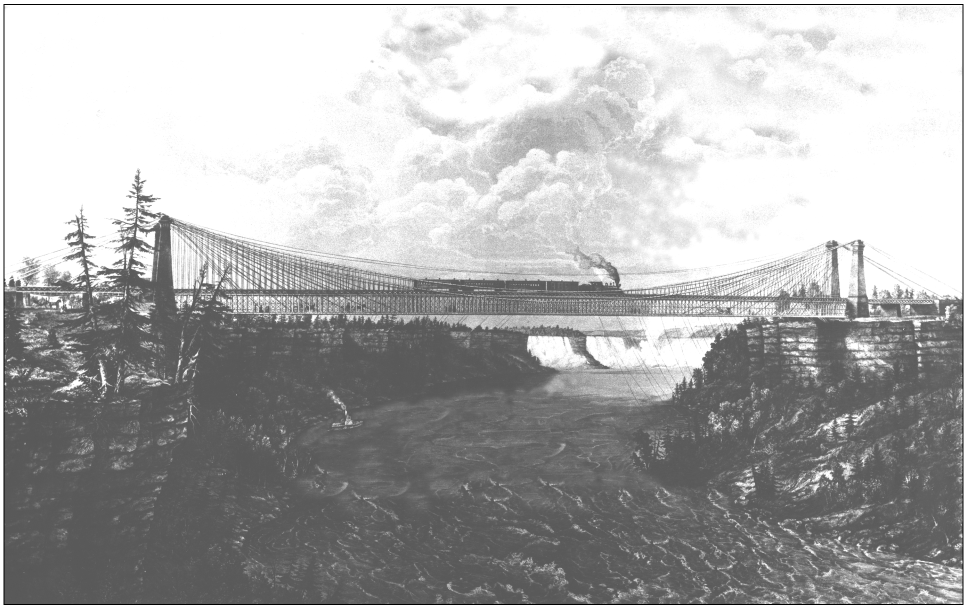
The Millennium Bridge was officially opened to the public on June 10, 2000, and immediate problems were noted. Maximum pedestrian loads of 2,000 people filled the entire bridge deck to capacity, with a resulting loading density of approximately 1.5 people per square meter. Under these conditions, the bridge exhibited severe lateral sway in a frequency band of 0.5 to 1.1 Hz, with lateral accelerations of up to 0.25 g. As many as five separate structural modes were being excited, and pedestrians found it virtually impossible to walk on the bridge. Many held on to deck handrails for support. On June 11, the number of people allowed on the bridge at one time was reduced, but the lateral shaking periodically reoccurred. On June 12, 2000, the bridge was closed and an extensive analysis and study of the vibration phenomena began. Dallard, Fitzpatrick et al (2001) [1] report on the bridge design and the subsequent extensive research that transpired after the bridge was closed. The severity of the problem was exacerbated by the ever-prolific media, with press headlines such as these:

> **"Wobbling Bridge Will Stay Shut" – BBC NEWS**
>
> **"£2 Million to Fix the Wibbly Wobbly Way and it Won't Open Until the Spring" – DAILY PRESS**
>
> **"The Sleek New Footbridge Across the Thames Swayed and Wobbled in the Wind so Much that Some Feared London's Bridge was Falling Down" – WASHINGTON POST**

THE PROBLEM

The phenomena of forced harmonic excitation of bridge structures is well understood, and has been well documented by many sources. Most military manuals dating back well into the 1800's have warnings about soldiers marching in step over bridges of any type. This was true even for substantial bridges. For example, in 1860 the famous 1854 Roebling two-deck railway suspension bridge across the Niagara River at Niagara Falls, NY USA was posted with a warning notice to pedestrians against walking in-step. This heavily built, record-setting span is depicted in Figure 2, from an 1850's engraving. The warning notice, reproduced from period photographs, is shown in Figure 3.

FIGURE 1
THE MILLENNIUM BRIDGE



D.L. Glover

FIGURE 2
JOHN ROEBLING'S RAILWAY SUSPENSION BRIDGE AT NIAGARA FALLS, NY – 1854

NOTICE

"A fine of $50. to $100. will be imposed for marching over this bridge in rank and file or to music, or by keeping regular step. Bodies of men or troops must be kept out of step when passing over this bridge. No musical band will be allowed to play while crossing except when seated in wagons or carriages"

FIGURE 3
WARNING NOTICE
RAILWAY SUSPENSION BRIDGE AT NIAGARA FALLS, NY USA , CIRCA 1860

What was unique about the Millennium Bridge was that resonance was occurring without any expected forced motion or marching. Indeed, the pedestrian motion appeared to be purely random in nature. After extensive review of available video footage during the period the bridge was open, a series of tests were performed to study the observed pedestrian-induced motion. These identified a unique biodynamic feedback phenomena, later called "synchronous lateral footfall," which resulted in seemingly random walking motions becoming synchronized over time among members of an unrelated group of people on the bridge.

In essence, when groups of more than 200 people were on the bridge, the loadings induced by their footfalls were indeed random, up until the point when a significant number of the people would, by pure chance, step in unison. This would produce a tiny, but still perceptible lateral motion at the first lateral mode frequency of the bridge. Depending on group size and location on the bridge, this first lateral mode was in the range of 0.5 Hz to 1.0 Hz. Frequencies in this bandwidth are coincident with a normal walking pace, and the bridge structure would respond at the same frequency, thus providing positive feedback to the pedestrians. This positive feedback would cause other group members to also begin walking in phase with the motion, providing an amplified input to the bridge structure, with the resultant amplified feedback. Since the bridge structure was essentially undamped, the amplification would continue until a large number of people either stopped walking, or were unable to walk due to the excessive motion. During the amplification process, the large induced lateral motions also excited higher modes in the bridge structure, causing even more discomfort to the occupants. Clearly, the solution to the problem involved finding a means to completely eliminate the biodynamic feedback between pedestrians and the bridge.

POTENTIAL SOLUTIONS

The project team evaluated numerous concepts that would reduce or eliminate the feedback response. The most promising solutions were:

- ***Stiffening the Bridge***

  Stiffening of the bridge structure could be accomplished by adding bracing or additional piers. Since the stiffening approach would have to shift frequencies as low as 0.50 Hz to values well above 1.0 Hz, a substantial amount of structural modifications would be required. The resultant changes would be exceedingly heavy and costly. More importantly, the unique architecture of the bridge would essentially be destroyed.

  The concept of adding additional support piers would not only have a negative architectural impact, but also would impede ship traffic in a waterway with high velocity tidal currents, conceivably even causing the bridge to become a hazard to navigation.

- ***Limiting the Allowable Number of People Allowed on the Bridge***

  This concept was unacceptable to the owner, even as an interim solution to the problem.

- ***Active Control***

  The use of controllable actuators to continuously oppose the cycling input of the pedestrians is theoretically possible for structures of this size, and is within the present state of the art. However, it is generally accepted that control of only one or two vibratory modes is possible at large scale with current technology, far short of the number of modes being excited. In addition, the required actuator response frequencies and forces at any point on the bridge must be able to vary with both the localized and macroscopic crowd sizes. Thus, a robust control solution was required, even if only one or two modes were to be suppressed by active methods. A further issue was raised with respect to the amount of control power required, and the need for a continuous guaranteed power supply. These issues could not be resolved, and the concept of active control was discarded.

- ***Supplemental Passive Damping***

  One of the most direct solutions to the problem utilized supplemental viscous damping devices to elevate total structural damping levels to the 20% critical range. This was compared to approximately 0.5% critical damping for the as-built structure. The design concept was based on the premise that added damping would reduce resonant deflections to a low level, such that the bridge would no longer provide any appreciable feedback to the pedestrians.

  The advantage of added damping in a structure undergoing forced resonance is well understood, although used more often by mechanical engineers in the technology fields of mechanisms and machinery. For a simple spring-mass-damper system, amplitude under steady-state forced resonance is:

$$X = \frac{X_0}{2\delta}, \quad \textit{or} \quad \frac{X}{X_0} = \frac{1}{2\delta}$$

where X = Resonant amplitude

X_0 = Zero frequency deflection of the spring-mass system under the action of a steady force

δ = Critical damping factor

$\frac{X}{X_0}$ = By definition, the magnification factor of the resonant response

Thus, if a simple first order system with 0.5% critical damping is excited by forced resonance, the magnification factor is:

$$\frac{X}{X_0} = \frac{1}{2 \mathrm{x} (.005)} = 100$$

If damping in the system is elevated to 20% critical, then the magnification substantially reduces to:

$$\frac{X}{X_0} = \frac{1}{2 \mathrm{x} (.2)} = 2.5$$

Previous studies and tests on scaled structural models with added supplemental damping have been reported by Constaninou and Symans (1992) [2] and Kasalanati and Constaninou (1999) [3]. This research revealed that the addition of viscous damping to a structure tends to suppress the response not only of the damped mode, but also of higher order modes. Thus, added viscous damping appeared to be a viable means to suppress the motions observed on the Millennium Bridge.

Several major design issues for the dampers were noted by the bridge design team, and all of these needed to be satisfied before added damping could be considered as a viable solution.

DAMPER DESIGN REQUIREMENTS

The application of damping devices to the bridge resulted in five major design issues, some of which are unique to this particular structure.

The primary issue was to address the fact that the dampers must continuously cycle at an average frequency of 0.8 Hz. It was understood that that majority of the cycles would take place at low amplitude, but the total number of cycles required by the owner was based on a 50 year bridge life. This equates to more than 10^9 cycles of life, far in excess of normal values for any sort of conventional damping device. Ideally, the damper should be maintenance free for the entire life cycle.

The second issue was that the damper must respond to tiny deflections as low as .025 mm with high resolution, otherwise the suppression of feedback would not be possible until the bridge was already well into resonance. Damper frequency response requirements were defined as D.C.–2 Hz with a high fidelity output over this entire bandwidth. This issue was compounded by the fact that due to wind, thermal, and static loadings, total damper deflections of up to plus or minus 275 mm were required.

The third issue was that the damper response must have low hysteretic content, to avoid pedestrians sensing the classical “stick-slip” motion of a conventional sliding contact fluid seal, with the resultant perception of instability in the bridge structure. This requirement became even more difficult when taken in context with the extremely long cyclic life. This is because conventional hydraulic practice is to use seals with heavy interference for long life under dynamic cycling. These high interferences in turn generate high seal friction, accentuating the “stick-slip” motion.

The fourth issue was that several distinct designs of dampers were required, each of which had different output forces, deflections, component equations, and envelope dimensions.

The final design issue was environmental in nature. The dampers are located outdoors, over a brackish waterway with tidal flows. The design life was such that all major operating elements of the dampers needed to be constructed from inherently corrosion resistant metals that would not degrade over time.

TAYLOR DEVICES' FRICTIONLESS HERMETIC DAMPER

Taylor Devices, a 50 year old manufacturer of damping products, proposed a unique solution to the damper design requirements for the Millennium Bridge. To address the various design issues, a unique and patented damper was proposed, previously used exclusively by NASA and other U.S. Government agencies for space based optical systems. These previous applications had similar requirements for long life and high resolution at low amplitudes, but required relatively low damper forces from small, lightweight design envelopes. Figure 4 is a photograph of a typical damper of this design, used in space on more than 70 satellites to protect delicate solar array panels. Figure 4 also shows the most unique element of this design, a frictionless seal made from a welded metal bellows. This type of seal does not slide, but rather flexes without hysteresis as the damper moves.

A cutaway of a typical Frictionless Hermetic Damper is shown in Figure 5. Two metal bellows seals are used to seal fluid in the damper. As the damper moves, the two metal bellows alternately extend and retract, by flexure of the individual bellows segments. Since the seal element elastically flexes rather than slides, seal hysteresis is nearly zero. The volume displaced by the compressing bellows passes through the crossover ports to the extending bellows at the opposite end of the damper. While this is occurring, damping forces are being produced by orifices in the damping head, and the pressures generated are kept isolated from the metal bellows by high restriction hydrodynamic labyrinth bushings. Because hydrodynamic bushings are used, no sliding contact with the piston rod occurs, assuring frictionless performance.

FIGURE 4
SPACE SATELLITE DAMPER

To adapt this basic design to the Millennium Bridge largely involved simply scaling the small satellite dampers to the required size range. All parts, including the metal bellows, were designed with low stress levels to provide an endurance life in excess of 2×10^9 cycles. The metal bellows and other moving parts were constructed from stainless steel for corrosion resistance.

A total of 37 dampers were constructed, of 7 different types, and are listed in Figure 6.

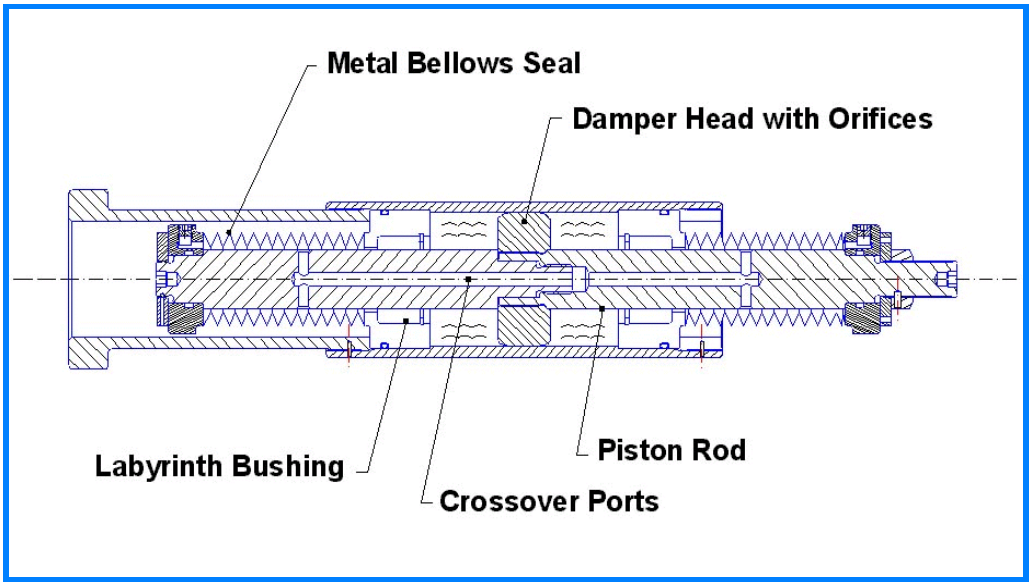


FIGURE 5
CUTAWAY OF DAMPER

DAMPER TYPE	QUANTITY	DESCRIPTION	USE	+/- STROKE (mm)	LENGTH (m)
V1	5	Chevron Damper	Lateral Mode	25	.7
V2	10	Chevron Damper	Lateral Mode	25	.7
V3	2	Chevron Damper	Lateral Mode	25	.7
V4	4	Vertical to Ground Damper	Lateral and Vertical Modes	275	2.3
V5	4	Pier Damper	Lateral and Torsional Modes	60	7.8/3.3
V6	8	Pier Damper	Lateral and Torsional Modes	60	8.2/3.6
V7	4	Pier Damper	Lateral and Torsional Modes	60	8.3/4.6

FIGURE 6
MILLENNIUM BRIDGE DAMPERS

To assure a high resolution output, it was required that all damper attachment clevises be fabricated with fitted spherical bearings and fitted mounting pins, such that zero net end play existed in the attachment brackets.

All dampers were fabricated and delivered to the bridge site in 2001, and testing of the structure with groups of pedestrians began in January 2002. Figures 7 through 9 are a sampling of the installed dampers.

BRIDGE TESTING

The bridge was subjected to three separate series of tests during the month of January 2002. Two of these were scheduled, one was unexpected.

The first test series used a group of 700 people as subjects. This statically loaded the bridge to approximately one-third capacity. The testing involved walking the test subjects across the deck at various metered speeds with variable group sizes. Maximum local loading density was one person per square meter. This first test series was essentially for preliminary assessment of the modified bridge, and no anomalies were noted.

The second test series was totally unplanned, and occurred in the period of January 27 through January 29, 2002, when severe windstorms swept the entire United Kingdom. The overall event was categorized as a ten year return period wind storm, with peak gusts at the bridge in the 120 km/hour range. Again, no anomalies were noted.

FIGURE 7
VERTICAL DAMPERS

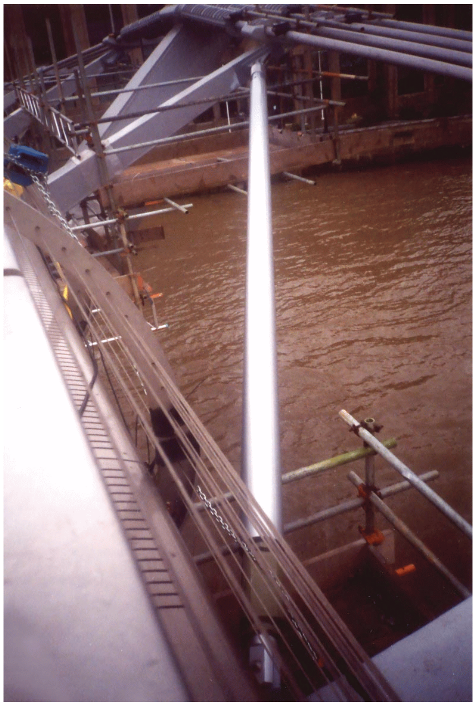


FIGURE 8
PIER DAMPERS

FIGURE 9
CHEVRON DAMPER

The third and final series took place on January 30, 2002, with a total of 2,000 people. The test began at 6:00 P.M., using office workers exiting from businesses near the bridge as test subjects. Crowd control was maintained by stationing the test subjects within fenced compounds at each end of the bridge, and furnishing food and beverages.

Testing consisted of leading the crowd across the bridge in a single large group at a speed metered by pacers walking at fixed intervals within the crowd. The average loading density was 1.5 persons/square meter, considered as a maximum for the structure. The crowd filled the bridge deck area to capacity. Pacers carried reflective flags so that the entire group remained well regulated in walking speed. With test safety being a critical issue, numerous rescue and police boats were stationed just downstream from the bridge in case of catastrophic problems. Large numbers of safety and police officials were stationed throughout the crowd to maintain order. Media coverage by television and the press was extensive; floodlights were placed on the dampers and on instrumented sections of the bridge.

The testing took place with a festive atmosphere, which also helped to insure that the large group of people would calmly fulfill all dynamic loading requirements. The procession was led across the bridge by the City of London's Town Crier and the Mayor of Southwark, representing the communities on either end of the bridge. Depicted in Figure 10, these two group leaders were dressed in Victorian garb. The Town Crier tolled his bell loudly to maintain the crowd's interest and reinforce the appearance of a festivity, rather than a test of the bridge.

Testing consisted of three well-regulated crossings on the bridge by the entire crowd at three different walking speeds. A fourth and final crossing was essentially random, with the crowd being told that additional food and refreshments were available at an off-bridge site on a first-come, first-served basis. All of these four final tests proved to be totally anticlimactic – the bridge behavior being generally described as "rock solid" by the crowd. More importantly to the engineering team, the damped bridge structure performed superbly:

- Peak measured accelerations reduced from 0.25 g undamped to 0.006 g damped.
- Dampers reduced the dynamic response by at least 40 to 1 for all modes.
- No resonance noted of any mode.
- No observable biodynamic feedback occurred.

FIGURE 10
HILARY WINES, MAYOR AND PETER MOORE, THE LONDON TOWN CRIER

CONCLUSIONS

The use of supplemental fluid dampers providing 20% critical damping to a suspension-style pedestrian bridge will dramatically reduce or eliminate the potential for biodynamic feedback occurring between the pedestrians and the bridge structure. This level of supplemental damping allows the use of unique bridge architecture, even when the bridge has modal frequencies which are coincident with normal walking motions of pedestrians.

Because of the world-wide attention focused on this particular bridge, the most satisfying conclusion is that of the public, and this was best expressed by the TV and printed media on January 31, 2002, following the final test, with comments such as this:

> **"The bridge was incredibly steady, I couldn't detect any signs of movement at all" – BBC NEWS**
>
> **"Whither the Wobble?" – THE LONDON TIMES**
>
> **"Repair work has been a success" – THE LONDON METRO**
>
> **"Really solid" – THE GUARDIAN**
>
> **"Bridge wobble free after utlimate test" "It didn't move a quiver" – THE LONDON EVENING STANDARD**

The Millennium Bridge was officially re-opened to the public on February 22, 2002, without problems or difficulties of any type. The bridge is expected to be used by upwards of four million people each year.

REFERENCES

[1] Dallard, P., et al, "The London Millennium Footbridge," The Structural Engineer, November 20, 2001, Volume 79/No. 22, Pg. 17.

[2] Constantinou, M., Symans, M., 1992, "Experimental and Analytical Investigation of Seismic Response of Structures with Supplemental Fluid Viscous Dampers," Technical Report NCEER-92-0032, National Center for Earthquake Engineering Research, Buffalo, NY.

[3] Kasalanati, A., Constantinou, M., 1999, "Experimental Study of Bridge Elastomeric and Other Isolation and Energy Dissipation Systems with Emphasis on Uplift Prevention and High Velocity Near-Source Seismic Excitation," Technical Report MCEER-99-0004, Multidisciplinary Center for Earthquake Engineering Research, Buffalo, NY.

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