A STUDY IN THE LONG-TERM PERFORMANCE OF SPECIALIZED LOW FRICTION HERMETICALLY SEALED FLUID VISCOUS DAMPERS UNDER NEARLY CONTINUOUS OPERATION ON A PEDESTRIAN BRIDGE

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In 2001, Taylor Devices Inc. developed special Viscous Dampers for use on the Millennium Bridge in London, United Kingdom. These dampers were specified and designed to be used for mitigating the dynamic response of the bridge due to pedestrian traffic. Prior to the integration of the dampers, the bridge had experienced unacceptable movements, especially during periods when larger crowds of people were on the bridge. The result was that the bridge had to be closed until a solution was found. Much research was done and several papers were published about the nature of that problem and the ensuing solution. After successful component level testing and the installation of 37 Taylor Viscous Dampers, the bridge was re-opened to the public in February, 2002. Tests with approximately 2000 people demonstrated a much improved dynamic response. Since that time, the dampers have been subjected to almost constant dynamic input, some more than others. Due to the location of the bridge in central London, there has been nearly constant pedestrian traffic on the bridge each day and even throughout the night. However, because of the specialized nature of the damper design, no degradation in damper performance or in the dynamic response of the bridge itself has been experienced. This paper will outline the specifics in quantifying the continued damper performance through an intermediate inspection after seven years, followed by a successful comprehensive inspection after eleven years. This included the removal, dynamic testing, and re-installation of three selected dampers.

INTRODUCTION

The unique design and the resulting unacceptable response of the Millennium Bridge in central London (see Figure 1) have been well publicized and documented. The specifics of this dynamic response and the resulting solution will not be reiterated within the context of this paper. However, in order to provide a necessary background, a short summary is presented here.

The Millennium Bridge spans 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 Theatre and Tate Modern Art Museum on the south. In June 2000, the bridge was first opened to the public. Shortly thereafter, with substantial pedestrian traffic present, the bridge began to sway in a lateral motion to the discomfort of many of the pedestrians. The bridge was subsequently shut down and significant studies were performed to provide solutions to stop the excessive swaying. Since the response frequency was near the frequency of human footfalls during walking, it was determined that stiffening of the structure was not a practical solution. The unique design and its aesthetic appearance would have been sacrificed if structural modifications were made to keep the various modal frequencies away from walking frequencies. A more acceptable solution was determined to substantially increase the damping level of the bridge over all input conditions in order to prevent pedestrian traffic from exciting the bridge. The required amount of added damping was determined to be nearly 20% critical, a value that is effectively unachievable with typical solutions, such as tuned mass dampers, frictional elements, or structural modifications.

Many challenges became immediately apparent when proposing a damping solution for this unique structure. One of the most significant was the fact that the owner of the bridge required a permanent and maintenance-free solution that would last throughout the life of the bridge; this being in excess of 50 years. Since the expected pedestrian traffic was such that the dampers would cycle nearly continuously at 1.3 Hz, it was necessary to specify a cycle life of 2×10^9 cycles minimum. Due to this stringent requirement, Taylor Devices proposed the use of specialized Fluid Dampers that employed the use of flexing metal bellows seals, rather than traditional sliding seals that are elastomeric in nature and therefore subject to wear and degradation over long-term environmental and cyclic conditions.

FIGURE 1 – THE MILLENNIUM BRIDGE

SPECIALIZED DAMPER DESIGN [1]

Taylor Devices' Fluid Dampers with metal bellows seals had been 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 2 is a photograph of a pair of typical dampers of this design, used in space on more than 70 satellites to protect delicate solar array panels. This figure also shows the metal bellows seals; one in the compressed position and one in the extended position. This type of seal does not slide, but rather flexes without hysteresis as the damper moves. This patented design is known as a Frictionless Hermetic Damper.

A cutaway of a typical damper of this type is shown in Figure 3. Two metal bellows seals are used to seal fluid in each damper, one at each end of the damping chamber. 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 near-frictionless performance.

FIGURE 2 – SPACE SATELLITE DAMPERS

Adapting this basic design for use on the Millennium Bridge largely involved simply scaling the small satellite Dampers to the required size range. All parts, including the metal bellows seals, 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. 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.

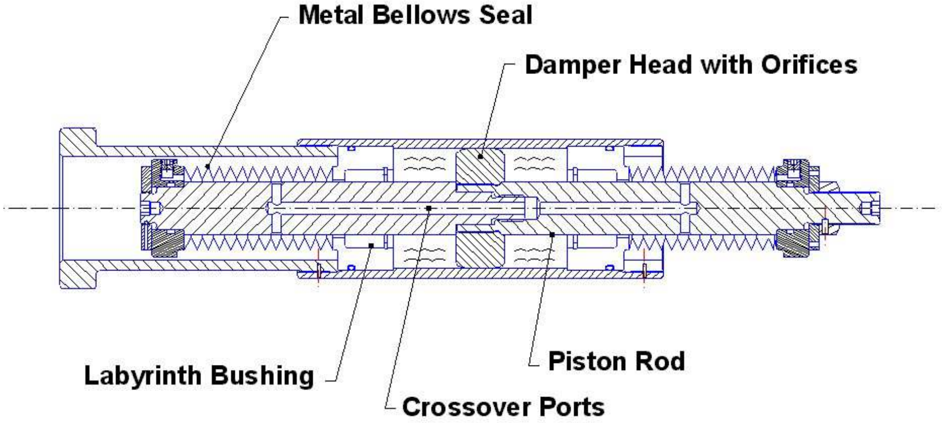

FIGURE 3 - CUTAWAY OF FRICTIONLESS HERMETIC DAMPER

A total of 37 dampers of this design were manufactured, component-level tested, and installed on the bridge in late 2001. There are 3 basic types of dampers. These are referred to as the Pier Dampers, the Deck Dampers, and the Vertical Dampers and are described below:

Damper Nomenclature: Pier Damper
Quantity on the Bridge: 16
Description: 2 Pier Dampers are located on each side of each of 2 piers on both the east and west side of the bridge, for a total of 8 dampers per pier. Damping coefficient values for the 8 dampers connected directly to the center span of the bridge are significantly higher than the other Pier Dampers. Dampers have varying overall lengths due to the location of the attachment points, the longest being 8.3 meters long. These dampers are quite apparent to pedestrians when crossing the bridge as illustrated in Figures 4 and 5 below:

FIGURE 4
4 OF 16 PIER DAMPERS

FIGURE 5
MOVING END OF PIER DAMPER

Damper Nomenclature: Deck Damper
Quantity on the Bridge: 17
Description: The Deck Dampers are located under various deck sections. A very limited number can be seen from under the north end of the bridge. Most deck dampers are not visible since they are situated directly under the deck panels. Lateral motions of the bridge are transmitted to the dampers through pairs of relatively long V-shaped chevron braces as shown in Figures 6 and 7 below:

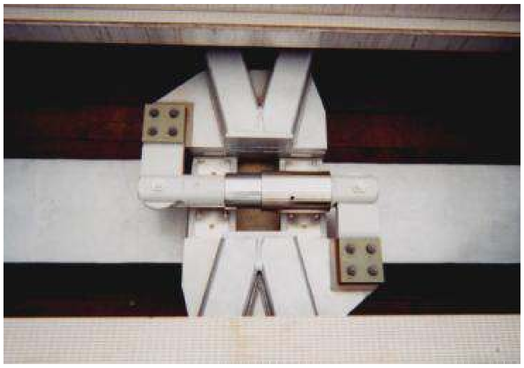

FIGURE 6
DECK DAMPER SHOWING CHEVRON CONNECTION

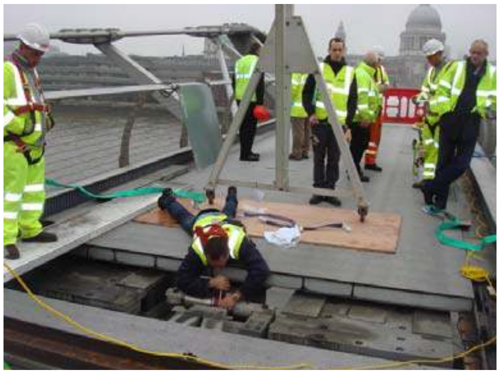

FIGURE 7
DECK DAMPER SHOWN WITH DECK PANELS REMOVED

Damper Nomenclature: Vertical Damper
Quantity on the Bridge: 4
Description: Vertical Dampers are located in 2 pairs under the south end of the bridge with damper ends connected between a structural arm and the ground. As illustrated below in Figures 8 and 9, the dampers are directly accessible to pedestrian traffic. Nearly continuous damped motion is felt and observed with even low to moderate pedestrian traffic on the bridge overhead.

FIGURE 8
INSPECTION OF VERTICAL DAMPER PAIR

FIGURE 9
VERTICAL DAMPER PAIR WITH PEDESTRIAN ACCESS

INTERMEDIATE INSPECTION AFTER SEVEN YEARS IN SERVICE

A visual inspection of each damper was performed looking for corrosion, damage to the unit from use or the surrounding environment, and for fluid leakage. The units were all found to be in 100% working condition with minimal signs of physical damage or deterioration, as well as no signs of fluid leakage. There were only minor signs of corrosion and some external contamination noted. The units had been subjected to nearly constant cycling for a period of use of over seven years at the time of this inspection. The total estimated cycles after seven years was estimated at 2.0×10^8 reversed cycles. The owner required no formal testing of installed dampers at this time.

PRINCIPAL INSPECTION AND TESTING AFTER ELEVEN YEARS IN SERVICE

The Principal Inspection after eleven years of service included two phases. The first was a visual inspection of all Pier Dampers and all four Vertical Dampers. All dampers appeared to be in 100% working order. A sample of five of the seventeen deck dampers were inspected per the owner's request to minimize deck panel removal costs. Similar to the case for the Intermediate Inspection four years earlier, there were only minor signs of corrosion and some external contamination noted. This minor corrosion and contamination appears to have been caused by caustic chemicals from the exhaust plumes from boats and ships navigating under the bridge. Dampers located under the deck of the bridge near the shore or over land exhibited nearly new appearance. Two of the five Deck Dampers and one of the four Vertical Dampers were temporarily removed for dynamic testing purposes as outlined below. Cycles on each damper after 11 years of service was estimated at 3.1×10^8 reversed cycles.

The second phase of the Principal Inspection consisted of performing dynamic tests on the three dampers that were removed. These three dampers were shipped to the Taylor Devices facility in North Tonawanda, New York so that they could be tested to the original Acceptance Test Procedure and compared to the original acceptance tests from 2001. This was done to determine if any of the performance outputs had deteriorated in any way. This Acceptance Test Procedure consisted of 2 types of tests. The first type consisted of subjecting the dampers to a series of sinusoidal input tests throughout the specified velocity range. These tests are referred to as the "Force vs Velocity" tests. The second type of test was performed at approximately .50 mm amplitude. These tests are referred to as the "Low Amplitude" tests. The Low Amplitude test was performed only in 2012 to demonstrate the ability of each Damper to produce substantial damping force for very small vibrations, and verify that there has been no loss of fluid. If any loss of fluid had occurred, the damper would demonstrate an inability to produce any substantial force at these small displacements.

Figures 10, 11, and 12 show the results of the Force versus Velocity tests for each Damper, measuring the output force at several velocity inputs. These plots also show the data points recorded through the same testing methods 11 years prior. The graphical data illustrates the fact that there is virtually no difference in output characteristics when comparing the results from 2001 to the results from 2012. Note that both the 2001 and 2012 tests were run in the same test machine. The calibrated force transducers were strain gage type load cells with ±2% gage accuracy on output force. The 2012 tests used a calibrated velocity transducer with ±2% accuracy, whereas the 2001 tests utilized a slope measurement on a calibrated displacement transducer with ±2% accuracy to obtain velocity.

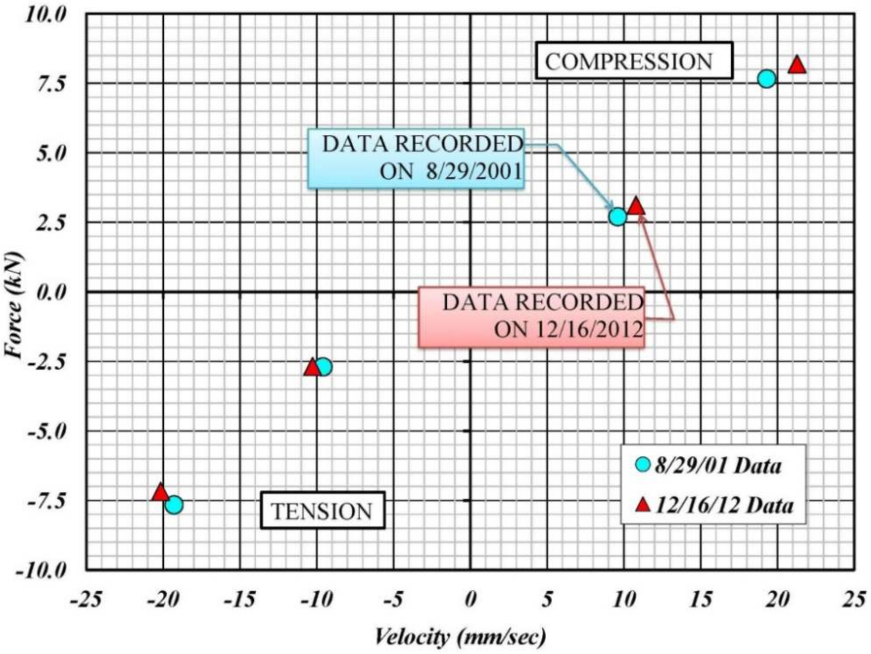

FIGURE 10
FORCE VS. VELOCITY TEST RESULTS OF DECK DAMPER
2001 & 2012

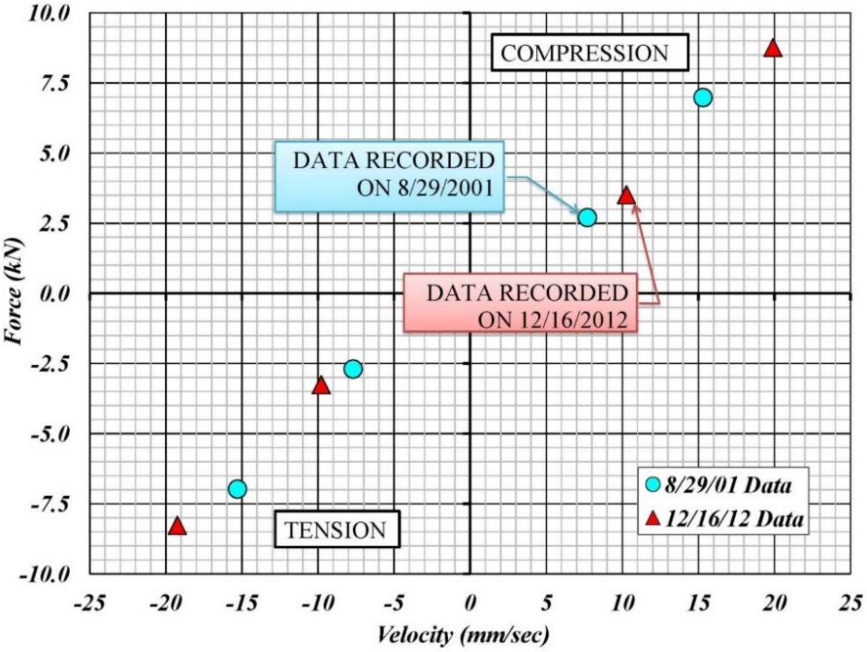

FIGURE 11
FORCE VS. VELOCITY TEST RESULTS OF DECK DAMPER 2001 & 2012

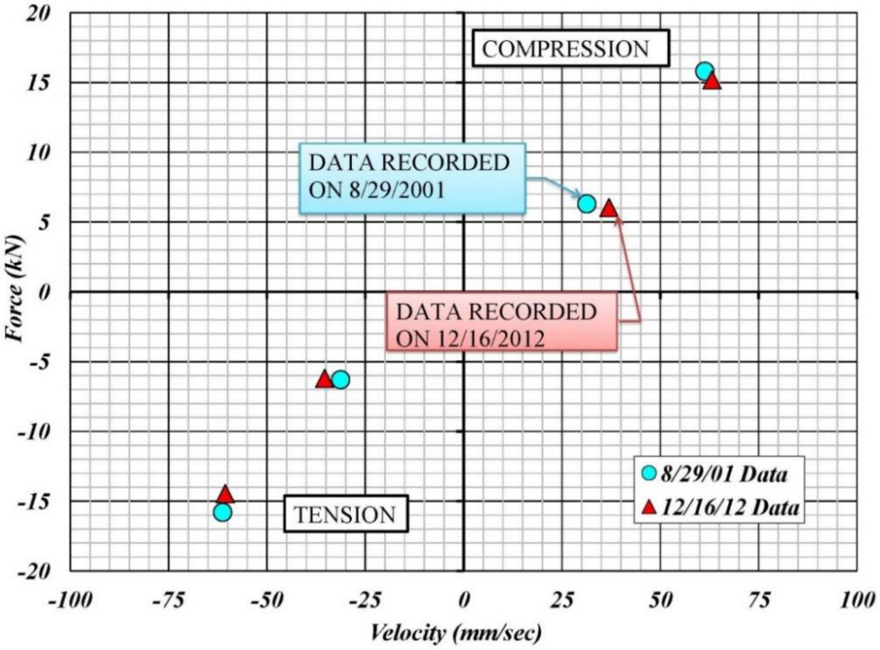

FIGURE 12
FORCE VS. VELOCITY TEST RESULTS OF VERTICAL DAMPER 2001 & 2012

Figures 13, 14 and 15 demonstrate the results of the Low Amplitude Tests for each of the three dampers that were tested. Note that in each case, the hysteresis loops (force vs. displacement) show no signs of free-play, loss of fluid, excessive friction, wear or degradation of any sort. It should be noted that the dampers were tested with their spherical bearings in place and their end attachment brackets still connected. Therefore, no degradation to these components has occurred and the bearings have maintained their tight fit requirement that is necessary to produce damping at very low displacements.

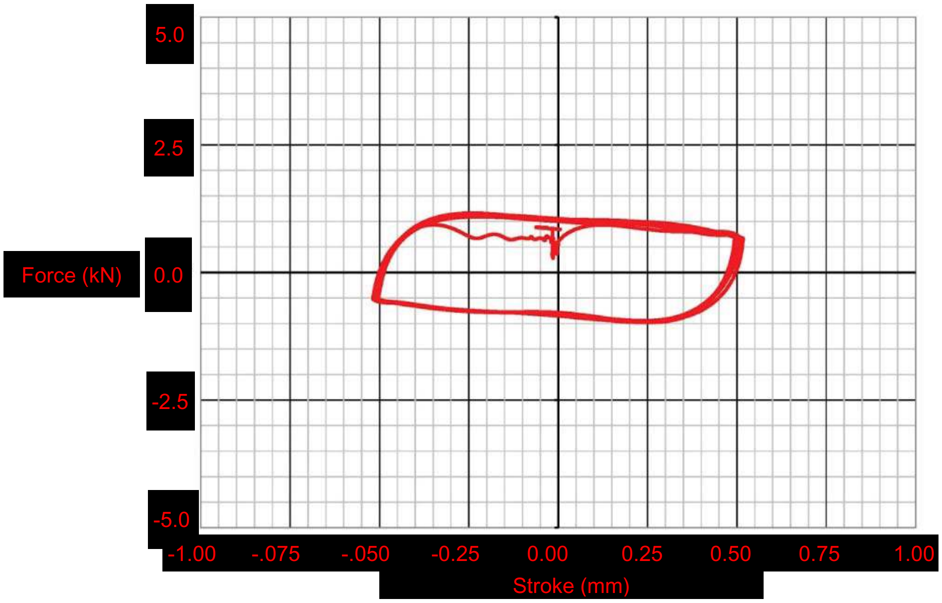

FIGURE 13
LOW AMPLITUDE TEST RESULTS OF DECK DAMPER 2012

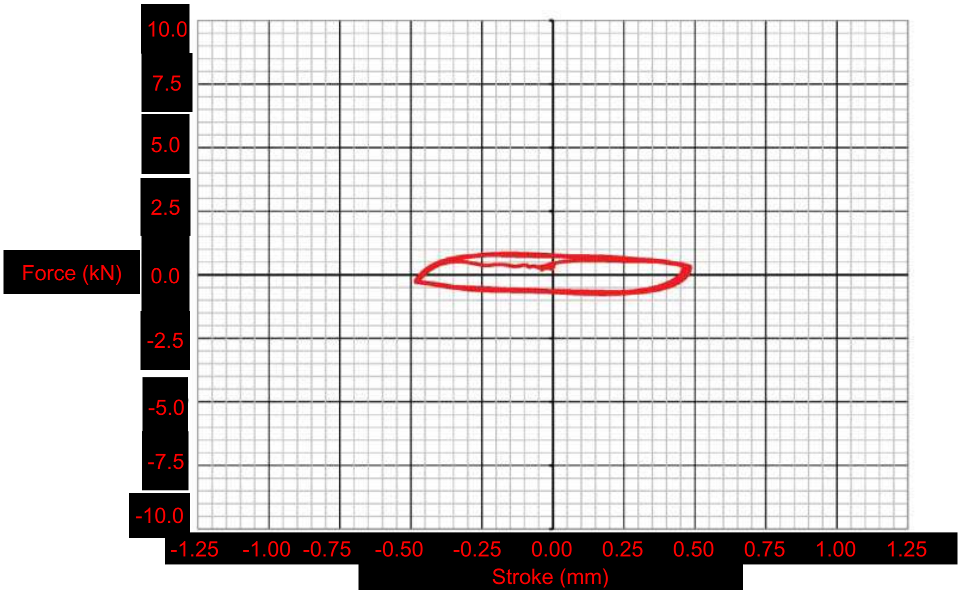

FIGURE 14
LOW AMPLITUDE TEST RESULTS OF DECK DAMPER
2012

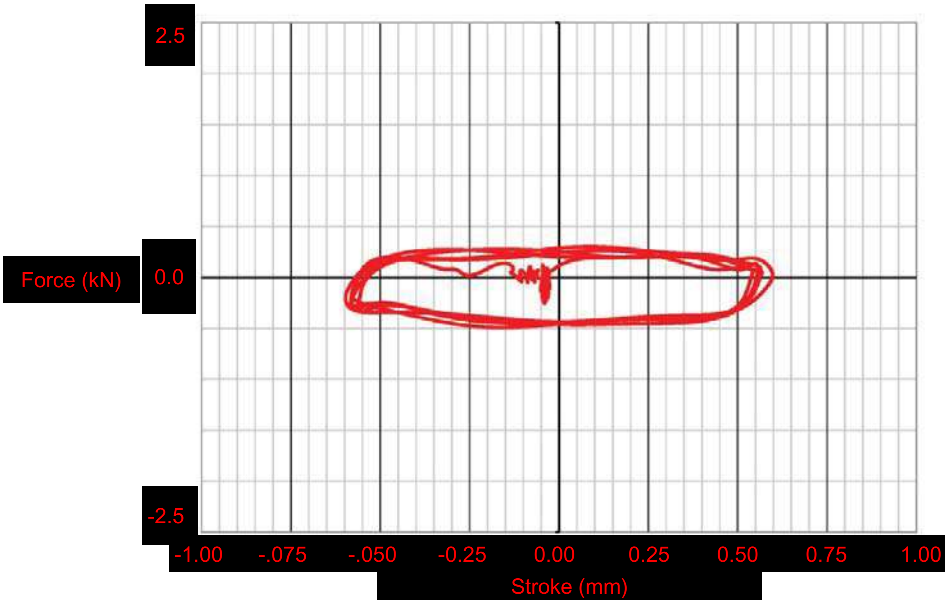

FIGURE 15
LOW AMPLITUDE TEST RESULTS OF VERTICAL DAMPER
2012

Subsequent to the successful testing of these 3 dampers, they were sent back to London and reinstalled on the bridge in January 2013.

CONCLUSIONS

The results of the seven-year Intermediate Inspection, the eleven-year Principal Inspection, and dynamic testing show that the Millennium Bridge dampers have experienced no physical or functional deterioration. The dampers displayed no measurable change in output, as well as no signs of leakage after eleven years of continuous service and nearly constant cycling.

The dampers were originally designed and built for this nearly constant cycling over a period of more than 50 years, projected to total approximately 2×10^9 (2 billion) cycles. Due to the fact that the results of the intermediate and principal inspections and testing show no signs of degradation, it is anticipated that the dampers will be able to meet this expected life time as anticipated.

REFERENCES

[1] Taylor, D., 2002, "Damper Retrofit of the London Millennium Footbridge - A Case Study in Biodynamic Design," *Proceedings of the 73^{d} Shock and Vibration Symposium*

ACKNOWLEDGEMENTS

The authora would like to thank Craig Winters, Robert Schneider and Sean Frye for their contributions to this paper.