
**STRUCTURAL CONTROL USING HYBRID SPRING-DAMPER
ISOLATOR WITH INTEGRAL GAPPING FUNCTION**

by

Douglas P. Taylor, President
Taylor Devices, Inc.
90 Taylor Drive
North Tonawanda, NY 14120-0748

John C. Metzger, Eng. Manager-Special Projects
Taylor Devices, Inc.
90 Taylor Drive
North Tonawanda, NY 14120-0748

STRUCTURAL CONTROL USING HYBRID SPRING-DAMPER ISOLATOR WITH INTEGRAL GAPPING FUNCTION

Douglas P. Taylor, President
John C. Metzger, Engineering Manager - Special Projects
Taylor Devices, Inc.
90 Taylor Drive
North Tonawanda, NY 14120-0748
716.694.0800

The design of a component to provide combined spring and damping output is strongly driven by scaling issues for the discrete mechanical elements used to provide the required output forces. Multiple design concepts and technologies are available to provide damping and/or spring forces. However, consideration of the relative force requirements, life cycle, operative environment, and space envelope available usually will result in a specific type of damper and a specific type of spring being optimum.

The spring-damper isolator described was designed and manufactured for use on the world's largest cable stayed bridge – the Sutong Bridge over China's Yangtze River, completed in 2008.

INTRODUCTION

Long-span bridges provide unique challenges in shock and vibration control for the design team and component manufacturers. Bridges of this type are normally intended for a long service life in the range of 30-100 years, with current trends favoring a 50-75 year life. A typical bridge of this type can periodically expect shock and vibration inputs comprised of the following events within its life:

1. Windstorms
2. Hurricanes/typhoons
3. Earthquakes
4. Impact shock to support piers or deck
5. Truck/car braking loads or accident loads
6. Traffic vibration
7. Synchronous traffic or pedestrian vibration

The Sutong Bridge is located north of Shanghai in China's Jiangsu Province, at a site where catastrophic earthquakes, typhoons, and ship impact are key design issues. The new bridge replaces an existing ferry crossing, and anticipated road traffic levels are expected to be high. The total length of the bridge is 4.7 miles, with a .67 mile long center span with a 200 ft. navigation clearance and expected ship traffic of 3,000 vessels per day. The center span is of the cable-stayed type using a fan-like array of cables emanating from the bridge's two towers to support the deck. The two concrete support towers are of an inverted Y configuration with a height of 980 ft. The longest cable stay which supports the deck is 1,890 ft long.

An artist's conception of the finished bridge is provided as Figure 1. It is readily apparent that the tall support towers and long support cables to the bridge deck will cause the deck to have long period/low frequency motions along the primary axis of the bridge. Because of the need to accommodate thermal expansion and contraction of the deck axially, extensive motion can occur in this direction. Motion of the suspended deck in the transverse direction is constrained by the towers.



Figure 1 - Artist's Bridge Rendition

STRUCTURAL CONTROL OF THE BRIDGE DECK

The configuration of the bridge will cause axial motion of the suspended deck to occur during earthquakes, typhoons, and synchronized truck/car braking loads such as would occur during a mass vehicular accident on the bridge. During dynamic earthquake loading, the long period of the suspended deck provides inherent isolation, albeit essentially undamped. Analysis indicated that added viscous damping would reduce deck motions substantially. During the other events listed, analysis determined that the most cost-effective solution was to incorporate a snubbing type spring element that would only engage (become active) when the damper was approaching its end of travel in either extension or compression. The type of spring-damper element resulting would have only damping forces through roughly 85% of the available displacement from the neutral (center of travel) position. Beyond this travel, the spring element would engage and a combined response of spring plus damper forces would result. Essentially, the spring elements would be “gapped” through all but approximately the last 15% of the damper stroke in either direction. Conceptual force-displacement plots for the desired isolator are shown in Figures 2-4.

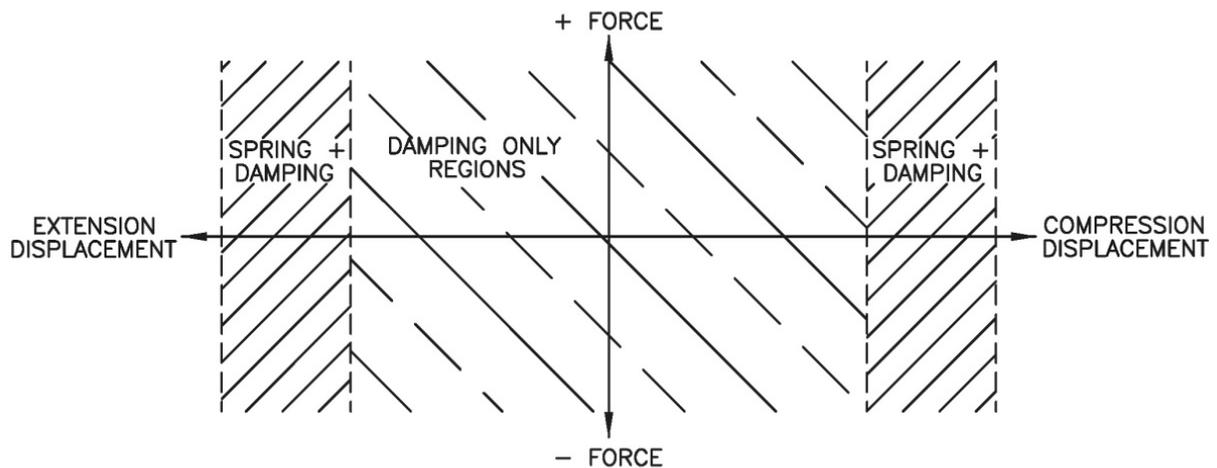


Figure 2 – Output Zonation

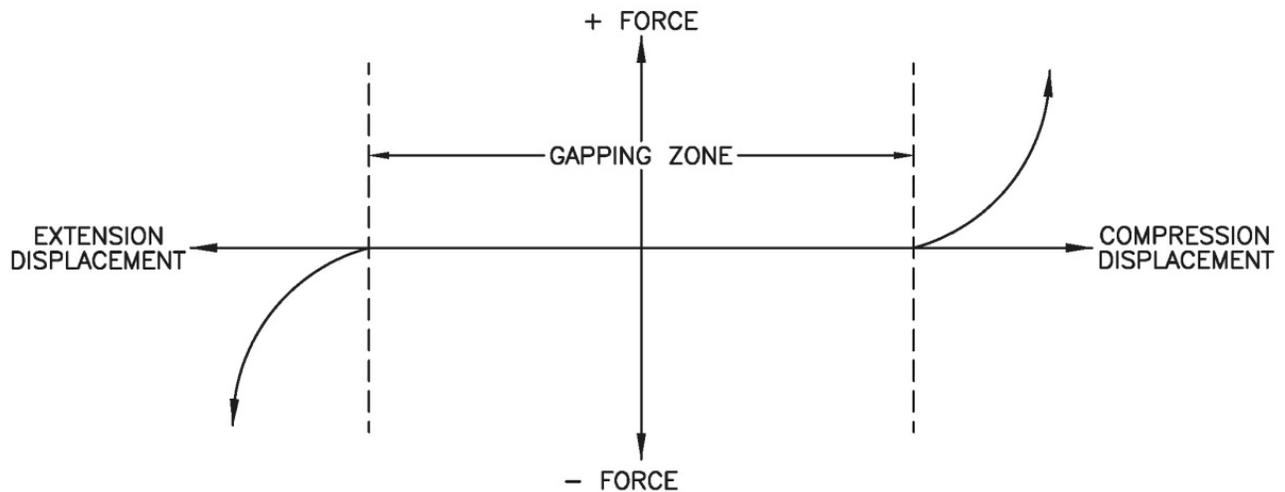


Figure 3 – Spring Response

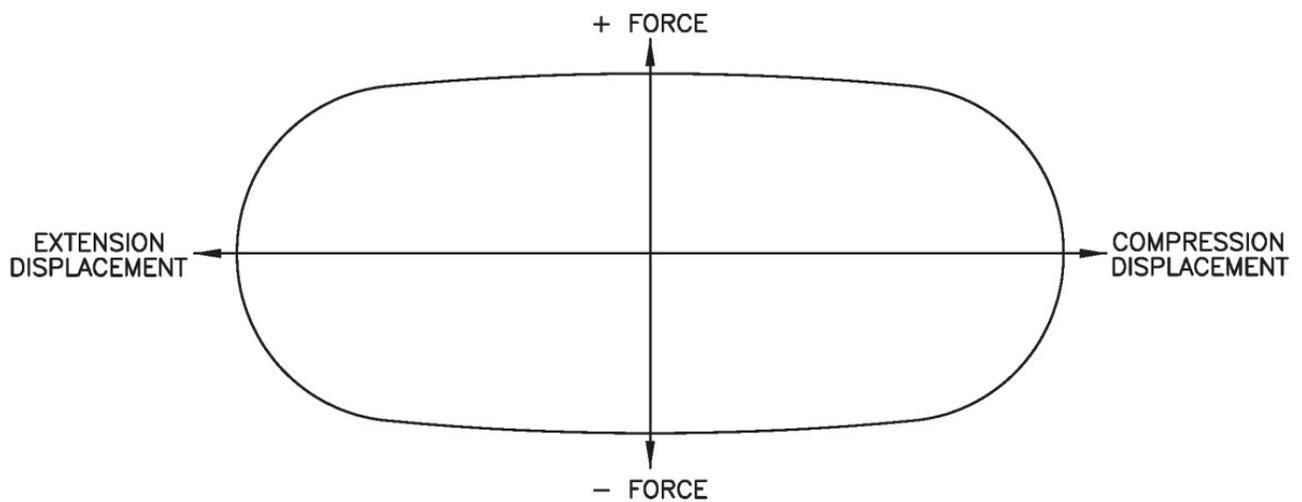


Figure 4 – Damping Response Under Sine Wave Excitation

HYBRID ISOLATOR DESIGN

The bridge design team desired to have the spring and damper output combined within a single isolation element, utilizing a total of eight of these isolators to control the response of the entire suspended bridge deck. The unloaded gross weight of the bridge deck is 48,000 metric tons. Despite the size of the structure, the space available to package the isolators was relatively small, located under the deck and restricted by structural members.

Analytical results revealed a large disparity between the maximum spring and damping forces. Peak damping force was 5.5 million pounds divided over 8 units. The peak spring force was 18 million pounds, again spread over 8 units.

The damping elements had to accommodate daily thermal expansion and contraction of the suspended deck. The deck overlaps the .67 mile distance between the support towers such that total deck length is slightly more than one mile. Required damper deflection before contacting the spring elements was plus or minus 29.5 inches. Spring travel was an additional 4 inches, for a total required isolator displacement of plus or minus 33.5 inches. Multiple computer runs were made to optimize damping response under the various expected inputs with the result being of the so-called low exponent type viscous damping.

The expected damping function was of the form:

$$F = CV^\alpha$$

where F = Damping Force
 C = Damping Constant
 α = Damping Exponent

The damping exponent α was specified as being equal to 0.4 to allow relatively unrestricted thermal expansion and contraction at very low speeds (in the range of 0.05 inches/second), yet provide high damping forces at seismic velocities up to 22 inches/second. A silicone oil-filled fluid damper was selected using a monolithic fluidic control orifice. This type of flow control orifice provides the required 0.4 damping exponent yet requires no control valves or spring-loaded poppets, thus gaining maximum reliability. The resulting fluid damper was 18 inches in diameter and is shown in Figure 5. Maximum nominal output force for each of the 8 dampers is 680,000 lbs. at 22 inches/second velocity.

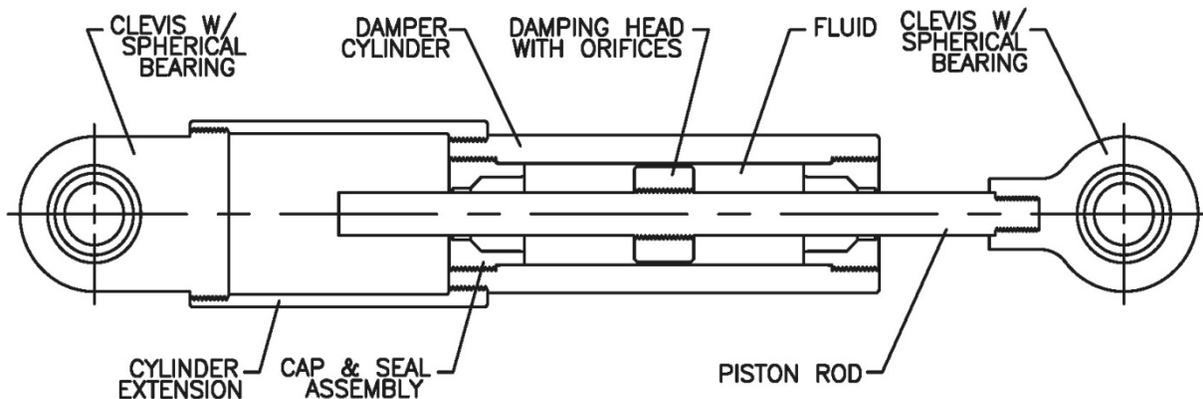


Figure 5 – Sutong Bridge Damper Element

The design for the spring elements proved to be far more difficult than the dampers. Each spring element required a stroke of 4 inches, with a resultant spring force of 2,250,000 lbs. Given the 18 inch diameter of the damper, the spring would either have to fit inside the damper cylinder or be such that the damper would fit inside the inner diameter of the spring. Scoping studies were performed to assess relative spring type vs. potential packaging and manufacturing considerations.

The spring types evaluated are listed below, with the results of the scoping study:

1. Mechanical Wound Coil Spring – Could not be manufactured.
2. Mechanical Stacked Belleville Washers – Material availability issues in large diameters; cumbersome size package.
3. Liquid Spring – Could not be packaged within the damper cylinder and could not be readily manufactured in a tubular configuration.

4. Pneumatic Spring – Highly non-linear when run at the 3,000 psi and higher pressures necessary to achieve reasonable package size. Lower pressures yielded a cumbersome, large diameter package.
5. Elastomer Spring – Reasonable package size, difficult to manufacture.

A review of the scoping study results indicated that the only viable spring type for this particular design was an elastomer spring, despite the admitted difficulty expected in manufacturing it. “First cut” design calculations were made to determine the rough volume and diameter of the elastomer element. This was found to be approximately 30 inches in diameter by 17 inches in length assuming a “well-constrained” elastomer design shape factor.

The cost and size of the spring element was such that the damper was modified to incorporate a so-called “lost-motion” mechanism. This allowed the use of only a single rubber element, which would be mechanically engaged by the lost motion mechanism at the required point of damper compression or extension. Figures 6 and 7 depict the incorporation of the spring element into the damper design. In Figure 6, the damper sleeve has been removed and the cylinder is turned down at one end. Figure 7 shows the addition of the tubular spring element.

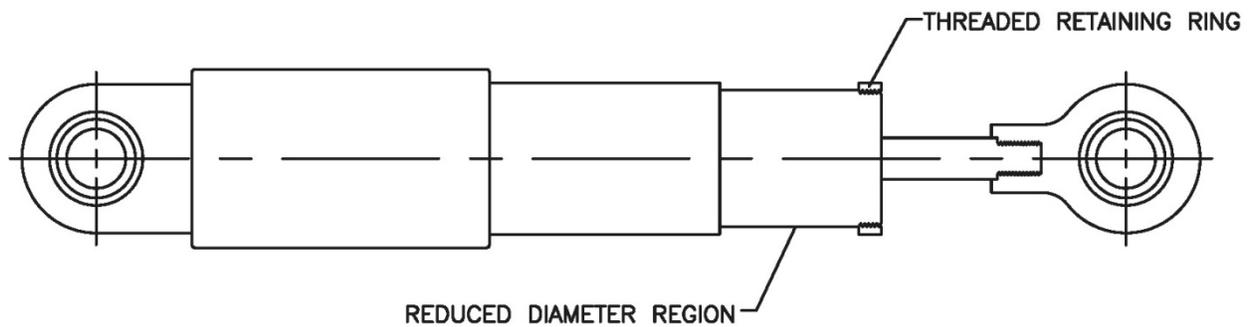


Figure 6

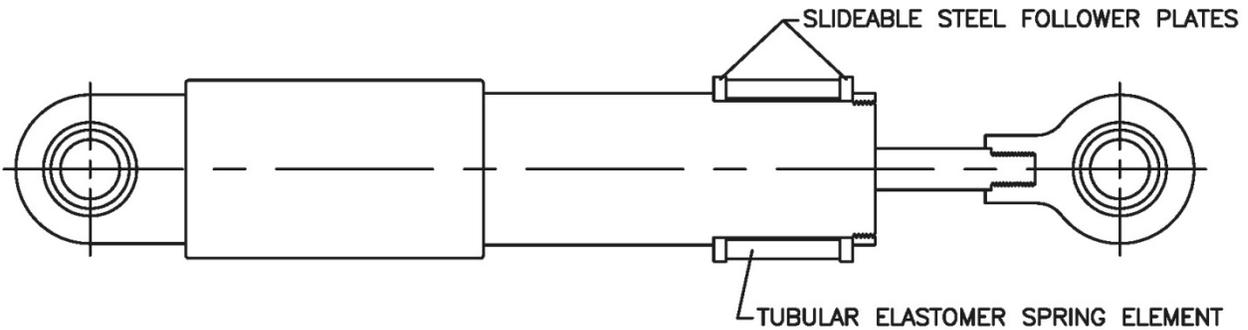


Figure 7

Figure 8 adds a modified piston rod guide sleeve to complete the lost motion mechanism. This is the final design configuration of the Sutong Bridge’s hybrid isolator. Figures 9-a and 9-b depict the unit compressed or extended with the spring element engaged.

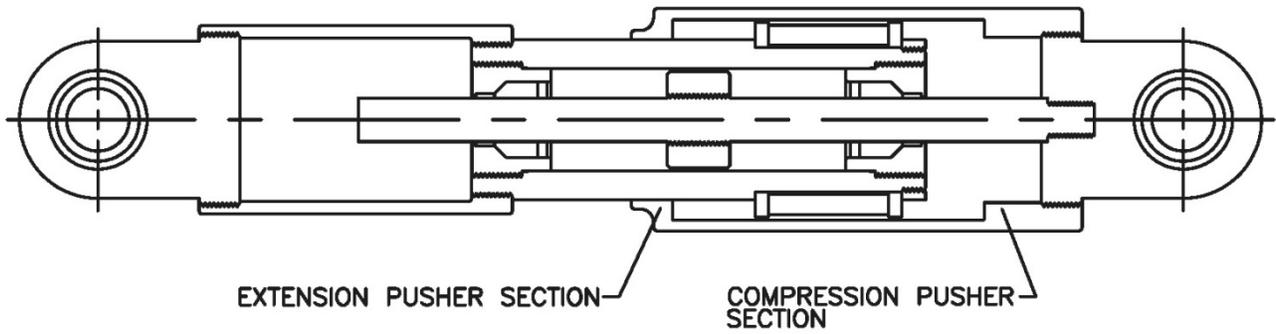


Figure 8

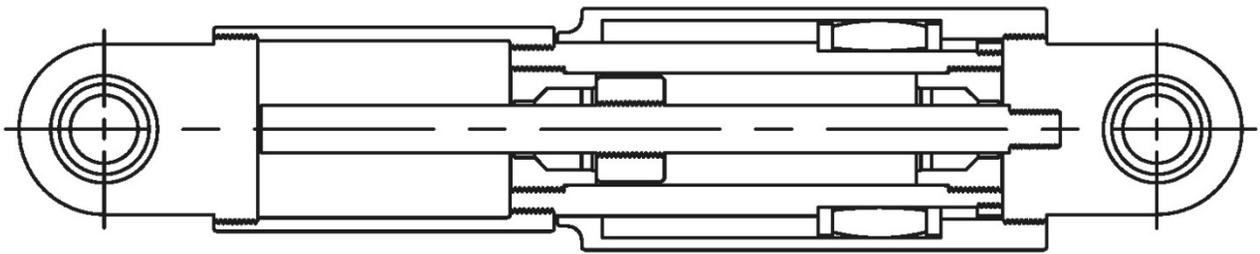


Figure 9-a – Compression Engagement of Spring

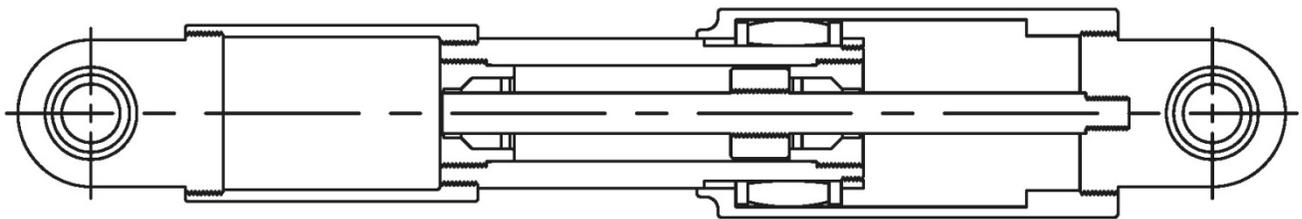


Figure 9-b– Extension Engagement of Spring

MANUFACTURING ISSUES

The metal parts of the isolator were manufactured using traditional machining techniques. Although the parts were large, they presented no particular difficulties. Manufacturing the elastomer spring elements proved to be far more difficult. A urethane elastomer was selected due to its ability to be simply melted and poured into a mold, making a so-called melt-cast blank.

Problems arose with the basic design in that a single tubular section tended to bulge excessively under moderate stress, thus reducing the spring rate to well below customer specifications. An alternate design was conceived using 4 thinner urethane elements sandwiched between alternating steel plates. This design was calculated to have a greatly reduced bulging tendency, which was verified by subsequent testing. Additional shear constraint against bulging was added by the addition of a locking ridge machined into the steel plates.

ASSEMBLY AND TESTING OF THE SUTONG BRIDGE HYBRID ISOLATOR

The external dimensions of the isolator are provided in Figure 10. Completed weight of each unit was 17,600 lbs. Assembly of the isolators was accomplished entirely in the vertical direction to avoid bending loads on subassemblies. Figures 11 and 12 show some of the assembly operations. In Figure 12, the elastomer spring elements and interspersed steel plates can be seen at the extreme bottom of the subassembly. Figure 13 shows the completed isolators.

The bridge owner had specified acceptance testing of each individual isolator. A total of 8 discrete tests were specified.

1. Proof Pressure Test – Each damper section of the isolators was statically pressurized internally to 200% of the damping pressure equivalent to the maximum rated damper output force. This pressure was held for 3 minutes on each isolator and for 24 hours on the first test article.
2. Velocity Testing – Each isolator was fixtured in a test stand and cycled at various displacements with peak velocities of 50%, 75% and 100% seismic velocity, plus a thermal creep velocity test at low speed. End of travel tests were performed to verify proper spring output.
3. Wind Fatigue Test – The first test article was subjected to a 50,000 cycle test at plus or minus 0.2 inches amplitude to simulate wind gusts applied to the bridge structure.

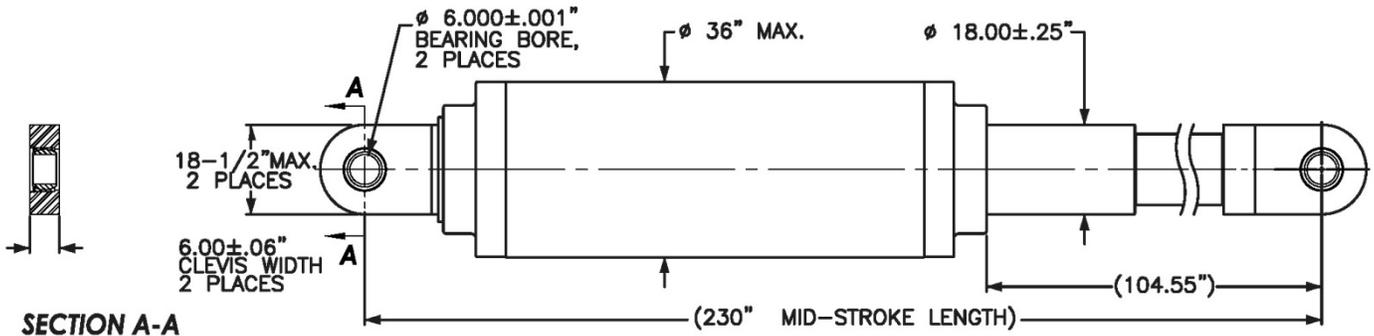


Figure 10



Figure 11 – Damper Cartridge



Figure 12 – Subassembly of Spring Elements



Figure 13 – Completed Isolators

Figure 14 shows the completed isolator installed in a cyclic test machine at Taylor Devices for damping and spring force testing. Representative plots from the acceptance tests are provided in Figures 15 to 20. All tests proved uneventful, surprisingly so when considering the rather large forces and displacements involved.

Installation of the dampers on the bridge took place in late 2007. Figure 21 shows two of the eight dampers as installed.

CONCLUSIONS

The size and capacity of the hybrid spring-damper isolators for the Sutong Bridge was optimized by selecting a fluid damper, an elastomer spring, and an internally placed gapping mechanism. If the same design concept was desired for smaller isolator forces, then design scaling issues might be such that the hybrid isolator would optimize with other types of spring elements. This would be based on relative size and cost of the spring element and damping element selected.

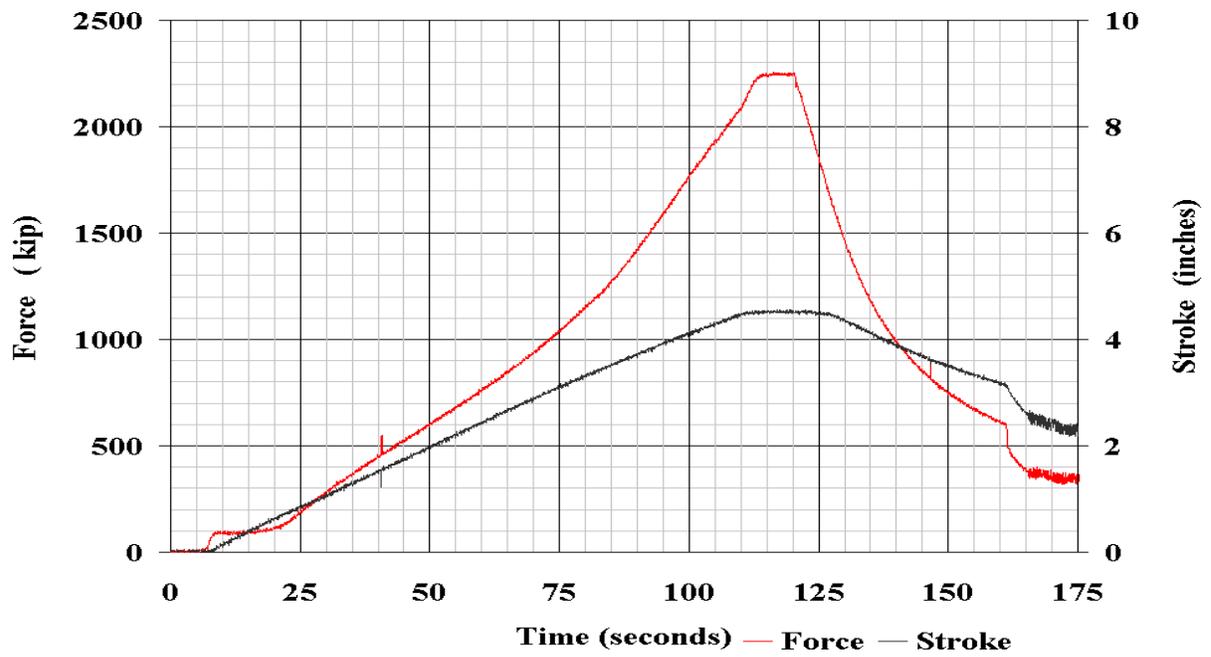
On this project, the customer required significantly more force from the spring elements than from the dampers, making it necessary to use the smallest possible diameter for the spring elements that was economically feasible. This was necessary because despite the divergent range of spring force compared to damper force, the customer still desired that the entire isolator incorporate both elements housed within a single hybrid component.

ACKNOWLEDGMENTS

The authors would like to acknowledge, and Lorrie Battaglia of Taylor Devices for her assistance with this paper.

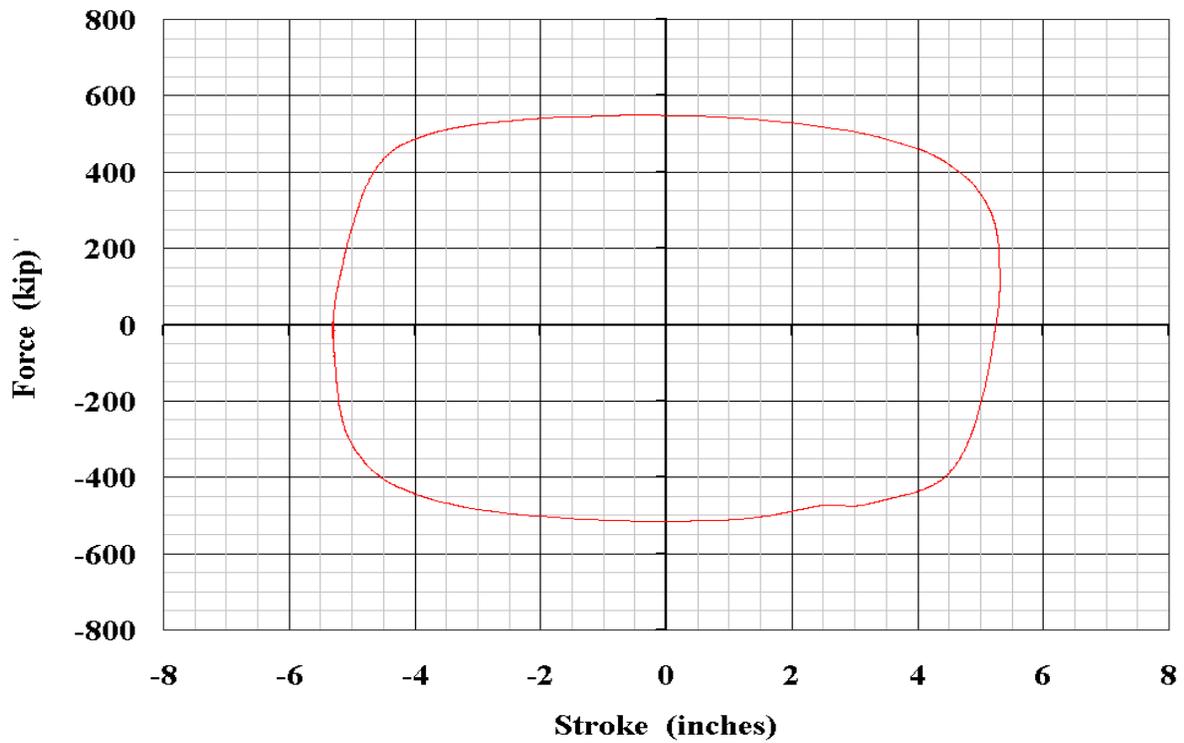
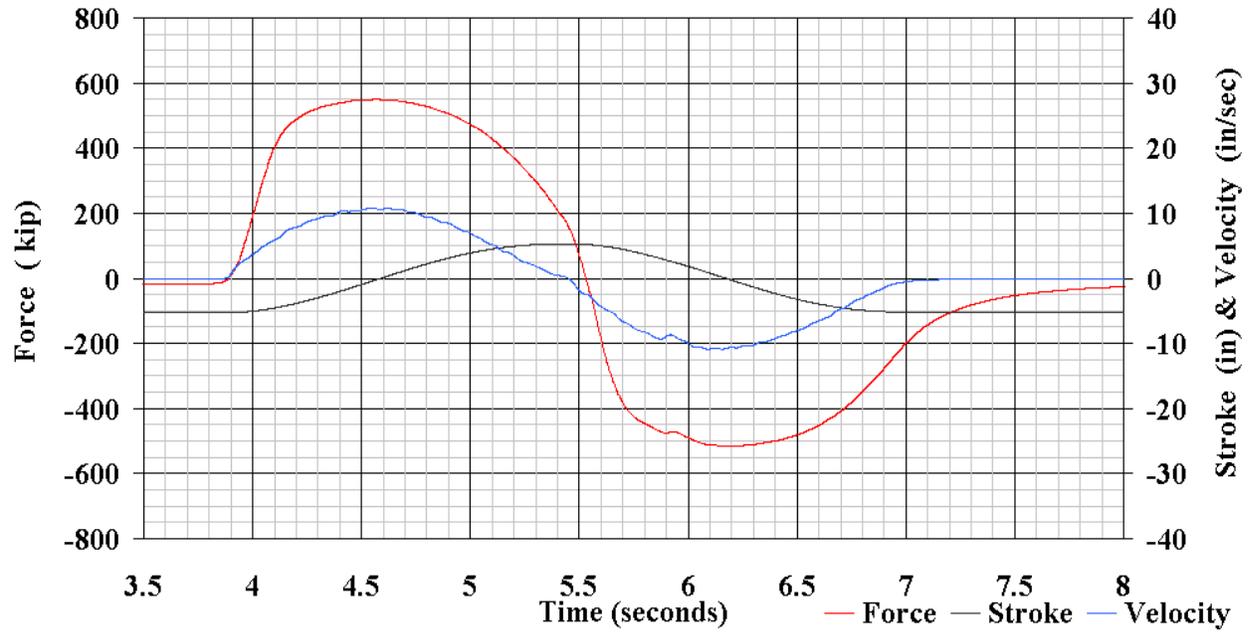


Figure 14 – Dynamic Testing



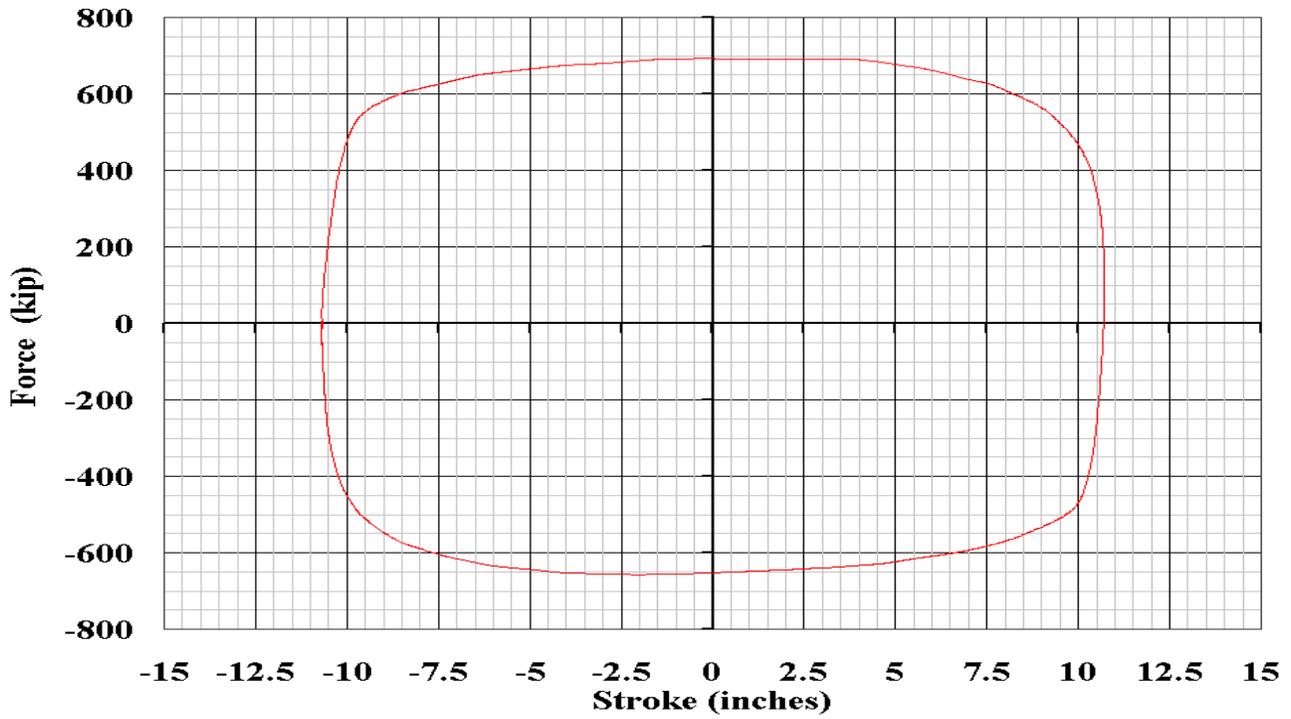
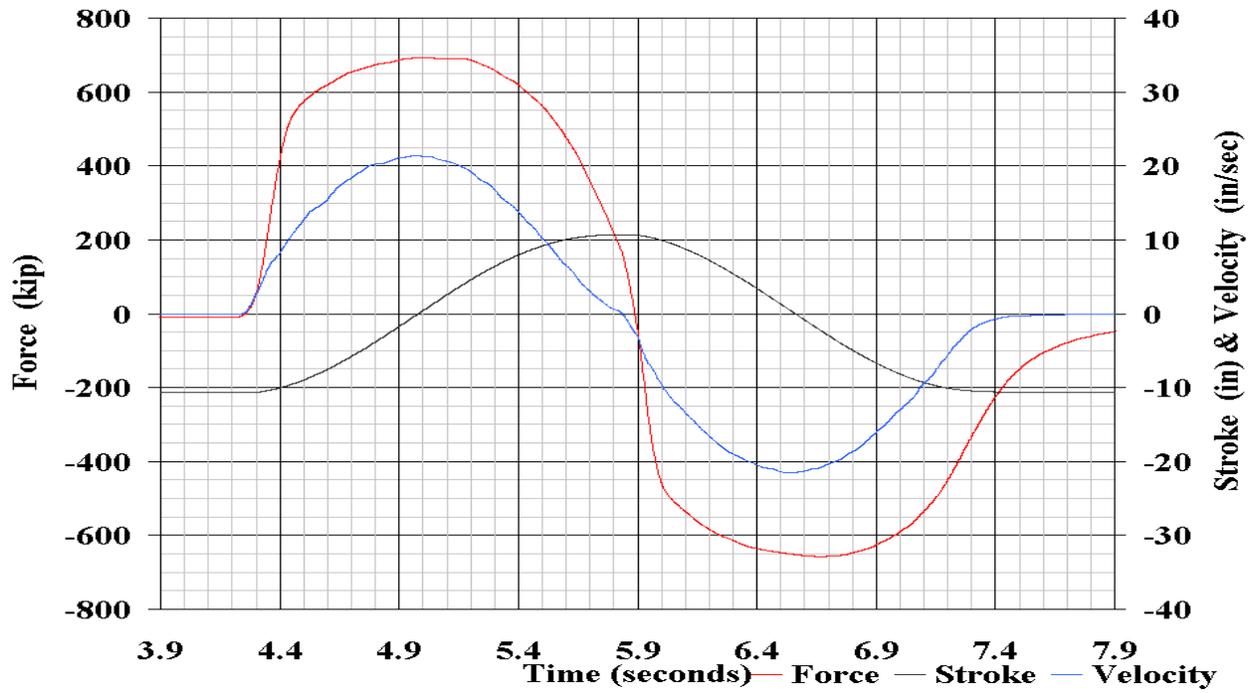
| |
|------------------------|
| Maximum Force (kip) |
| 2254.7 |

Figure 15 – Typical End of Travel Spring Force Test



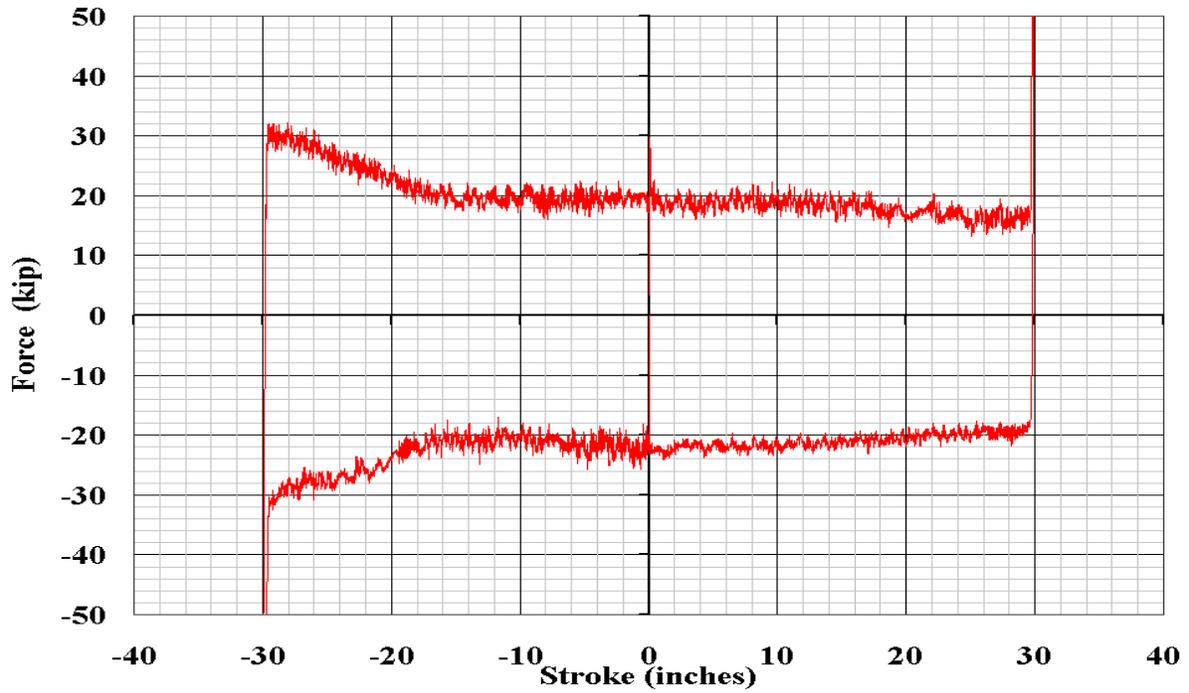
| Compression | | Tension | |
|-------------------|-------------|--------------------|-------------|
| Velocity (in/sec) | Force (kip) | Velocity (in/sec.) | Force (kip) |
| 10.9 | 549.7 | -10.9 | -515.2 |

Figure 16 – 50% Speed Damper Sine Wave Tests



| Compression | | Tension | |
|-------------------|-------------|--------------------|-------------|
| Velocity (in/sec) | Force (kip) | Velocity (in/sec.) | Force (kip) |
| 21.4 | 692.1 | -21.5 | -657.5 |

Figure 17 – 100% Speed Damper Sine Wave Tests



Full Stroke = ±30.0 inches

Figure 18 – Thermal Creep Velocity Test

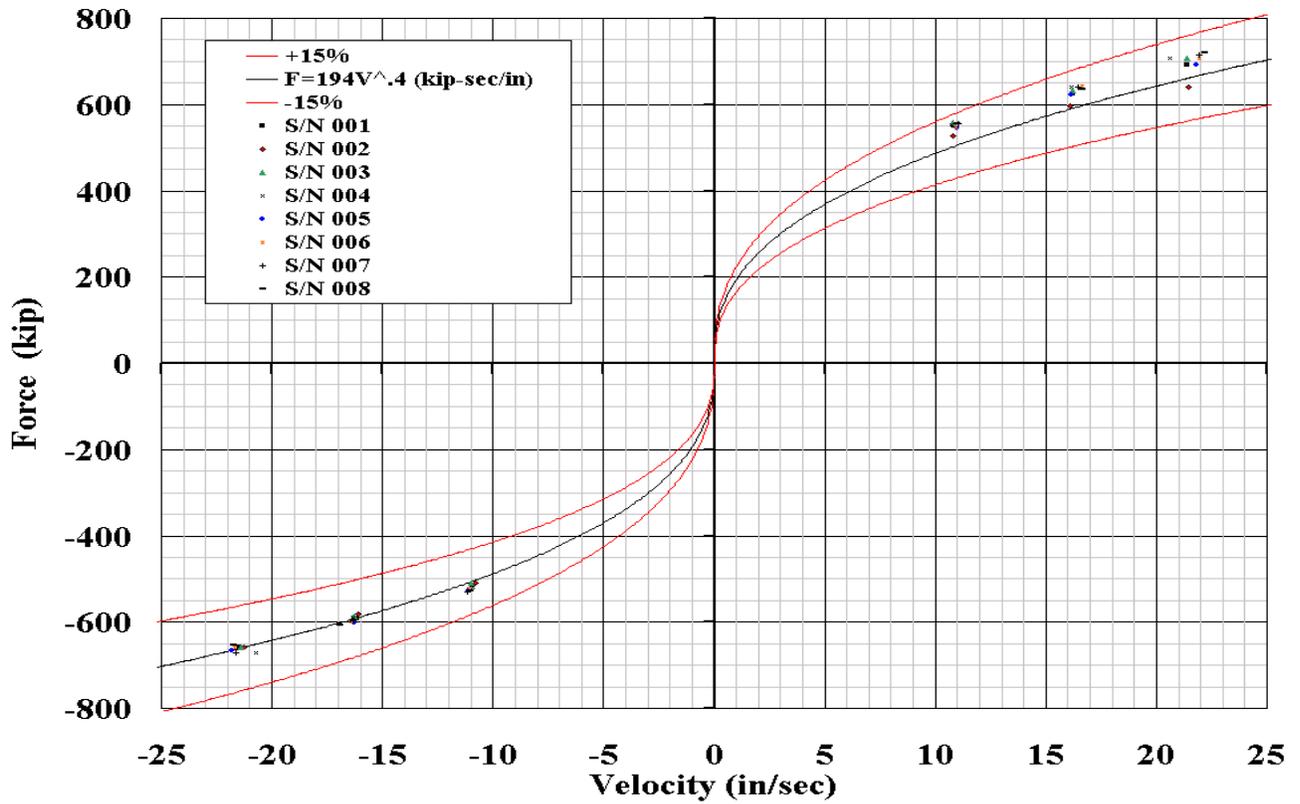


Figure 19 – Production Damping Test Data

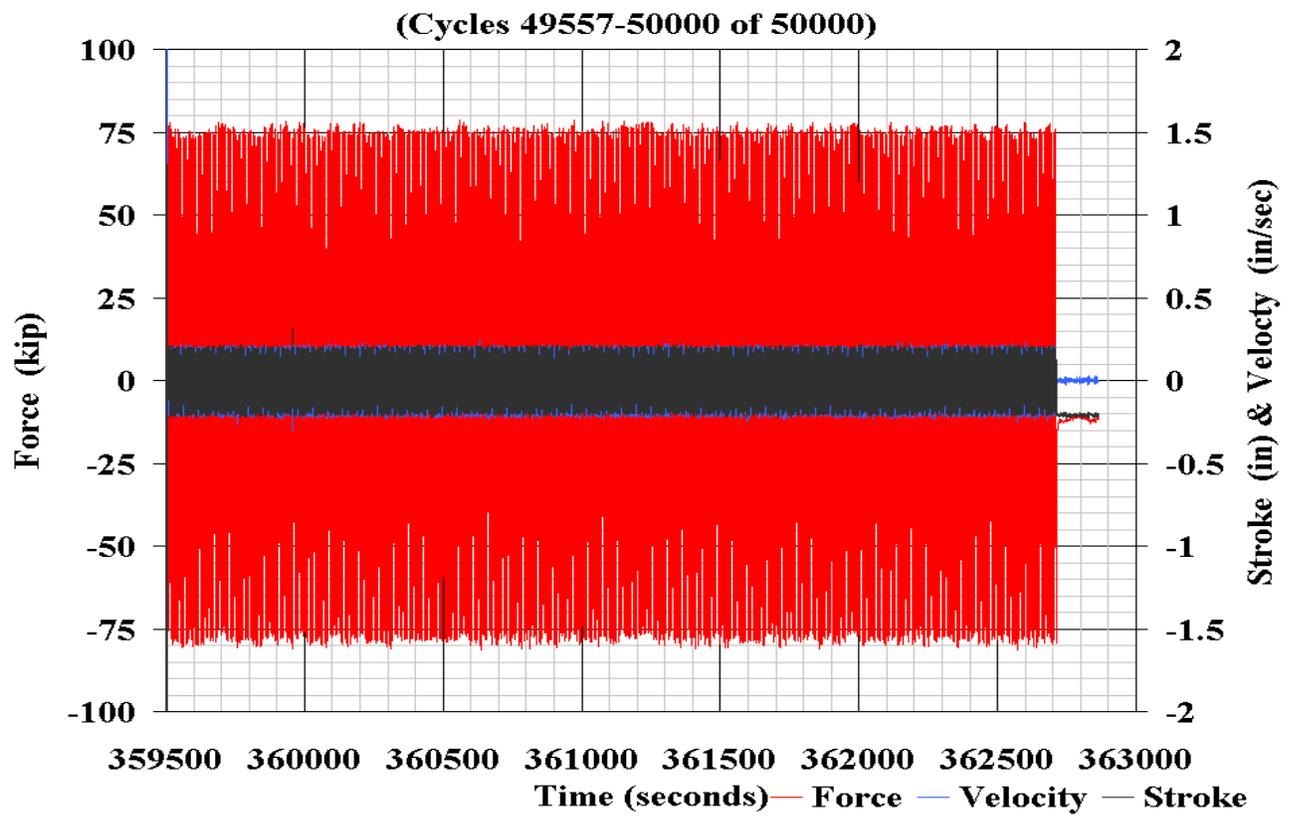
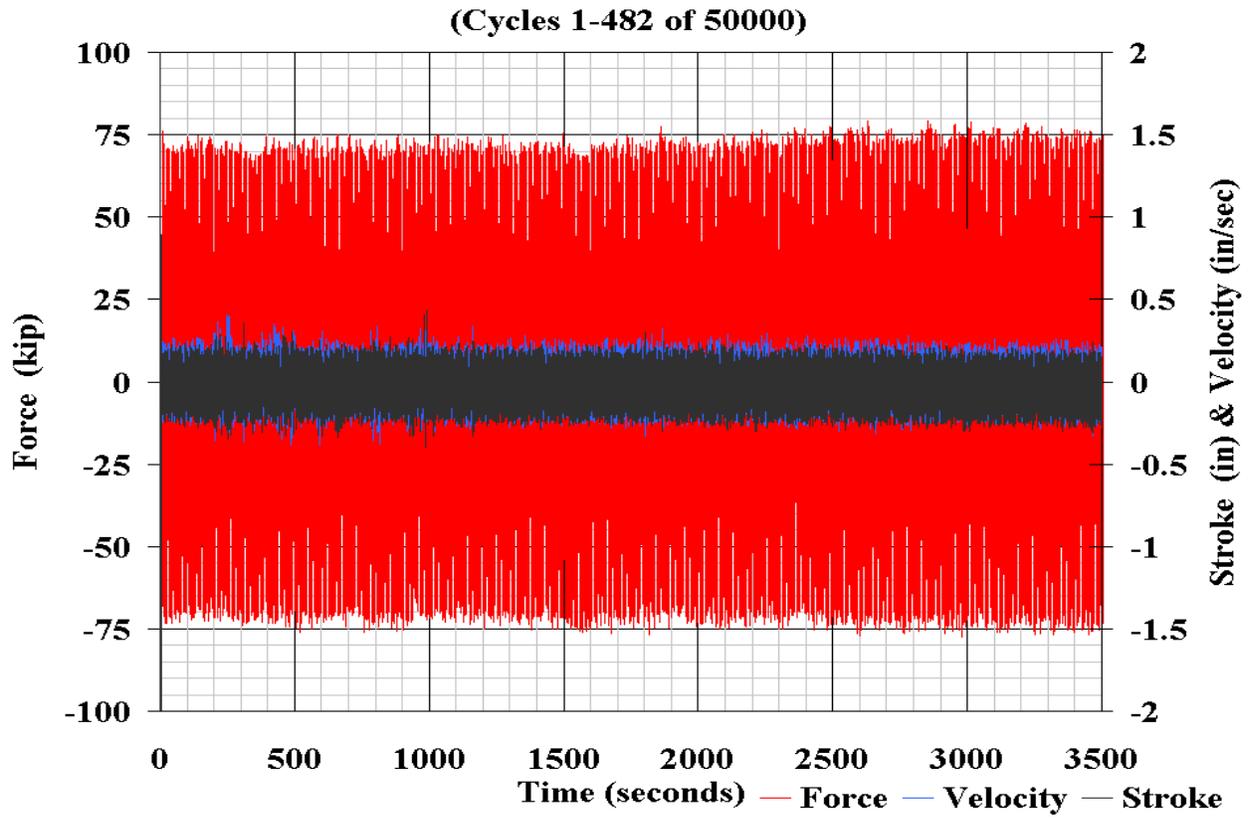


Figure 20 – Wind Fatigue Test



Figure 21 – Isolators Installed on Sutong Bridge