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RION-ANTIRION BRIDGE: DESIGN AND FULL-SCALE TESTING OF THE SEISMIC PROTECTION DEVICES

***Samuele INFANTI[1], P. PAPANIKOLAS[2], G. BENZONI[3] , M.G. CASTELLANO[4]**

SUMMARY

The Rion-Antirion Bridge, that crosses the homonymous strait in Greece, is located in a very active seismic region. The deck of this multi-span cable-stayed bridge is continuous and fully suspended from four pylons (total length of 2252 meters). Its approach viaducts comprise 228m of concrete deck on the Antirion side and 986m of steel composite deck on the Rion side. Said structures are designed to withstand seismic events generating ground accelerations of up to 0.48g through the use of fluid viscous dampers and other seismic devices.

The Main Bridge seismic protection system comprises fuse restraints and viscous dampers of dimensions heretofore never built. The same act in parallel, connecting the deck to the pylons. The restrainers are designed as a rigid link intended to withstand high wind loads up to a pre-determined force. Under the action of the design earthquake, fuse restrainers will fail and leave the dampers free to dissipate the earthquake-induced energy acting upon the structure. The Approach Viaducts are seismically isolated utilizing elastomeric isolators and viscous dampers.

This paper aims to describe the aforesaid seismic protection systems as well as the results of the extensive full-scale testing they underwent to verify design assumptions. The Damper Prototype tests were performed at the of the University of San Diego California Laboratory (USA), while the Fuse Restraints test and all production tests were carried out at the FIP Industriale Testing Laboratory in Italy.

INTRODUCTION

The Rion-Antirion Bridge (see Teyssandier [1]), located in the Gulf of Corinth - an area prone to strong seismic events and windstorms – comprises a cable-stayed bridge and two approach viaducts (986 m long on the Rion side and 228 m long on the Antirion side). The main bridge, that has four pylons, is the

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cable-stayed bridge with the longest suspended deck in the world (2252 m), its span distribution comprising 286m + 560m + 560m + 560m + 560m + 286m.

The critical factor in the design of the main bridge was its resistance to earthquakes with a 2000 years return period and a PGA of 0.48 g. The fully suspended, continuous deck is free to accommodate all thermal and seismic movements in the longitudinal direction, while movements in the transverse direction are controlled by the protection system described below, comprising fluid viscous dampers and fuse restraints.

The cable-stayed deck is a composite steel structure made of two longitudinal plate girders 2.2m high on each side of the deck, with transverse plate girders spaced at 4m intervals and a concrete slab, with total width of 27m. Each pylon is composed of four legs 4x4m, made of high strength concrete, joined at the top to provide the necessary rigidity to support asymmetrical service loads and seismic forces. The pylons are rigidly embedded in the pier head to form a monolithic structure, up to 230 m high, from the sea bottom to the pylon top (Figure 1).

Figure 1 - The main bridge under advanced construction (November 2003).

The Approach Viaducts are also seismically protected by a seismic isolation system comprising elastomeric isolators designed to provide the bearing function as well as the required period shift effect and by viscous dampers that provide energy dissipation.

This paper describes the different seismic devices to be installed in the Rion-Antirion Bridge, and focuses on the full-scale tests carried out for qualification and acceptance purposes.

MAIN BRIDGE SEISMIC PROTECTION SYSTEM

The main bridge is equipped with a seismic protection system that, given its characteristics and for the strict design requirements, entitles this structure a place in the next generation of seismic protected structures.

Said protection system comprises viscous dampers of dimensions and design capacity never built before that connect the fully suspended deck to the pylon base in the transverse direction, so as to reduce the transverse swing of the deck during an earthquake.

Notwithstanding, the requirements for appropriate and safe seismic behavior do not always line up in agreement with the everyday service life of the structure. Thus, large structural displacements induced by moderate earthquakes or windstorms are avoided by an additional restraint system, that fails at the occurrence of a major design event and allows the structure to freely oscillate with its damping system. This restraining system comprises fuse restraints installed in parallel with the dampers, so the deck, , is linked rigidly to the substructure when subjected to lateral loads not exceeding their design capacity, and after their failure it leaves the deck free to swing coupled to the dampers. The design failure force of the Four viscous dampers (Fmax 3500 kN, Stroke ±1750 mm) and one fuse restrainer are installed at each pylon, while at the transition piers there are two viscous dampers (Fmax 3500 kN, Stroke ±2600 mm) and one fuse restrainer. Figure 2 shows the general arrangement of the viscous dampers and the restraint devices at each of the four pylons, as well as at the transition pier. The latter is composed by a rotating frame pivoting at the base. The dampers are installed at the deck to substructure interface aligned along the deck transverse center line and rotate with the pier itself. The fuse restrainer is installed on one of the two dampers as a component of the damper itself.

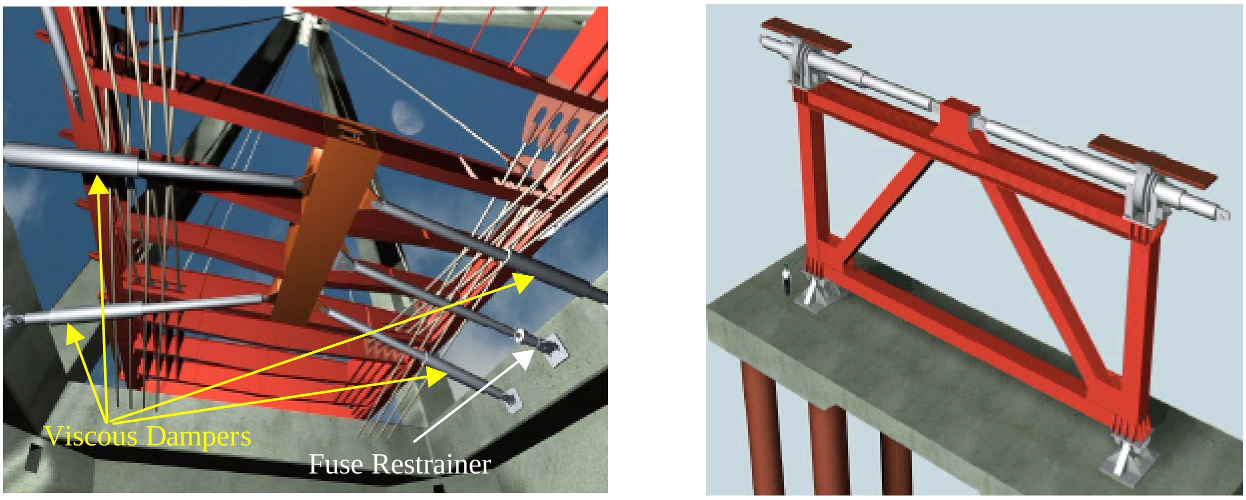


Figure 2 - Rion Antirion Main Bridge: arrangement of fluid viscous dampers on the main piers (left) and on the transition piers (right).

The fluid viscous dampers used are non linear, i.e. with a force vs. velocity law $F=c\ v^{\alpha}$ with $\alpha=0.15$, thus guaranteeing an almost constant reaction within a wide velocity range and a very high energy dissipation capacity (see Castellano [2] and Infanti [3]). FIP Industriale non linear viscous dampers, before use in the Rion-Antirion Bridge, had undergone major testing programs at independent facilities in the USA, including the testing program according to HITEC protocol (see Infanti [4], [5], [6]).

The fuse restraints located on the main pylons are characterized by a failure load of 10500 kN and are designed as single units equipped with spherical hinges at their ends. This configuration allows for design rotations as well as correct alignment of the load along the device axis for any deck position.

The element that fails when it reaches a desired design load – the so-called Fuse Element - is installed in the middle of the unit (for the unit general configuration see Figure 3). Similarly, the units installed at the transition piers, as components of the dampers, are characterized by a failure load of 3400 kN.

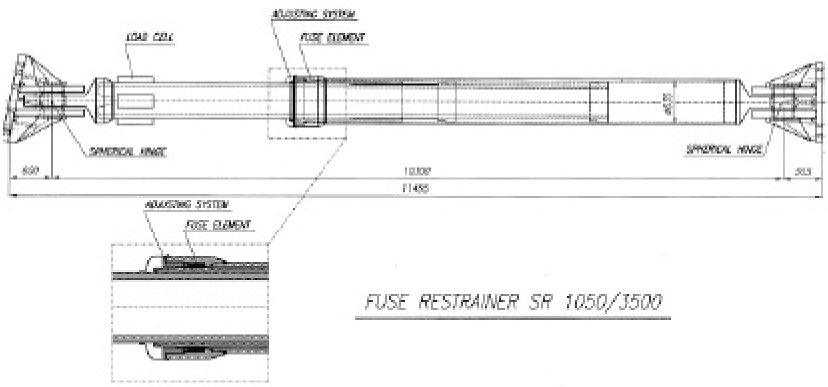


Figure 3 - General configuration of fuse restraint installed on main pylons.

A major design complication with the fuse restraints arose from the need to minimize the internal forces of the laterally restrained deck induced by slow tectonic movements originating from a seismic fault located under the bridge. Thus, the restraint units located on the main pylons are equipped with a system designed to allow for length adjustment. This operation has to be performed when a pre-defined load level is constantly applied to the link. Therefore, it requires a load cell to monitor the load on the unit. As part of the monitoring system of the bridge, this will permit the identification of the moment at which re-adjustment of the deck is required. Since another design requirement was that the units should not disassemble after failure of the main component, the units were designed to allow for the same stroke provided by the dampers.

Strict specifications were imposed by design engineers regarding the behavior of the seismic

protection system in order to ensure a stable performance of all the devices: dampers reaction shall be within ±15% of its theoretical constitutive law (found through an optimization study based on non-linear time-history analyses on a 3-D model of the entire bridge) and fuse restrainers failure shall be within ±10% of the design value (a very strict design performance for such a high capacity units). Full-scale tests aimed at verifying the design characteristics are briefly described in this paper. Further details are given by Benzoni [7] and Infanti [8].

SEISMIC ISOLATION OF THE RION-ANTIRION BRIDGE APPROACH VIADUCTS

The approach viaducts, being of critical importance to the functionality of the main bridge after a seismic attack, have been designed to withstand the same earthquake intensity level as the main bridge. The viaducts on the Rion and Antirion sides present different design and construction technologies but use the same type of seismic isolation system.

The Antirion approach viaduct, which has already been completed (Figure 4), is located on the Greek mainland and has 6 spans (2 37460 m spans and 4 38460 m spans). It is made of pre-cast, pre-stressed concrete girders with an r.c. deck slab. Longitudinally, it comprises simply supported spans linked by continuity deck slabs at its supports. A typical cross section comprises 8 pre-stressed concrete girders with transverse diaphragm cross beams on supports. The viaduct piers r.c. frames in the transverse direction, made of four columns connected at their lower portion by a pile-cap and a cross head beam at their upper portion.

Figure 4 - The Antirion Approach Viaduct.

Figure 5 - Approaches isolation system.

The Rion viaduct is located on the Peloponnesus side and has a total length of 986 m. It is currently under construction. It comprises two independent composite bridges, each made of two girders connected by cross beams (see Figure 5). A typical cross section consists of a concrete slab connected to steel beams by connectors. The piers are r.c. frames in the transverse direction made of two columns connected at their lower portion by a pile-cap and at their upper portion by a cross head beam. The piers are founded on piles.

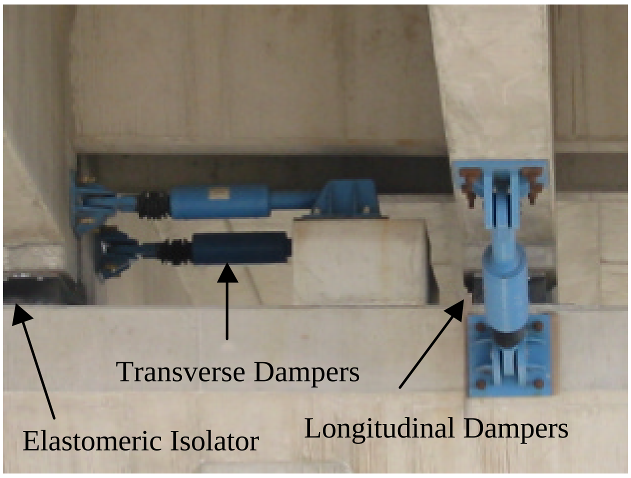


Figure 6 – Isolation system in the Antirion approach viaduct.

The seismic isolation system used for the protection of all the approach viaducts comprises a combination of low damping elastomeric isolators and non linear fluid viscous dampers of the same type as those used in the main bridge (Figures 5 and 6). The isolators provide the bearing function as well as the horizontal flexibility required to increase the fundamental period of the structure and thus reduce energy input. Viscous dampers are set up in both the longitudinal and transverse directions between the deck and the pier heads so as to dissipate energy and limit relative displacements. The isolators and dampers installed in the Antirion Approach Viaduct have already undergone an extensive test program. The isolator tests are described by Infanti [9] while the viscous dampers tests are described herebelow. The Antirion Approach Viaduct has already been subjected to an earthquake with PGA about 0.2 g measured at the site. Tests on devices for the Rion Approach Viaduct are presently underway.

VISCOUS DAMPERS FULL-SCALE TESTING

The following paragraphs present the main results of the qualification tests performed at both FIP Industriale Testing Laboratory and at the Seismic Response Modification Device (SRMD) Testing Laboratory of Caltrans at the University of California at San Diego (UCSD) on a full-scale prototype of the viscous dampers to be utilized on the main bridge as well as the production tests carried out at FIP

Industriale Testing Laboratory on actual viscous dampers installed both in the main bridge and the Antirion approach viaduct.

Qualification tests on Prototype

The prototype is characterized by a 3220 kN reaction at the maximum design velocity of 1.6 m/s (damping constant C=3000 kN·$(s/m)^{0.15}$) and a ±900 mm stroke. Table 1 compares its characteristics with those of dampers installed on the pylons and the transition piers, which are deemed to be the largest ever-built to date. The prototype is equal in every detail to the dampers designed for final installation with the exception of their length (and consequently stroke thereof) which is shorter (6.14 m pin to pin) so as to fit into the existing test rig of the SRMD Laboratory. In said laboratory, the prototype was officially tested up to its maximum design conditions in the presence of the client (Kinopraxia Gefyra - Greece) and the bridge design checker (Buckland & Taylor - Canada).

Table 1 - Fluid Viscous Dampers Characteristics.

Characteristics	Pylons	Transition Piers	Prototype
Damper Series	OTP350/3500	OTP350/5200	OTP350/1800
Design Capacity (kN) at 1.6m/s	3220	3220	3220
Stroke (mm)	-1650/+1850	± 2600	± 900
Pin-to-Pin Length (mm)	10520	11320	6140
Total Length (mm)	11310	12025	6930
Maximum Diameter (mm)	500	550	500
Damper Weight (kg)	6500	8500	3300
Total Weight (kg)	9000	11000	5500

Before shipping the prototype to the SRMD Laboratory, preliminary tests were carried out at FIP Industriale Testing Laboratory, which is equipped with a power system providing for 630 kW at 1200 l/min (the most powerful in Europe for full-scale dynamic testing of seismic devices). In view of the prototype's exceptional characteristics, it was tested up to the maximum velocity provided by the available system, which was 0.2 m/s. Results are reported below, in Figure 8, together with the results of tests carried out at the SRMD Laboratory.

The matrix of tests carried out at the SRMD Laboratory is reported in Table 2 (tests are listed in the same order they were carried out). It is worth noting that the tests were performed up to the maximum design velocity equal to 1.6 m/s. It was the first time that a damper of so high a load capacity was tested at such high velocity.

Table 2 - Test Protocol on Viscous Damper Prototype FIP OTP 350/1800.

Test #	Test Name	Input	Number of cycles	Stroke	Testing conditions (V = Peak Velocity)
1	Thermal	Linear	1	± 895 mm	V<0.05 mm/s for 5 minutes Increase velocity to 1mm/s up to completion of the displacement.
2	Velocity Variation	Sinusoidal	5 5 5 3 2	± 300 mm	V=0.13 m/s V=0.40 m/s V=0.80 m/s V=1.20 m/s V=1.60 m/s
3	Full stroke & Velocity	Sinusoidal or step loading	1	± 850 mm	V_{max}=1.6 m/s
4	Wear	Linear	20000	± 5 mm	V=15 mm/s Every hour change position of the piston of about 100mm
5	Velocity variation	Sinusoidal	2	± 300 mm	V_{max}=1.6 m/s

The specimen was horizontally installed in the testing rig, connected at one end to a reaction wall and at the other end to the movable platen. Its six degrees of freedom table is capable of unique levels of displacement, forces and velocities. For this specific application, the platen was moved in the longitudinal direction with a displacement control loop capable of keeping components of motion in the other directions at negligible levels. Figure 7 shows the damper installed on the testing frame.

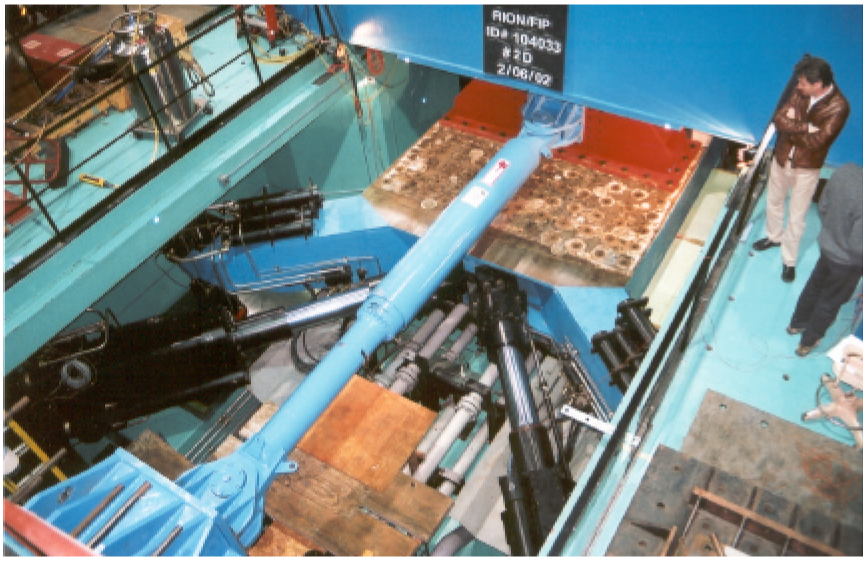


Figure 7 - Prototype testing at SRMD Facility (UCSD).

Average forces measured at different velocity levels (test # 2) are reported in Figure 8, together with those measured at a lower velocity at FIP laboratory. It is worth stressing the fact that the test results obtained at the SRMD facility agreed very well with the measurements performed at FIP testing laboratory. The extrapolation of the damper reaction in the range of velocity 0.13-1.6 m/s (test # 2) from the results of the tests performed at FIP laboratory up to 0.2 m/s differed from the measured reaction at the SRMD facility by only a few percentage points. Such results demonstrate how very predictable damper behavior can be within the full testing range.

Maximum forces appear to be very symmetric in the entire range of velocities: a difference of 7% was recorded at maximum speed (1.6 m/s) only during the first cycle. The second cycle of the same test shows instead a deviation of 1.6%. The comparison among peak forces of different cycles shows that the damper provides stable reaction wthin a very wide velocity range (0.002 – 1.6 m/s): a reduction of the peak force of 3.8% between fifth cycle and first cycle was measured in test Velocity A (0.13 m/s); for the high speed tests the maximum force reduction is equal to 10.4%.

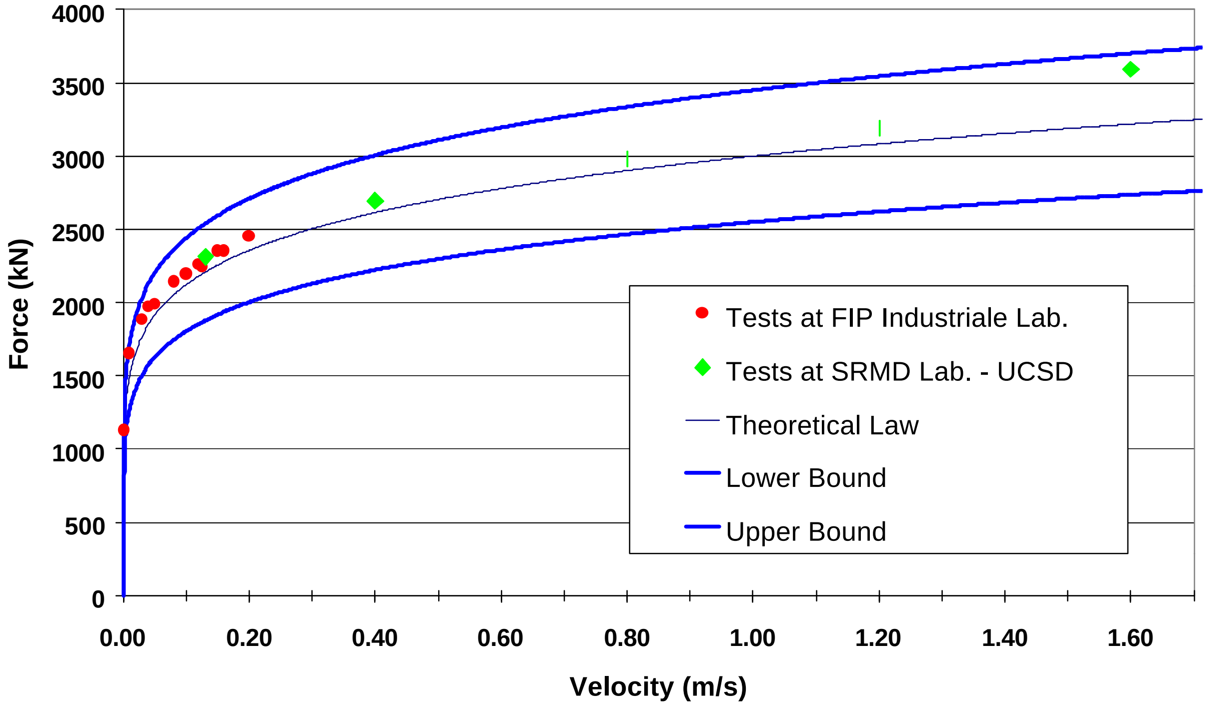


Figure 8 - Experimental vs.theoretical – damper constitutive law.

The typical force vs. displacement response of the damper is reported in Figure 9 for the sinusoidal tests (#2) with 0.8 and 1.2 m/s peak velocity.

The calculated energy dissipated per cycle (EDC) for the Full Stroke and Velocity Test (test #3) was 11035 MNm (+6% of the theoretical EDC). In order to perform this test a 3.3 MW average power input was required.

Thermocouples were installed both inside and outside the damper body to monitor any temperature rise during and after the motions. Air and nitrogen gas was used, in a cooling box, to restore the ambient temperature on the damper before a new test. Temperature rises were recorded for each test. The maximum increase took place at the end of the test Velocity Variation B, with 40 degrees Celsius recorded from the sensor installed inside the damper.

Wear tests were completed with 10 sets of 2250 cycles, at constant velocity of 0.015 m/s and 10 mm total stroke.

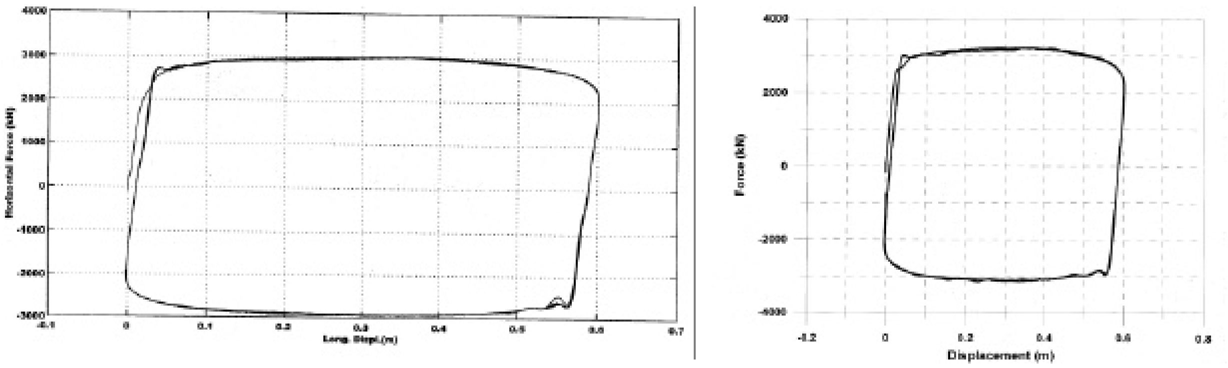


Figure 9 - Experimental damper hysteresis loop (V=0.8 m/s – left; V=1.2 m/s - right).

All the test results were deemed to be in agreement with the design specifications.

Quality Control (production) tests on main bridge dampers

The aim of the production tests was to verify the compliance of the production units with the contract specification or, in other words, whether their reaction and damping characteristics fall within the design tolerance range. The tests were performed on 100% of the produced units at FIP Industriale Laboratory in Italy (see figure 7 for the testing configuration of a production unit).

The contractual test program requires the following tests:

- Proof Pressure test: the test aimed to verify whether the damper vessel can withstand 125% of the design internal pressure with no damage or leakage.
- Low velocity test: the test aimed to verify whether the damper reaction at low velocity (less than 0.1 mm/s) is less than 200 kN to allow for ease of length adjustment as well as avoid fatigue loads on the bridge.
- Dynamic test: the test aimed to verify whether the units can provide a reaction that follows the theoretical constitutive law with a maximum deviation of ±15%.

All the above mentioned tests yielded a positive outcome. The measurements confirmed the results obtained during the prototype testing at the SRMD Facility of the University of California at San Diego.

Figure 11 shows the measured reaction for all the units of the first two production lots (serial numbers from 414946 to 414953), normalized with reference to the theoretical reaction, obtained imposing three sinusoidal cycles of 250 mm stroke amplitude and reaching a peak velocity of 100 mm/s.

Figure 12 shows a typical force vs. displacement loop, obtained on one of the longest dampers, i.e. those to be installed in the transition piers, in a sinusoidal test with amplitude ± 250 mm and a peak velocity of 175 mm/s.

Figure 10 - Production tests at FIP laboratory on a fluid viscous damper for the main bridge.

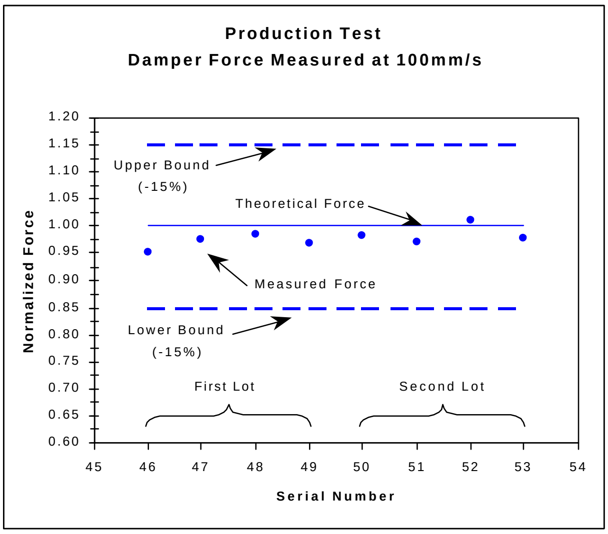


Figure 11 - Normalized reaction of the production units.

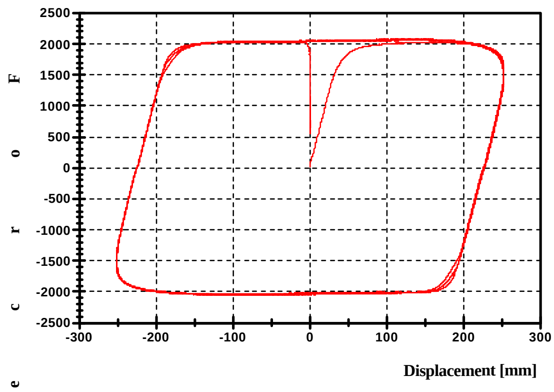


Figure 12 – Hysteresis loop measured in sinusoidal dynamic tests at V_{max}=175 mm/s on a transition pier damper.

Quality Control (production) tests on dampers for the approach viaducts

Tests aimed to verify the effective damping capacity under dynamic loads, the displacement capacity and the accordance with the expected performance law (Force vs. velocity relationship) were performed on about 5 % of the produced units. Tests on dampers for the Antirion Viaduct were completed in 2002, while tests on dampers for the Rion Viaduct are presently underway and will be completed by February 2004.

The Antirion Viaduct requires 44 dampers to be installed both longitudinally and transversally (see figures 4 and 6). The longitudinal dampers (24 units) are characterized by a 1200 kN load capacity and strokes ranging from ±200 to ±250 mm, whilst the transverse dampers (20 units) are characterized by an 800 kN load capacity and strokes equal to those used longitudinally. Quality control tests were carried out on one longitudinal and one transversal damper. Figure 13 shows a longitudinal damper under testing at FIP Industriale Laboratory. The hysteresis loop obtained testing at constant velocity is presented In Figure 14.

Figure 13 - Production Tests at FIP Laboratory on a longitudinal damper for the Antirion Approach Viaduct.

The Rion Viaduct requires the installation of 134 units characterized by 300, 600, 1200 and 2400 kN load capacity and strokes ranging from ±250 to ±405 mm that are currently under production and testing.

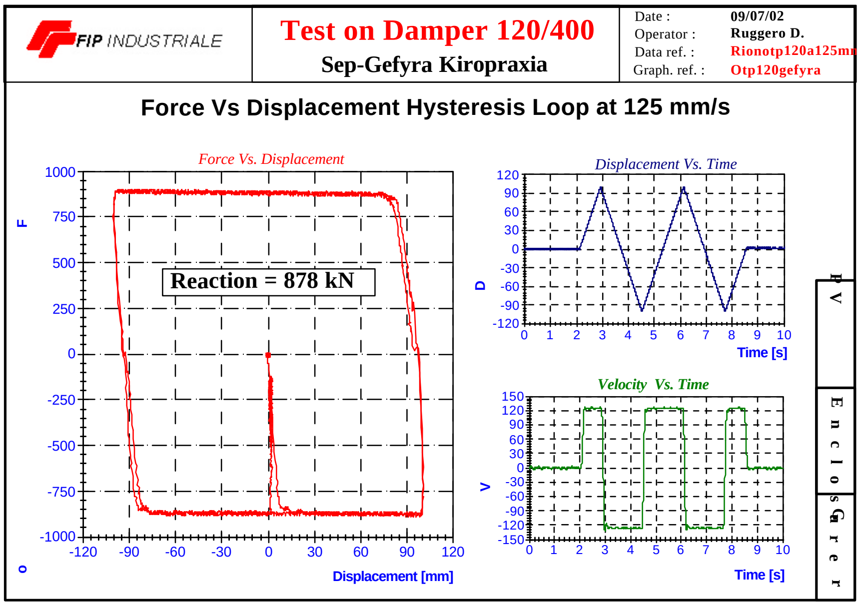


Figure 14 - Hysteresis Loop measured in a constant velocity test.

FUSE RESTRAINTS TESTING PROGRAM

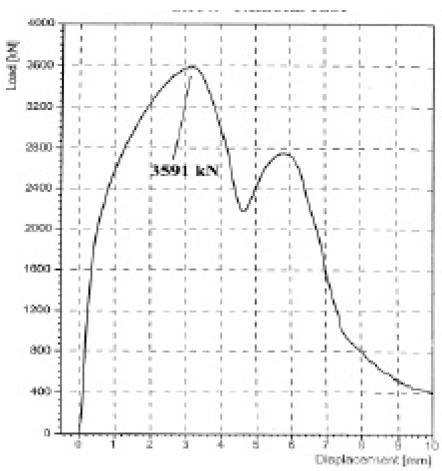
The testing program was carried out on two full-scale prototypes of fuse elements of each type. It comprised a first test performed on one unit monotonically increasing the load up to failure, followed by a second test performed on the other prototype imposing two millions of cycles at a load level equal to 10% of the design failure load and then monotonically increasing the load up to failure. Since the restraints first function is that of withstanding every day actions (service loads), a second test was required to evaluate fatigue life as well as any influence of fatigue on failure strength.

Failure test and fatigue test were carried out on different test rigs, the first one a 8000 kN capacity rig commonly used for bearing tests while the second is a 3000 kN dynamic test rig: the same used for damper testing.

Test results showed that both prototypes failed within design tolerances. The difference between the measured failure loads before and after the fatigue test confirms the fact that the design fatigue load cannot be considered as affecting the ultimate capacity of the fuse restraints. All test results are presented in the following table. Figure 16 shows typical graphs obtained with both the 3400kN and 10500kN units.

Table 3**. Test Results**

Device Type	Failure Load Capacity (kN)	Tolerance Range (kN)	Measured Load (kN)	Deviation (%)
SR340	3400	3060-3740	3545	+4.3
SR340	3400 (Fatigue)		3591	+5.6
SR1050	10500	9450-11550	10382	-1.1
SR1050	10500 (Fatigue)		11765	+12.0



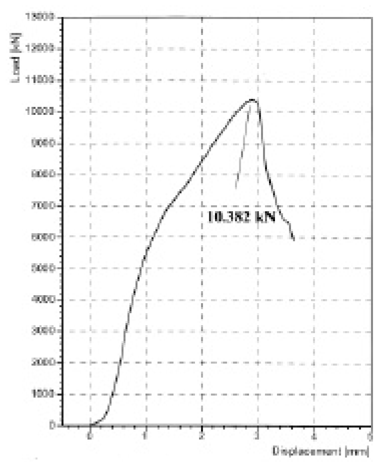


Figure 15 - Failure test results on Fuse Restraints SR340 (left) and SR1050 (right).

Figure 16 - SR1050 Fuse element during fatigue test.

Conclusions

Testing of full-scale viscous dampers and fuse elements was performed to confirm the characteristics and main design assumptions of the seismic dissipation system used for the Rion-Antirion Cable Stayed Bridge and its approach viaducts.

Tests performed on Fuse elements positively verified the design assumption, showing that it is possible to achieve a very tight tolerance (±10%) on the predicted ultimate capacity even when the units are designed for a very high failure load (10500 kN).

The Viscous Damper prototype showed very stable behavior even when tested under extreme dynamic conditions, up to a velocity of 1.6 m/s. The measured energy dissipation and viscous reaction were always well within the design tolerance of ±15% of the theoretical design parameters. Testing aimed to represent the effect of structural vibrations induced by traffic and/or movements induced by structure thermal expansions did not produce any appreciable change in damper behavior.

The production tests confirmed the fact that the dampers to be installed on the bridge do provide the same characteristics as the prototype with little deviation from its theoretical constitutive law.

Full-scale testing of such large size dissipating devices proved to be a real challenge compared to previous testing experiences as it pushed the limits of equipment available worldwide.

Experimental results on full-scale units give a high degree of confidence on seismic devices as a means to protect large and important structures such as the Rion-Antirion Cable Stayed Bridge and its approaches.

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