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FLUID VISCOUS DAMPERS OF THE IZMIT BAY BRIDGE, TURKEY: DESIGN REQUIREMENTS AND FULL-SCALE TESTING

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Abstract

The Izmit Bay Bridge is a 3020m long cable suspension bridge, located at the eastern end of the Sea of Marmara, Izmit, Turkey. The bridge consists of a steel box girder deck sustained by cables and 2 towers made of stiffened steel plate (252m height). The restrained system for seismic, wind actions and traffic loads is provided by 7 fluid viscous dampers; 3 for the transition spans (Fmax=5000kN, stroke ±500mm and maximum velocity 1.25m/s) and 4 for the main suspended span with Fmax=5000kN, stroke ±2m and maximum velocity 2m/s, resulting the biggest hydraulic devices ever built with 13.5m pin-to-pin length. This paper presents a description of the full-scale type tests conducted at FIP Industriale Test Laboratories on two viscous dampers (one of each type) to confirm the compliance with the European Standard EN15129 and the contract specifications. A series of dynamic tests were performed in order to verify the force vs. velocity constitutive law and to evaluate the dynamic stiffness and damping characteristics of the units, at the entire temperature range of 10°C/+80°C. The experimental results demonstrated a very stable behavior at any velocity up to 2m/s, througout the temperature range, guaranteeing the damping capacity reliability and satisfying all requirements.

Keywords: viscous damper, seismic protection, dynamic testing, cable suspended bridges

1. Introduction

The Izmit Bay Bridge, currently under construction in Turkey, is a suspension bridge with 1550 m long main span and two 566 m long side spans, planned to be the fourth longest suspension bridges in the world by the length of central span. Connecting the north eastern and south eastern coast of the Izmit Bay, in the Sea of Marmara, the bridge will reduce the congested condition of the regional traffic as part of the motorway from Gebze to Izmir. The project site is located in the area of the North Anatolian Fault, that forms the tectonic boundary between the Eurasian Plate and the Anatolian block of the African Plate. The site area could be therefore subjected to strong seismic events, considering that part of the fault occupies the Izmit Bay and projects across the bridge alignment [1].

1.1 Seismic protection system

In order to control the bridge response to the strongest design dynamic action, i.e. earthquake with 2475 years return period, and at the same time ensure the functionality of the bridge under service condition, special structural devices have been considered and finally implemented for both the suspended deck and transition spans (Fig. 1). As shown in Fig. 2, twelve (12) free sliding spherical bearings with anti-lifting capacity have been selected to carry the vertical loads, whilst sixteen (16) lateral elastomeric bearings will provide the transversal restraint. In order to reduce the movements in the longitudinal direction between the bridge decks and the substructures two types of special Fluid Viscous Dampers (FVDs) are installed, one type between the suspended deck and the side span piers and one type between the transition spans and the transition piers (Fig. 3). The dampers restraint the movements of the bridge deck due to fast acting loads, such as traffic and dynamic wind loads, while movements caused by slow acting loads, such as temperature, static wind and traffic allow to take place freely. During seismic events the dampers limit the loads acting between the structure to a certain threshold value, providing an effective damping system, while allowing the piston to move under constant restraining load.

Fig. 1 - Bridge layout

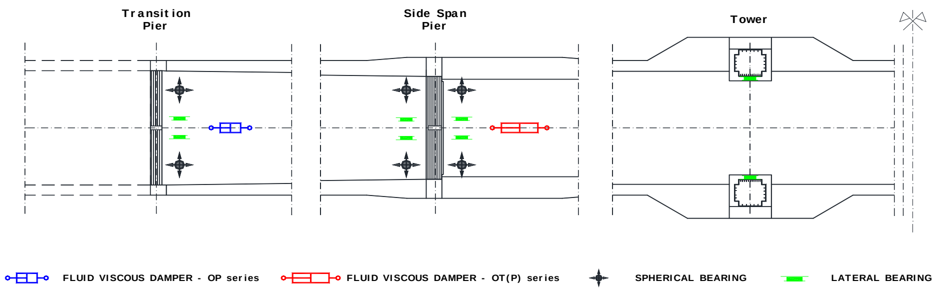
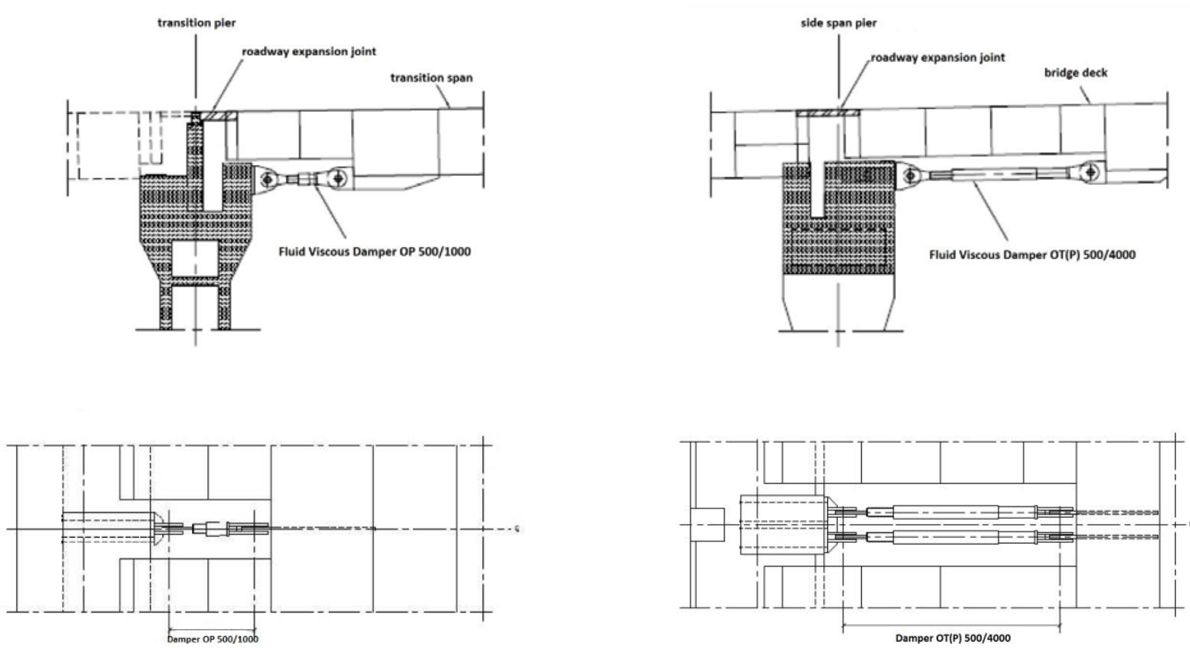


Fig. 2 - Bridge viscous dampers and bearings layout (one half of the bridge is represented, the layout is almost symmetrical, apart the number of viscous dampers on the transition piers).



(a) (b)

Fig. 3 – Positioning of the two types of FVDs in the transition pier (a) and side span pier (b) [8].

Four (4) viscous dampers, referred as OT(P) 500/4000 type (in red in Fig. 2) were installed at the side span piers, with a dynamic force capacity of 5000 kN and stroke of ±2000 mm, equipped with an hydraulic end-stop of 11750 kN static capacity. The final dimensions of the devices, reaching about 15.5 meters in length at their maximum extended configuration, make these devices the longest viscous dampers ever built in the world. At the transition piers other three (3) fluid viscous dampers were installed, referred as OP 500/1000 type (in blue in Fig. 2), 5.7m length pin-to-pin, 5000kN max. force and ±500 mm stroke. Their scope is to ensure an almost rigid connection between the girder and the piers in the normal load cases, as traffic and wind loads, as well as ensuring that a certain force level is not exceeded in case of earthquake. For seismic load cases (velocities up to 1.25m/s for OP 500/1000 and 2m/s for OT(P) 500/4000), both types of FVDs will provide a threshold force higher than 5000kN, above which the deck is allowed to move, while maintaining the restraining threshold force and thus dissipating energy.

All fluid viscous dampers were designed, constructed and tested in FIP Industriale in Italy. This paper focuses on the full-scale Type Tests performed on two (2) FVDs, one of each type, carried out at FIP Industriale Laboratories. The tests were performed according to the European Standards EN15129:2009 and the contract specifications in order to confirm the characteristics of the devices and the main design assumptions of the seismic dissipation system of the bridge. In the following paragraphs the testing program, procedure and results are presented.

1.2 Viscous damper behaviour

Fluid viscous dampers are axial devices whose force is proportional to velocity through the relationship $F=c\ v^{\alpha}$, the exponent α usually ranging from 0.01÷0.15 (highly non-linear devices) to 1 (linear devices), and sometimes up to 2 for wind damping applications. The highly non-linear FVDs are preferred due to their constant reaction within a wide velocity range, achieving higher energy dissipation during the relatively short duration of the earthquake and consequently reducing of the displacements at a given level of maximum load transmitted to the structure [2, 3, 4, 5 and 6].

From the plot in Fig. 4, it can be noted that this typical hysteresis loop of a highly non-linear damper is almost rectangular (behaviour almost independent from velocity) even if the displacement time-history is sinusoidal (velocity dependent). The most appropriate mathematical model to represent the behaviour of FVD is to use a Maxwell constitutive law characterized by a linear spring (elasticity of the system mainly due to the compressibility of the silicon fluid) in series to a non-linear dash-pot element (damping properties) (Fig. 4 right).

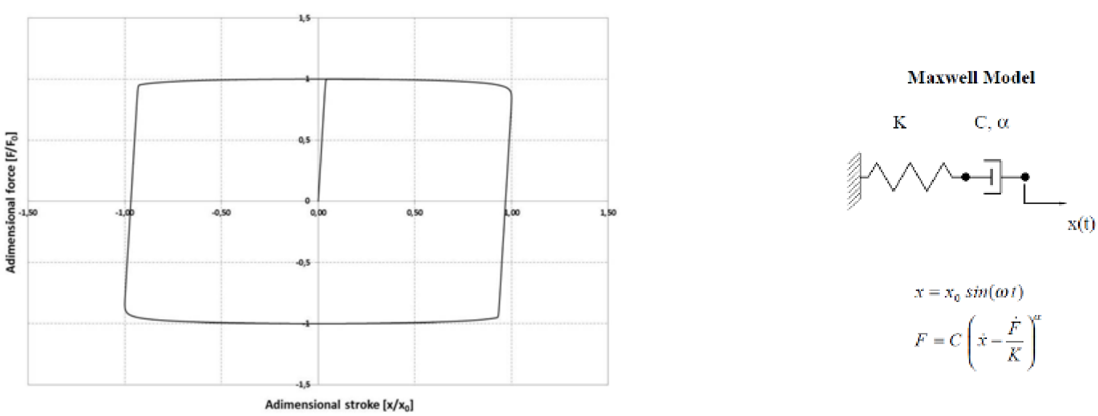


Fig. 4 – Typical hysteresis loop for viscous damper (left), Damper constitutive law and mathematical model (right).

The dampers used on the Izmit Bay Bridge considering their characteristics and the strict design requirements could be considered as a unique engineering application. Damper type OT(P) 500/4000, installed at the side span piers is designed in order to:

a) Provide restraint of the bridge deck for fast acting and frequent loads, such as traffic loads, in order to reduce the accumulated movements on the bearings and the expansion joints.

b) For normal load cases allows longitudinal movements for slow acting loads, such as temperature variations or any other low velocity displacements, without appreciable reaction and without introducing significant loads into the structure (Fig. 5a). At the same time, it ensures an almost rigid connection between the girder and the piers in presence of forces of sudden onset, or when high velocity movements are applied to the structure. A flow rate regulator (0.02mm/s – 4.0mm/s) is provided coupling, by means of a circuit, the two OT(P) dampers on each side span pier (Fig. 3b) for the continuously uniform distribution of the pressure between them and assuring an equilibrated distribution of loads on the structural elements.

c) A hydraulic static end stop function was considered, in order to limit the bridge deck movements at the side span pier to ±1.3m and avoid possible damages of the expansion joints. This end stop function is able to transmit a static force 17.5MN (Fig. 5a). In case, however, of a seismic load (deck movements up to ±2.0m), the device has been also equipped with an hydraulic system in order to inactivate the static end stop, thus allowing the piston to move beyond ±1.3m.

d) For seismic load cases (velocities up to 2000mm/s) the damper provides a threshold force value higher than 5000kN above which the deck is allowed to move, while maintaining the restraining threshold force and thus dissipating energy (Fig. 5b).

The scope of the damper type OP 500/1000 placed at the transition piers is instead to ensure an almost rigid connection between the girder and the piers in the normal load cases, such as traffic and wind loads, as well as ensuring that a certain force level is not exceeded during the seismic event. For seismic load cases (velocities up to 1250mm/s) the damper OP provides a threshold force higher than 5000kN, above which the deck is allowed to move while the damper maintains the restraint threshold force and dissipates energy (Fig. 5c). Both types of dampers are designed with the lower bound force of 5000kN and an upper bound force of about 6500kN in their entire velocity range respectively. In order, therefore, to provide a stable reaction and energy dissipation under this high velocity range, both types of dampers were properly designed for a large flow rate of hydraulic fluid. To achieve this, two external lines of valve blocks, in parallel configuration, were provided for the OP type and four for the OT(P) type in order to uniformly distribute and control the flow rate of the fluid.

Both types of devices allows the compensation of the fluid volume variation due to temperature changes, by using suitable accumulators filled with nitrogen which can expand or contract, maintaining the required level of pressure.

Another important parameter considered is the behaviour of both types of dampers along an entire range of temperature variations. The specific design and the special oil used assure a constant behaviour of the devices in the entire range temperature of -10°C / +80°C.

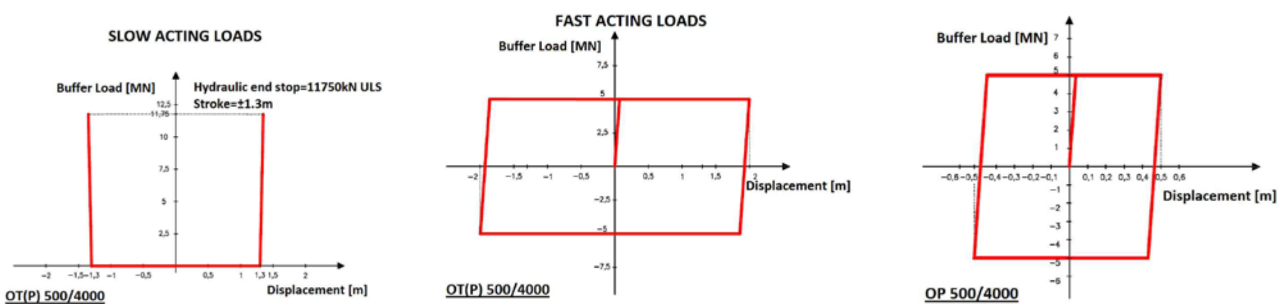


Fig. 5 – Load-displacement relations for damper OT(P) 500/4000, slow acting loads (left), fast acting loads (middle) and damper OP 500/1000 (right).

2. Full scale testing program

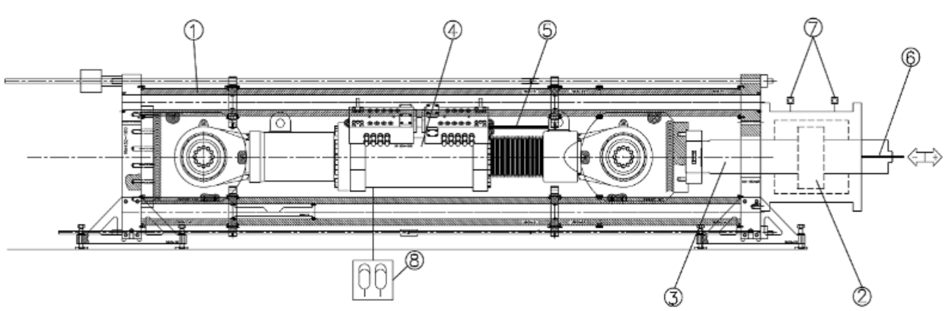
2.1 Experimental set up

The test equipment was especially chosen and built considering the load capacity and dimensions of the devices. The test rig comprises of a steel frame support structure of 17.8m max. length - for testing damper type OT(P) 500/4000 - housing a servo-hydraulic actuator electronically governed by closed circuit feedback loop. The device under testing is connected to the fixed part of the rig and to the hydraulic actuator piston on the other side. Fig. 6 shows the two dampers when arrived at the laboratory ready to be tested and in Fig. 7 is shown the final position of the damper OT(P) 500/4000 in the test rig.

FIP Industriale's Dynamic Test Facility satisfies the huge demand of hydraulic power, required for this test campaign, with 3500 litres of oil accumulation and pressurization through nitrogen gas up to 34 MPa. Direct pumping, designed for both long duration tests and for accumulator charge, provides 300 litres per minute at 34 MPa.

Fig. 6 – FVDs arrived at FIP Industriale Laboratory to be tested. Damper type OP 500/1000 (left) and damper type OT(P) 500/4000 (right)

Fig. 7 - Viscous damper OT(P) 500/4000 under testing at FIP Industriale Laboratory.



1. Test rig frame
2. Servo control actuator
3. Actuator piston
4. Damper test arrangement
5. Dispalcement transducer on device
6. Displacement transducer on actuator
7. Pressure transducers
8. Damper's accumulators

Fig. 8 – Test set-up scheme

The steel frame is comprising of two end plates separated by 4 struts located on each plate corner. Six pre-tensioned bars per strut are providing the stiffness of the rig, for a compressive load of 17520kN. Externally to the frame, the actuator is fixed with its piston aligned with the centre line of the frame. The capacity of the actuator is 11000kN and the total stroke is 600mm. The damper's clevis plates are pinned to the actuator piston at one side and to the end plate on the opposite side. The devices were tested with its centre line laid horizontally in its centred condition. In Fig. 8 is presented the test set-up scheme.

The command and control functions are achieved by using electronic MTS and Bosch-Rexroth units connected with various measurement transducers. The applied load was monitored by means of pressure transducers reading directly the pressure acting on the actuators. The imposed displacements were measured by means of two SSI transducers (total stroke 600mm); the first connected to the piston actuator and the second between the actuating rod and the damper's cylinder. The second transducer eliminates the effects of gaps and elasticity within the system.

All tests were conducted monitoring in real time the load (pressure), displacement and temperature on the damper, using a MGC HBM measuring amplifier connected to a PC equipped with a DIA-Dem data acquisition and processing software (National Instruments). Record sampling has been performed at a suitable frequency depending upon the test velocity (max. 2400Hz).

2.2 Experimental program

According to the European Standard EN 15129:2009 [7] (clause 7, Velocity Dependent Devices) and the contract specification, the type tests performed on both types of dampers were the following:

a) Static Tests: static stiffness test, static pressure test and low velocity test (OT(P) 500/4000 only);
b) Dynamic Load Tests: Impulsive load test (OT(P) 500/4000 only), constitutive law test and dynamic loading test;
c) Fatigue, Wear and Durability Tests: Damping efficiency test, seal wear test and stroke verification test.

All tests were performed at ambient temperature (approx. +20°C). However, in order to assure for both dampers a constant behaviour throughout a temperature range of -10°C / +80°C, two additional series of the dynamic tests and the damping efficiency test were repeated, simulating the critical temperatures of -10°C and +80°C. This was achieved by using different oil types with viscosity identical to that of the original oil at these temperatures. Table 1 below summarizes the main characteristics of the viscous dampers and the main test parameters.

Table 1 - Characteristics and test parameters of the viscous dampers.

Characteristics	**OP 500/1000**	**OT(P) 500/4000**
Maximum velocity [m/s]	1.25	2.0
Minimum design force [kN]	5000	5000
Maximum design force [kN]	6500	6500
Seismic design displacement [mm]	±500	±2000
Pin-to-pin length [mm]	5200	13500

Due to the huge amount of power required to test the dampers (up to 10MW), the constitutive law test and damping efficiency test were carried out at the maximum design force F_{max} and at an equivalent reduced velocity. The real on-site conditions (i.e. v_{max}=1.25m/s and 2.0m/s) were simulated by excluding 50% (for OP 500/1000) and 25% (for OT(P) 500/4000) of the relief valves of the main circuit in order to ensure that the flow passing through the single operating valve during the tests is equal to the maximum flow rate, per each valve, expected during the seismic event.

3. Test Procedure and Results

The following paragraphs present the results of the type tests performed on both viscous dampers at ambient temperature, including a comparison of the dynamic tests repeated, simulating the -10°C and +80°C temperature conditions.

3.1 Static stiffness tests

The static stiffness test was carried out in order to measure the compressibility of the oil, that fills the cylinder body, when loaded up to a force of 4500kN. The valve system was kept closed and the device was loaded up to the target load. The deformation measured, corresponding to the design load, was calculated for both devices about 2.0% of the total stroke, corresponding to 50% less than the maximum allowable deformation (4% of the total stroke).

3.2 Static pressure test

Before the installation of the accumulators, the devices were imposed to the static pressure test in order to assess their ability to withstand an internal pressure of 125% of the pressure corresponding to the maximum nominal force for more than 120s. The pressure read during the test and the final examination of the hydraulic system showed no visible leakage or signs of physical deterioration of the units.

3.3 Low velocity tests

The low velocity test aims to determine the system's resistance to thermal movements. Therefore, this test applies only to damper type OT(P) 500/4000, since damper OP 500/1000 was designed to provide for a restraint to service loads (not allowing thermal movements), reacting with a spring like behaviour. The test was conducted by applying one fully reversed cycle at a constant velocity of 0.02mm/s and 25mm stroke and at the same time reading and recording the resulting reaction. The reaction force was found about 110kN, which is less than 10% of the nominal design load (500kN), as required by the EN standards and the contract specifications.

3.4 Impulsive load test

This test aims to verify whether the damper type OT(P) 500/4000 reaches the maximum load of about 4500kN (lower than 5000kN due to the transient behaviour of the circuit) with movements imposed at different velocities, considering the different regulation of the flow control valve. The load was maintained constant for approx. 5 sec. and then reversed to reach the same load in the opposite direction. This procedure was repeated for five settings of the flow control rate valve ranging from 0.02-4.0mm/s. Additionally, for each of the 5 velocities, 3 tests were performed at different stroke positions of the piston i.e., central and ±150mm off-axis. From Fig. 9 is clear that the damper reached the maximum nominal load at all five settings of the flow control valve and in all three positions of the piston stroke, with only 4% of maximum force variation. The results ensure a uniform distribution of pressures among the two OT(P) dampers of each pylon connected through the flow control valve from one damper to the other and thus assuring an equilibrated distribution of loads on the structural elements.

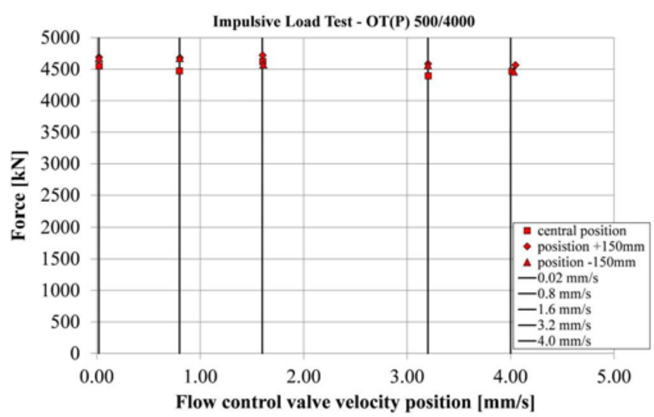
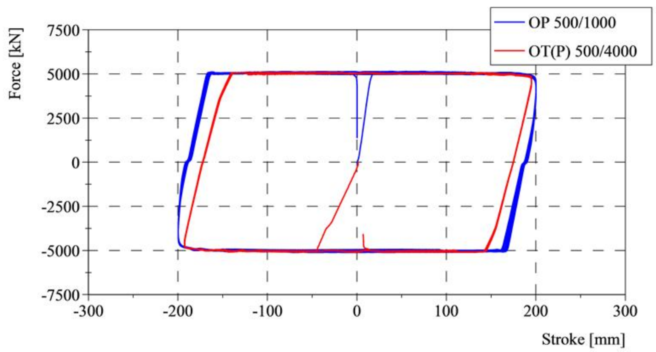


Fig. 9 – Impulsive load test results of OT(P) - Force vs. flow control valve velocity

3.5 Dynamic load test

The dynamic load test aims to evaluate the damping reaction stability of the devices by applying 10 sinusoidal cycles at ±200mm stroke and 10mm/s velocity. The load vs. displacement was recorded during the test and the EDC between the 2nd and 9 following cycles was calculated, ensuring a variance less than 15% of the EDC at the 2nd cycle (reference cycle according to EN 15129). As it is clear from the hysteresis loops in Fig. 10, a very stable reaction was achieved through the cycling and a negligible EDC variation was obtained, ranging from 0.8% to 3.0% for damper type OP 500/1000 and 1.3% to 2.0% for OT(P) 500/4000 (Fig. 10 right).



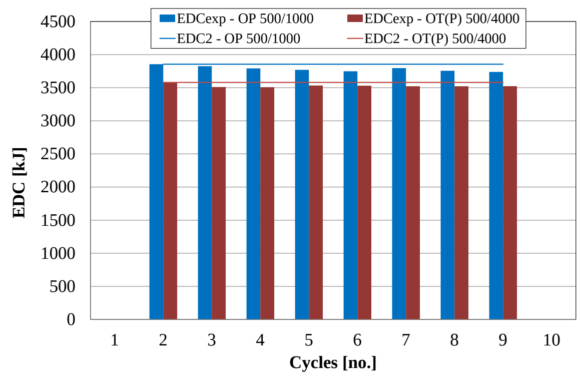
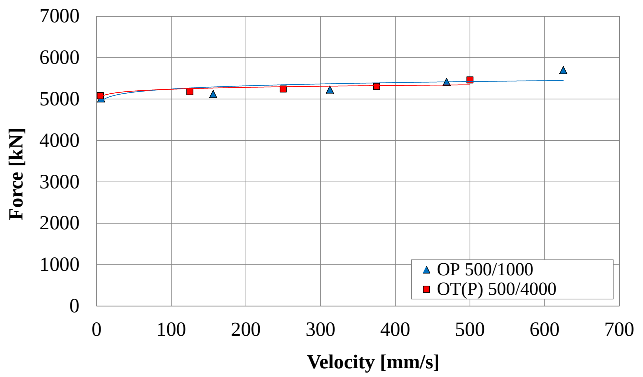


Fig. 10 - Dynamic loading test results: Hysteretic loops (left) and energy dissipation results compared with the 2nd loop cycle (reference cycle).

3.6 Constitutive law test

The scope of the constitutive law test is to determine the damper's force vs. velocity curve i.e., the parameters C and α which define the constitutive law. Five series of three sinusoidal cycles were carried out, imposing the test displacement at amplitude equal to ±200mm, with frequencies corresponding to velocities equal to 1%, 25%, 50%, 75% and 100% of the maximum velocity.

For each velocity, the experimental force values were calculated as the average of the positive and negative intercepts with the force axis of the second hysteresis loop cycle. Both dampers provided a velocity exponent α lower than 0.02 (Fig. 11, left). The Energy Dissipation per Cycle (EDC) calculated varies from 0.7% to 2.7% between the second and the third cycle for each velocity test, ensuring a variance less than ±15%, as required by the specifications and the European Standards (Fig. 11, right).



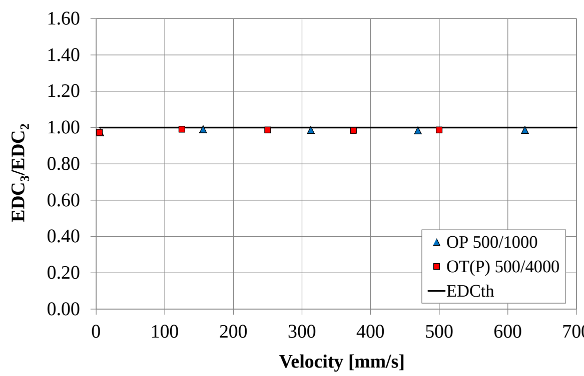


Fig. 11 - Constitutive law test results for both dampers in ambient temperature. Force vs. velocity curve (left) and normalized energy dissipation values (right).

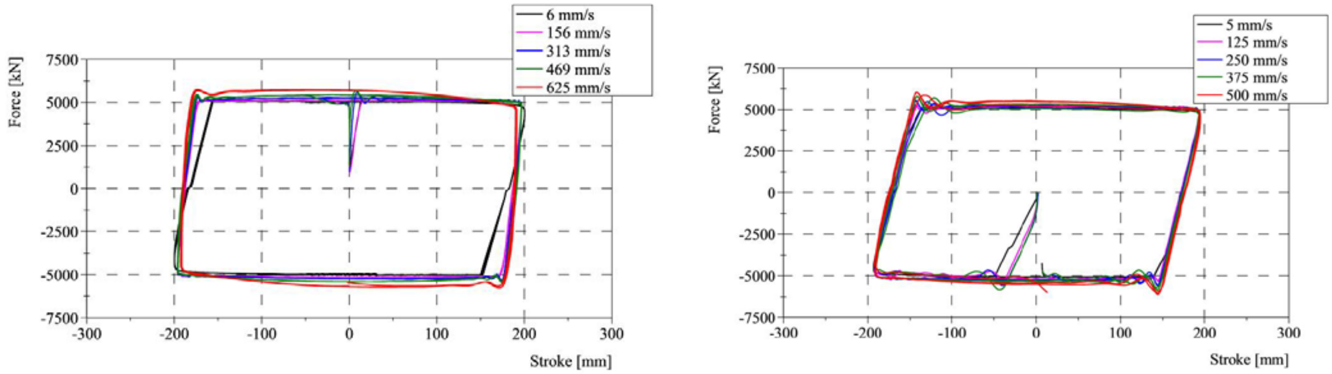


Fig. 12 – Constitutive Law test - Force vs. displacement curves at all velocities, for OP 500/1000 (left) and OT(P) 500/4000 (right)

Fig. 12 gives the force vs. displacement curves obtained al all velocities, for both dampers. From the hysteresis loops it is evident an almost rectangular force-displacement relationship and very stable behaviour, at any velocity. It is also clear the small dependence of the force with velocity, due to the small velocity exponent (<0.02) and the high non-linearity of the devices.

3.7 Damping efficiency test

The test aims to evaluate the energy dissipating capacity of the devices and their reaction stability. Five (5) sinusoidal cycles were imposed at a frequency producing the maximum velocity (625 mm/s for OP type and 500mm/s for the OT(P) type) and an amplitude equal to the test design displacement ±200mm, at ambient temperature. Both devices showed a stable behaviour with a very small variation of the maximum force. Fig. 13 (left), shows the force vs. displacement loops obtained for both dampers tested at the maximum design velocities of 625mm/s and 500mm/s for OP and OT(P), respectively (1.25m/s and 2.0m/s simulation velocities). Is clear that both devices maintained a steady output force reaction at max. velocity in all five cycles, with an almost rectangular hysteresis loop.

The EDC variation per cycle for both devices obtained was ranging from 0.4% to 1.8%. Furthermore, higher energy dissipation was achieved (about 17% for OP and 6% for OT(P) respectively) compared to the minimum allowable value (EDC_{min}=3600kJ), corresponding to the minimum reaction force of 5000kN (Fig. 13, right).

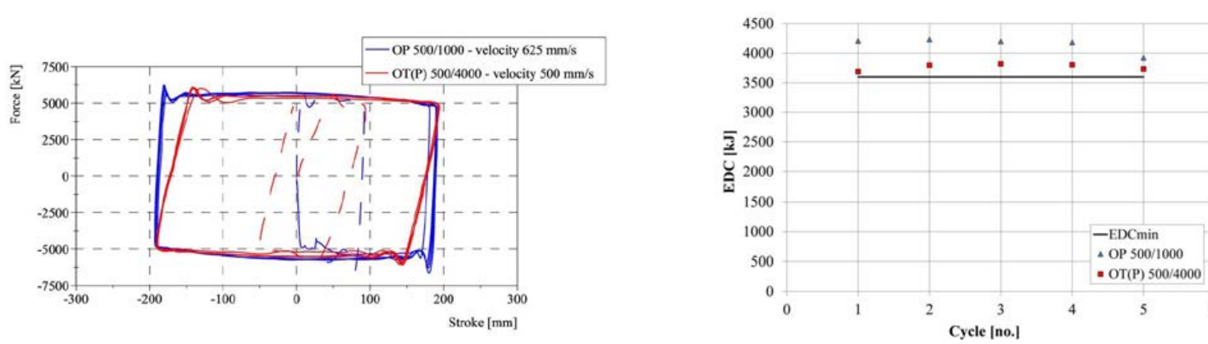


Fig. 13 - Damping efficiency test. Hysteretic loops for OT(P) 500/4000 (left) and EDC compared with the minimum allowable EDC_{min} (right) for both dampers.

3.8 Seal wear test

The scope of the seal wear test is to ensure that the sealing system works over the assumed design life of the device without leakage of the internal fluid. Both dampers were tested for 10000 cycles at force equal to 10% of the nominal reaction. The test was completed successfully with no leakage of the internal fluid.

3.9 Stroke verification test

The stroke verification test was performed in order to ensure that the devices are able to accommodate the design stroke, by applying to the device one full-stroke cycle (±500mm and ±2000mm respectively). The test was performed successfully, satisfying the client's requirements and the European standards.

3.10 Influence of temperature

The aim of these tests was to assess the effects of extreme temperatures on the dynamic performance characteristics of the device. The impulsive load test (OT(P) damper only), constitutive law test, dynamic loading test and damping efficiency test were repeated at -10°C and +80°C, following exactly the same procedure as in ambient temperature. The very similar and stable behaviour - for both devices - is evident in all three temperature conditions, in all dynamic tests.

Damper OT(P) 500/4000 reached the maximum nominal load at all five settings of the flow control valve, in all positions of the piston, at all temperatures when tested under the Impulsive Load Test (Fig. 14 left).

Comparing the reaction force results at -10°C and +80°C with those at ambient temperature, the maximum percentage change for damper OP 500/1000 was 6.0% at -10°C and 0.7% at +80°C and for damper OT(P) 500/4000 was 2.4% at -10°C and -2.7% at +80°C, throughout the entire velocity range (*Constitutive Law Test*). This negligible percentage variation can be clearly seen from the Force vs. velocity curves in Fig. 15, with a small exponent $\alpha<0.02$ at both extreme temperatures.

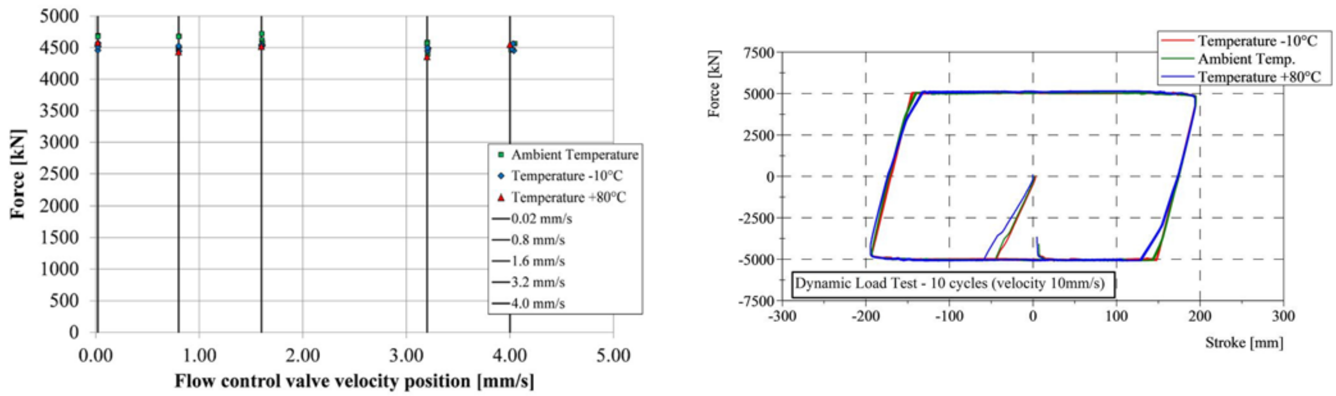


Fig. 14 – Comparison of different temperatures for damper type OT(P) 500/4000 - Impulsive Load Test (left) and Dynamic Loading Test (right).

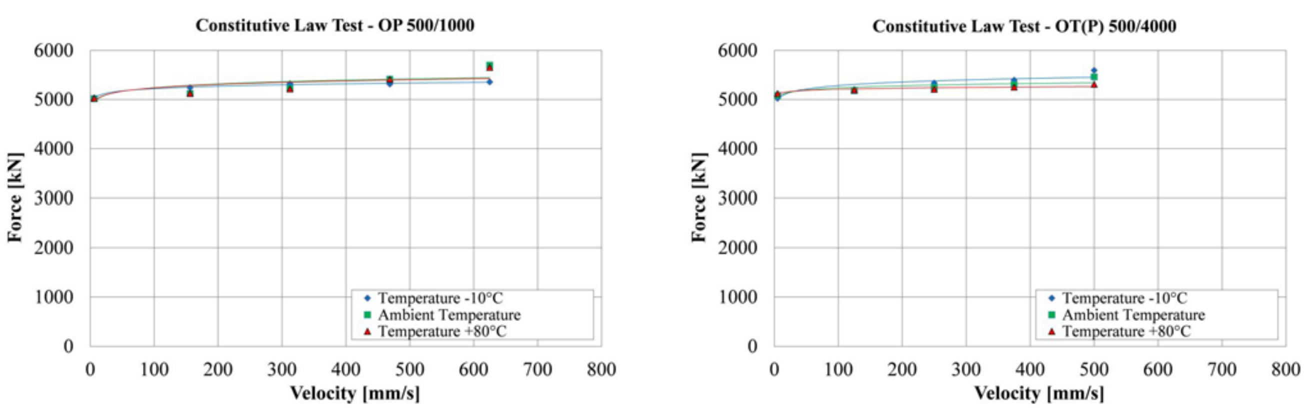


Fig. 15 - Comparison of Constitutive Law Test results at -10°C, ambient temperature and +80°C. Force vs. velocity curves for damper OP 500/1000 (left) and damper OT(P) 500/4000 (right).

As in the ambient temperature conditions, the EDC variation, for both dampers, was negligible with the maximum percentage of 2.0%, ensuring a variance less than 15% of the EDC at the second cycle (*Dynamic*

Loading Test) (Fig. 14, right). The same satisfying results were obtained when the dampers were imposed at a large number of cycles (5) and at the maximum velocity, throughout the whole temperature range (*Damping Efficiency Test*). The energy dissipation variation was less than 6% between the three temperatures (hysteresis loops of damper OT(P) in Fig. 16).

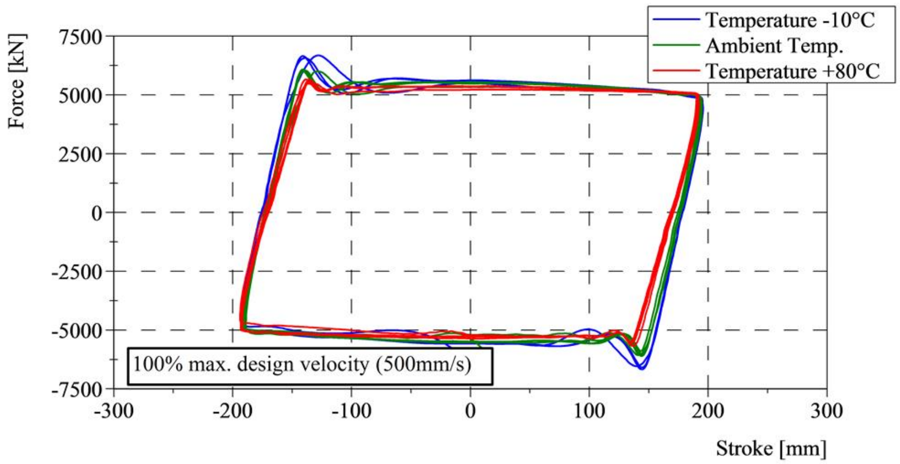


Fig. 16 – Comparison of Damping Efficiency Test results at -10°C, ambient temperature and +80°C. Hysteresis loops for damper OT(P) 500/4000.

4. CONCLUSIONS

The seismic dissipation system of the Izmit Bay Bridge in Turkey is achieved by two types of fluid viscous dampers, specially designed to reduce the movements in the longitudinal direction between the bridge decks and the substructures, providing restraint and effective damping.

The two types of dampers, nominated as OP 500/1000 and OT(P) 500/4000, are used in the transition and side span piers of the bridge, respectively. They are designed with a lower bound design force of 5000kN and upper bound force of about 6500kN, in the entire range of velocity i.e., up to 1.25m/s and 2.0m/s, respectively. Damper type OT(P) reaches about 15.5 meters in length at its maximum extended configuration, making this device the longest viscous damper ever built in the world.

The Type testing of the two full-scale fluid viscous dampers was performed in FIP Industriale Laboratories, according to the client's specifications and the European Standards EN 15129:2009, in order to confirm the characteristics of the devices and the main design assumptions. The experimental program consisted of a series of static, dynamic, fatigue, wear and durability tests. The tests were performed at ambient temperature including also two additional series of the dynamic tests simulating the critical temperatures of -10°C and +80°C. The test equipment chosen for the performance of the tests was especially built considering the load capacity of the dampers and their dimensions.

Both dampers demonstrated a very stable behaviour under dynamic conditions at any velocity up to the maximum test velocity of 625mm/s for type OP and 500mm/s for type OT(P) (simulation of maximum design velocity 1.25m/s and 2.0m/s, respectively) and throughout the entire temperature range of -10°C / +80°C.

A steady output force reaction was obtained with the negligible maximum variation of about 6% within the entire velocity range of 5mm/s÷625mm/s and the full temperature range (-10°C / +80°C). Both devices exhibited almost rectangular hysteresis loops, due to the small velocity exponent (α=0.02), and thus their high non-linearity.

A steady Energy Dissipation per Cycle was achieved even when subjected to a high number of consecutive cycles (10), exhibiting a maximum percentage variation per cycle of about 3.0% in ambient temperature, 1.4% at -10°C and 2.0% at +80°C, complying therefore with the tolerance variation of less than ±15%. Such results guarantee the reliability of damping capacity under the design climate temperature. The same steady energy dissipation capacity was achieved, throughout the entire temperature range, even when tested at maximum velocity applying five consecutive cycles.

Additionally, a series of performance and resistance tests were carried out (seal wear test, pressure test, stiffness tests and stroke verification test) confirming the compliance of the dampers with the requirements of the European Standards and those of the contract specifications confirming also a successful long operational life of the installed devices. Damper OT(P) 500/4000, due to its particular design and performance characteristics, was also subjected to a Low velocity test and an Impulsive load test. The damper proved its capability to accommodate thermal movements (*low velocity test*) and its performance was assured during the presence of sudden forces reaching its maximum nominal load (*Impulsive load test*).

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