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Seismic isolation of bridges through curved surface sliders and viscous dampers

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Abstract

Seismic isolation and energy dissipation devices have been widely used in Italy since the seventies of the past century for the seismic protection of different structures, pioneered by applications on bridges and viaducts. At the end of the eighties, Italy was world leader for the number of bridges and viaducts protected with antiseismic devices. Since then, Italian antiseismic devices have been applied all over the world, from all European seismic-prone countries to South America and Asia. Over the years, together with the development of new antiseismic devices and the increase in the number of their applications, in Europe there was a continuous development in guidelines and codes culminating in the Eurocode EN 1998, as well as the European Standard on antiseismic devices EN 15129:2009, that are a reference for many non-European countries. The most recent trend of seismic isolation foresees the use of pendulum isolators, alone or combined with fluid viscous dampers, in bridges as well as in other structures (buildings, tanks, etc.). The paper describes some examples of seismic isolation of bridges and viaducts. In particular it focuses on the Saina Ryskulova Bridge in Almaty, Kazakhstan, a curved concrete viaduct divided in 3 sections, made of 11 spans supported by 10 piers plus the abutments. The seismic isolation system includes double concave curved surface sliders (also known as pendulum isolators) and non-linear fluid viscous dampers, the latter allow to increase the energy dissipation of the seismic isolation system and consequently to significantly reduce the horizontal displacements, otherwise too high due to the high seismicity of the area characterised by a PGA of 0.4 g.

Key words: seismic isolation, energy dissipation, pendulum isolators, curved surface sliders, fluid viscous dampers, bridges

1 Introduction

In bridges the seismic isolation system is usually located between piers and deck; its main aim is to keep the substructure, i.e. piers and foundations, in the elastic field, i.e. without any damage; consequently, the use of the bridge is guaranteed even immediately after a major earthquake. The use of pendulum isolators has been proven to be very effective for the seismic protection of bridges and viaducts. However, if a bridge is located in a high seismicity area, resorting only to pendulum isolators might lead to significant deck displacements that can be either difficult to accommodate or require the use of special expansion joints.

The paper reports on the design of a curved bridge located in Almaty (Kazakhstan) in which a combination of Double Concave Curved Surface Sliders (DCCSS) and Fluid Viscous Dampers (FVD) has been successfully adopted in order to achieve a full seismic protection while, at the same time, limiting the horizontal displacements, otherwise too high because of the severe seismicity of the area.

The design of the isolators and dampers has been optimised through a series of nonlinear time history analyses carried out on a simplified, although sufficiently detailed to correctly reproduce the static and dynamic behaviour of the bridge, finite element model (FEM) in which nonlinearities are concentrated in the finite elements representing the seismic devices. In the following a detailed description of the devices used is reported along with the design methodology adopted and the main results obtained.

2 Combined seismic devices

The proposed solution for the seismic isolation of the bridge foresees the use of DCCSS in combination with FVDs.

Curved Surface Sliders is the European name for pendulum isolators, as per the European Standard on Anti-seismic Devices EN 15129:2009 [1] which is the reference standard setting rules for the design, testing, manufacturing and certification of any antiseismic device. This type of isolators has been used in the USA since 1990 [2], while their manufacturing and use in Europe is more recent [3]; they are basically sliding isolators based on the working principle of the simple pendulum, in which the period of oscillation does not depend on the mass but on the length of the pendulum. In a structure isolated with curved surface sliders, the period of oscillation therefore depends on the radius of curvature of the curved sliding surface, i.e., it is almost independent on the mass of the structure. The energy dissipation is given by friction due to movement on the sliding surface, while the re-centring capability is ensured by the curvature of the sliding surface itself.

There are two main types of curved surface sliders: simple (CSS) or Double Concave Curved Surface Sliders (DCCSS). CSS has a main sliding surface that accommodates the horizontal displacement, provides restoring force and energy dissipation through friction, and a secondary sliding surface – lubricated – aimed at accommodating rotations only (Fig. 1, left). DCCSS is made of two facing primary sliding surfaces with the same radius of curvature, both contributing to the accommodation of both horizontal displacement and rotation, as well as restoring force and energy dissipation (Fig. 1, right). In DCCSS each single sliding surface is designed to accommodate only one half of the total horizontal displacement, and consequently the plan size of the DCCSS devices may be significantly smaller compared to the CSS devices, for the same vertical load and horizontal displacement capacity.

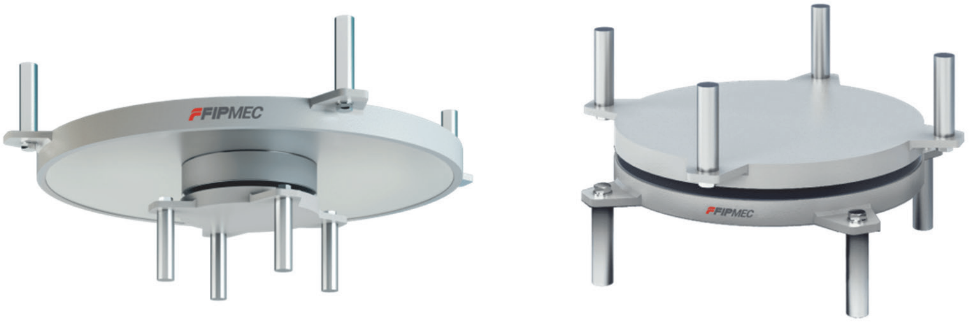


Figure 1. CSS configuration (left); DCCSS configuration (right)

The use of CSS/DCCSS is continuously increasing in the last years and their use is now becoming even more common than elastomeric isolators (high damping rubber and/or lead rubber bearings) in any kind of structure, e.g. buildings, tanks, and bridge and viaducts. In particular, DCCSSs are widely used, thanks to their reduced dimension in plan compared to CSS. Pendulum isolators can be easily adapted to meet different project's need, from load to seismicity level: actually, by changing the main design parameters, i.e. the friction coefficient and the radius of curvature, the hysteretic curve can be modified and optimized.

In Italy, pendulum isolators are frequently used in new bridges and viaducts as well as for seismic retrofit of old ones. Italian pendulum isolators have also been used in several bridges abroad, from South Korea to Greece, from Kazakhstan to Albania [4, 5].

Fluid Viscous Dampers (FVDs) are axial devices whose output force is proportional to the velocity through the relationship $F = c\, v^a$. For seismic protection of structures, strongly non-linear FVDs (typically with exponent $\alpha = 0.15$) are commonly used in Italy and Europe, thanks to their high energy dissipation capacity within a wide range of velocities, i.e. during all the design earthquake duration, but also for earthquakes lower than the MCE which are more frequent. Fig. 2 shows the typical hysteresis loop of a fluid viscous damper with $\alpha = 0.15$ tested using sinusoidal time-history input and the mathematical Maxwell model of the device.

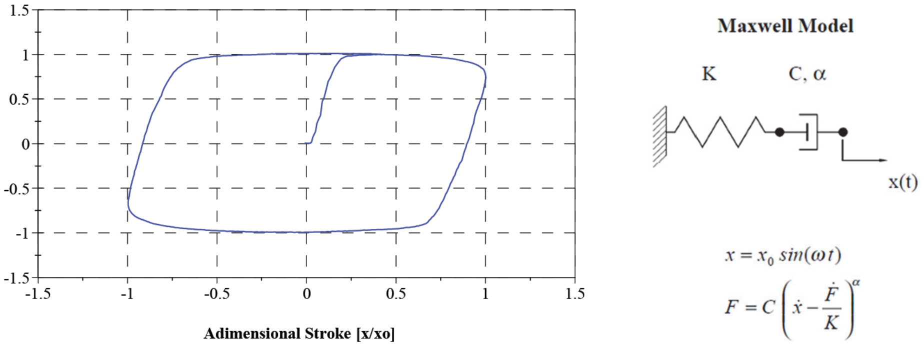


Figure 2. Hysteresis loop for nonlinear viscous damper with a = 0.15 (left) and its mathematical model (right)

Seismic protection of bridges with nonlinear FVDs started in Italy in 1984 and in Europe (outside Italy) in 1989, at that time FVDs were used in combination with structural bearings. Italian nonlinear FVDs were also applied in Croatia, for example in the Krka arch bridge near Split [6]. The current trend is nowadays to combine FVDs with pendulum isolators instead simple structural bearings, in order to guarantee higher recentering capacity as well as additional energy dissipation.

FVD are also used in important long span bridges, either cable-stayed or suspended, located in high seismicity areas, to reduce the deck displacement. Some outstanding examples are the Rion Antirion Bridge in Greece [7], the Izmit Bay Bridge [8] and the Çanakkale 1915 Bridge in Turkey.

2 The Saina-Ryskulova bridge

2.1 Bridge description

The Saina-Ryskulova bridge (Fig. 3) is a curved bridge located in Almaty (Kazakhstan) at the intersection of Ryskulov avenue and Saina street, 2 km east of the Tastak historic district; design was carried out in 2014 and the bridge opened to traffic in 2016.

The bridge, with a total length of 311.43 m., rests on two abutments (P1 and P12) and 10 piers, as shown in Fig. 4, and is divided in three sections by joints located over piers P5 and P9. Each pier consists of three reinforced concrete columns connected at their top by a pier cap.

Figure 3. Aerial view of the Saina-Ryskulova bridge in Almaty (courtesy of Kazroadinnovation LLP)

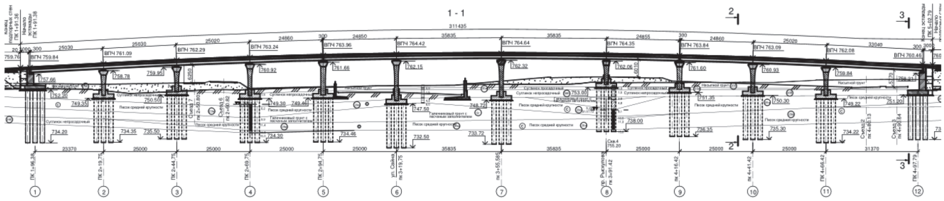


Figure 4. Lateral view of the Saina-Ryskulova bridge

2.2 Seismic input

About the 11 % (300 thousand km^2) of the territory of Kazakhstan are classified as high seismic zone, including the largest industrial and cultural centre of the country, the city of Almaty. In the late XIX - early XX centuries Almaty was subjected to the strongest North Tian Shan earthquakes, i.e. the 1887 Verny Ms7.2 earthquake, the 1889 Chilik Ms8.3 earthquake, the 1911 Ms8.2 Kemin earthquake, and repeatedly experienced weaker events.

Seismic microzoning maps, in agreement with the seismic design principles of Eurocode 8 and expressed in terms of not only seismic intensity, but also engineering parameters (peak ground acceleration - PGA), of Almaty city have been recently developed [9]. The map reported in Fig. 5 shows the PGA isolines of the territory of Almaty city for probability of exceedance 10 % in 50 years (return period of 475 years); it indicates that for the location of the Saina-Ryskulova bridge a PGA = 0.38g is to be considered. In the design, however, based on the recommendations made by the Kazakh Research and

Design Institute of Construction and Architecture (KazNIISSA), a PGA of 0.4g has been assumed. Given the horizontal and vertical design response spectra, a set of horizontal and vertical spectrum compatibles accelerograms has been generated. The duration of all the synthetic accelerograms is 30 s, with an initial part at increasing amplitude of 5 s., a pseudo-stationary part of 10 s. while the final part at decreasing amplitude has a duration of 15 s.

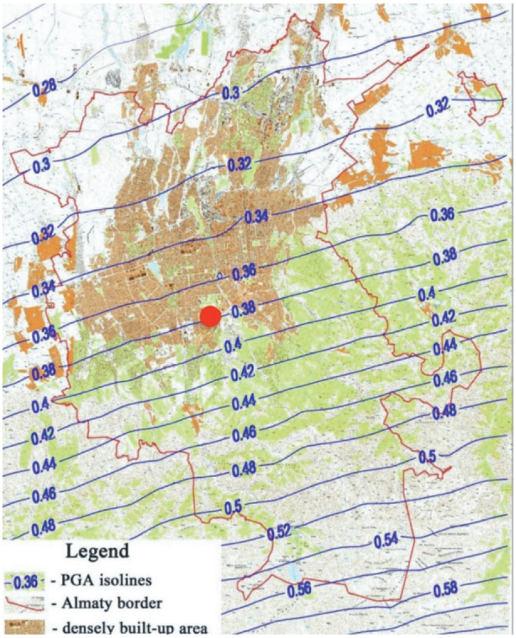


Figure 5. Seismic Hazard Maps of the territory of Almaty city for probability of exceedance 10 % in 50 years in PGA. The red circle shows the location of the bridge

2.3 Finite Element Model

The seismic isolation system has been optimised through a series of nonlinear time history analyses carried out on a simplified, albeit sufficiently detailed to correctly reproduce the static and dynamic behaviour of the bridge, finite element model (FEM) in which nonlinearities are concentrated in the finite elements representing the seismic devices. The following figure (Fig. 6) shows a partial view of the FEM depicting the bridge from the abutment to the first pier.

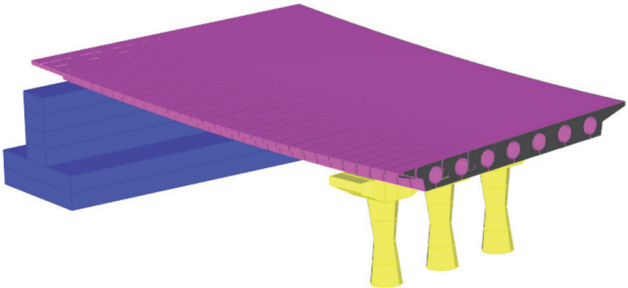


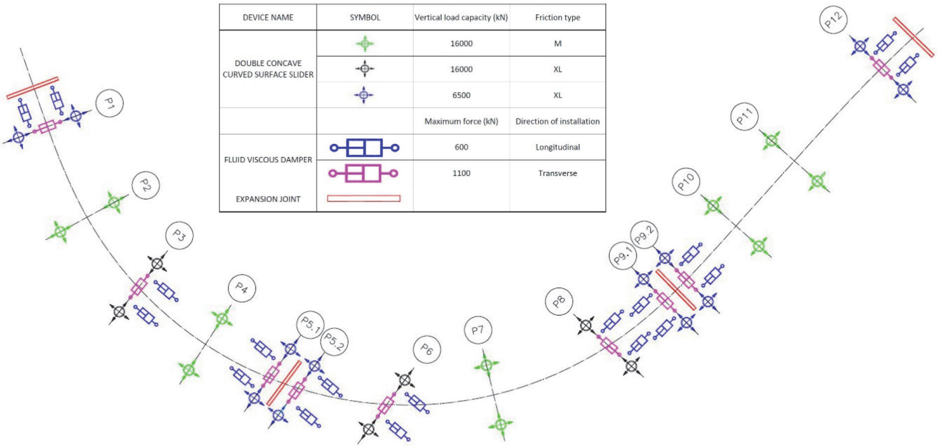
Figure 6. FEM partial 3D view

2.3 Seismic isolation system

A first design, in which only DCCSSs were placed on the abutments and on the piers' top already showed a significant reduction of seismic forces on piers and foundations compared to a conventional design solution but led, due the high seismicity of the site, to significantly high horizontal deck displacements hardly to accommodate without resorting to complex and expensive expansion joints.

Therefore a seismic isolation system in which DCCSSs are combined with FVDs has been conceived. Design of isolators and dampers have been optimized by means of numerical simulations carried out on the previously described FEM.

The isolation system in its final configuration (Fig. 7) is made of 28 DCCSSs, of three different types having all the same equivalent radius of curvature (4500 mm), the same maximum displacement capacity of ± 375 mm, but differing in the vertical load capacity (ranging from 6500 kN to 16000 kN) and friction material, combined with 18 longitudinal FVDs and 9 transverse dampers, installed at selected locations; the maximum force for longitudinal dampers is equal to 600 kN, while raises up to 1100 kN for the transverse ones.



DEVICE NAME	SYMBOL	Vertical load capacity (kN)	Friction type
DOUBLE CONCAVE CURVED SURFACE SLIDER	⌖	16000	M
	⌖	16000	XL
	⌖	6500	XL
		Maximum force (kN)	Direction of installation
FLUID VISCOUS DAMPER	⊟	600	Longitudinal
	⊟	1100	Transverse
EXPANSION JOINT	▭		

Figure 7. Seismic isolators and viscous dampers layout

The friction coefficient in the isolators was designed as very low (about 1 %, type XL) in the positions where the DCCSS are associated with viscous dampers, e.g. on the abutments (P1 and P2), on the piers corresponding to the joints (P5 and P9), etc.; i.e., in positions where non-seismic displacements are higher. An higher value of friction coefficient (about 8 %, type M) was selected for isolators in the positions without dampers (P2, P4, P7, P10, P11). See Figure 7 for the layout of DCCSS and FVDs.
The displacement capacity of the isolation system of course takes into account the seismic displacement as well as the displacement induced by long-term deformations (shrinkage, creep) and 50 % of the thermal action. Figure 8 shows the isolation system as installed.

Figure 8. Viscous dampers and isolators as installed in the Saina-Ryskulova Bridge, Kazakhstan

3 Other examples of bridges protected with DCCSS

As discussed above, the design choice to combine DCCSS and non-linear viscous dampers for the Saina-Ryskulova Bridge was due to the very high seismicity in Almaty, and the consequent need to reduce the horizontal displacement without increasing too much the friction coefficient. In effects, increasing the energy dissipation capacity of the isolation system (and thus decreasing the displacement) could be obtained increasing the friction coefficient in the isolators themselves; but when the friction coefficient is very high, also the horizontal forces associated to non-seismic horizontal displacements (e.g. due to thermal variations) result too high. This is why in such cases it is better to give part of the dissipation to viscous dampers, i.e. dampers with reaction proportional to velocity; when the velocity is very low, such as in thermal variations, the force results low as well. When the seismicity is not so high, DCCSS with low or medium values of friction coefficient can be used alone as in the examples shortly described here below.

3.1 Rho-Monza Viaduct, Italy

The Rho-Monza Viaduct, on the northern outskirts of Milan, Italy, has 5 spans of length 40, 55, 110, 50, and 50 m respectively, overstepping a complex intersection of roads on several levels [10]. The viaduct, designed by the Italian Engineering Company

MATILDI+PARTNERS, has a curvilinear axis of an average radius of 7500 m, and was installed in a short time, between March and May 2017, thanks to specific design and mounting choices aimed at reducing as much as possible the interruption of the roads below the viaduct. The deck is 29.4 m wide, sustained by 3 beams having height of 4 m and span of 6.5 m. The choice of the 3 beams was related to the needs of deck launch, using external beams for pulling, while the main span is supported by the central beam only.

The support system was selected as a seismic isolation system, despite the small seismicity of the area (PGA = 0.10g at the return period of 1898 years; PGA = 0.11g at the return period of 2475 years, the latter corresponding to the Collapse Limit State), in order to reduce as much as possible the horizontal forces on the piers and keep them elastic. The isolation system is composed by single curvature CSS on piers and by free sliding pot bearings plus a guided bearing on the abutments. In particular, the isolators supporting the central span have very large vertical load capacity, 80 MN, and are the largest manufactured in Italy. The isolators on the external piers have a vertical load capacity of 22 MN. All the isolators are characterized by an effective radius of curvature of 3.1 m and low friction coefficient. The isolation system guarantees an effective fundamental period of 2.63 s and consequently a very low horizontal force transmitted to the piers and foundations during earthquake. Figure 9 shows the isolators as installed in the viaduct.

Figure 9. Pendulum isolators as installed in the Rho-Monza Viaduct, Italy (courtesy of Matildi+Partners, Italy)

3.2 Terzolle-Mugnone Viaduct, Firenze, Italy

The Terzolle-Mugnone Viaduct is located in the center of Firenze, Italy, and is part of the tramway line. The design PGA is 0.22g for the Life Safety Limit State and 0.26g for the Collapse Limit State (the latter to be used for verification of the seismic isolation system, according to the Italian Seismic Code). The viaduct has been designed by the Italian Engineering Company MATILDI+PARTNERS. The viaduct is a slender structure with mixed steel/concrete deck (Figure 10) with four spans (76 - 51 - 65 - 40 m). On each pier and abutment the deck is supported by a couple of pendulum isolators, characterized by maximum vertical load capacity of 16500 kN, maximum seismic load 15500 kN, radius of curvature 3.7 m. Of course the isolators were tested according to the European Standard EN 15129:2009, mandatory in every EU country. Some typical experimental hysteretic graphs are shown in Figure 11.

Figure 10. The Terzolle-Mugnone Viaduct, Italy (left), and detail of the pendulum isolators installed in it (right) (courtesy of Matildi+Partners, Italy)

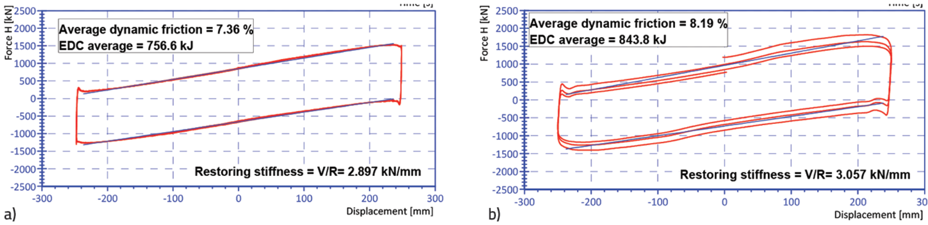


Figure 11. Examples of type test results, according to EN 15129:2009, on a pendulum isolator for the Terzolle-Mugnone Viaduct: a) benchmark test (50 mm/s); b) dynamic test at maximum design velocity, in this case equal to 0.4 m/s

4 Conclusions

The projects shortly described above are just few examples of the most recent trend of seismic isolation, that foresees the use of pendulum isolators (DCCSS or CSS), alone or combined with fluid viscous dampers. In the last 10 years, almost 8000 DCCSS or CSS designed according to EN 15129 and manufactured in Italy have been installed in bridges and viaducts, in Italy as well as in other countries. In most cases DCCSS are preferred because of their lower dimensions in plan (as compared with CSS). When they are used alone, the energy dissipation is controlled by the friction coefficient only. When the seismicity is very high, a big amount of energy dissipation is needed to reduce the displacement and the associated cost of expansion joints; if such energy dissipation is offered by friction only, the friction coefficient is high, and consequently the horizontal forces due to non-seismic horizontal displacements (e.g. thermal displacements) could result too big. Conversely, when viscous dampers are used together with DCCSS (or CSS), energy dissipation is offered partly through friction in the isolators, and partly through viscous damping in FVDs. Thus, through a proper selection of friction coefficient and viscous damping, the horizontal forces related to non-seismic actions can be reduced, because the reaction of viscous dampers to slow movements (e.g. thermal displacements) is small. Furthermore, giving part of the energy dissipation to FVDs also help in improving the bridge response to frequent earthquakes; otherwise, the isolation system could be not activated when the earthquake is not big enough to induce forces higher than the friction force. In conclusion, FVD combined with DCCSS or CSS offer to the Engineer an higher freedom to adapt the seismic isolation system behaviour to the needs of each bridge.

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