Seismic Protection on Cable-Stayed Bridges

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Abstract I Seismic Protection is a fundamental issue when it comes to high seismic risk areas design. This protection becomes even more important when we talk about crucial structures such as bridges. Cable-stayed bridges are obviously included in this crucial group of structures. There are several seismic protection systems available and it´s important to make the right choice when one of them is needed. The right approach to this subject is to make an exhaustive comparison between the systems considered relevant in a particular case. When dealing with a cable-stayed bridge the designer should first of all understand correctly the dynamic behavior of the structure. Ground motions force the deck, the pylons and the stays to oscillate. By this time the points of the structure with potential to install a device should be identified. This study aims at identifying these points and also to install the most suitable devices in the most suitable places. The tests will include a viscous damper, a hysteretic damper and also a Tuned Mass Damper (TMD). The three systems will be installed in a cable-stayed bridge with a span of 420m. The goal of this study is the minimization of deck displacement. This displacement is important because it affects the design of structural joints, connections with overpasses and also abutments. In Seismic Protection the forces the devices introduce in the structure should be evaluated. The final choice of a device of this type should always be a balanced commitment between the minimizing of the longitudinal deck displacement and the increase of the stresses transmitted to the original structure.

Keywords :Seismic Protective Systems, Cable Stayed Bridges, Longitudinal Displacements, Viscous Damper, Hysteretic Damper, Tuned Mass Damper

1.Introduction

The design of bridges in seismic areas, such as Portugal, requires quite important concerns since the conception phase. This includes dynamic analysis and design (Reis, 2006). So it is not possible to separate the structural solution from the seismic resistance system of the bridge whatever it is. A cable-stayed bridge is no exception and this should, since its conception, contemplate earthquake resistance through its own capacity of deformation or through protection systems. It is important to realize what an earthquake is to such a structure and how much damage can it cause to it. After the designer can decide which is the best strategy to protect the bridge.

The goal of this study is the minimization of deck displacement. Any action taken to reduce the longitudinal displacement, should be analyzed in comparison with the situation in which the deck has a joint to accommodate the movement . The challenge is the reduction of the deck displacement and the efficiency of the protection system tested. A compromise between them must be found. In this paper was only considered the longitudinal component of the seismic action. The vertical and transversal components were neglected because the design of long bridges in seismic areas frequently leads to solutions with very low horizontal stiffness in the longitudinal direction (Guerreiro et al, 1998)

Many seismic isolation construction designs and technologies have been developed over the years in attempts to mitigate the effects of earthquakes on buildings, bridges and vulnerable contents (Skinner et al, 1993). Developments on this area have been made mainly using the deformability of the structure itself, changing its dynamic properties or its ability to dissipate energy.

It is intended to study two widely known dampers: the viscous damper and the hysteretic damper. These two types of damper exhibit a versatility that favors their use, because they are easy to introduce into the structural system and also because they give the designer freedom to define their characteristics (Guerreiro, 2006).

This paper also aims to study the applicability of a Tuned Mass Damper (TMD) to a cable-stayed bridge. The final choice of a device of this type should always be a balanced commitment between the minimizing of the longitudinal deck displacement and the increase of stresses transmitted to the original structure.

The devices are designed and applied to a case study – alternative Vasco da Gama Bridge – and the main results and conclusions are a summary of the research project on “Seismic Protection on Cable-Stayed Bridges” (Freire, 2014). Nonlinear analysis follows Eurocode 8 requirements applicable to Lisbon area.

2. Seismic Protection Devices

Viscous Damper

This device operates according to the equation [1] (Figure 1).

$$F = C \parallel v \parallel^{\alpha} \quad sinal\ (v)\ [1]$$

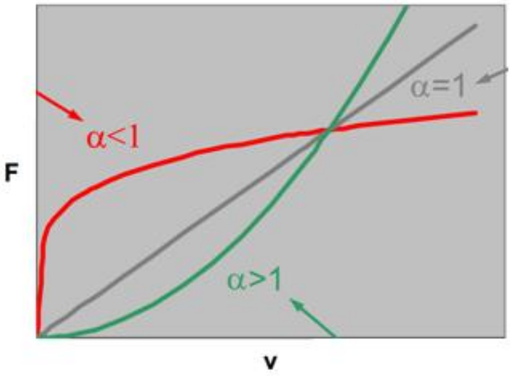

Figure 1 – Force-Velocity relation for Viscous Damper (Guerreiro, 2009)

Where F is the force in the damper, C and α are damper`s coefficients and v is the velocity between two points of the damper.
The initial design of this damper was made considering α=0,2 and C as 10% of the deck weight. It was also defined that the viscous damper has a maximum deformation of 10^{-5}m.

Hysteretic Damper

This device is usually a steel cantilever that uses metal plasticity to dissipate energy (Figure 2) This device is defined by its stiffness (K_1) and by its yielding force (F_y). When the damper reaches it’s yielding force the stiffness beyond that moment is a percentage of K_1. This stiffness is called post-yielding stiffness (K_2).The initial sizing of this device was made considering $\frac{K_1}{K_2} = 1\%$ and K_1 corresponding to an elastic displacement of the damper equal to 6% of the deck displacement in seismic case. The yielding force (F_y) was considered equal to the maximum force registered in the viscous damper.

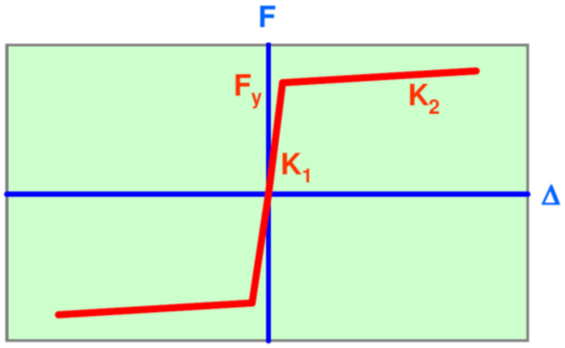

Figure 2 – Force-Displacement relation for Hysteretic Damper (Guerreiro, 2006)

Tuned Mass Damper

This device is a mass attached to the structure in order to reduce its dynamic response (Figure 3). The TMD is tuned to the structure fundamental frequency to produce inertia forces that counterbalance the original motion.

The initial design of this device was made by fixing its mass between 0,5% and 10% of the deck´s mass.

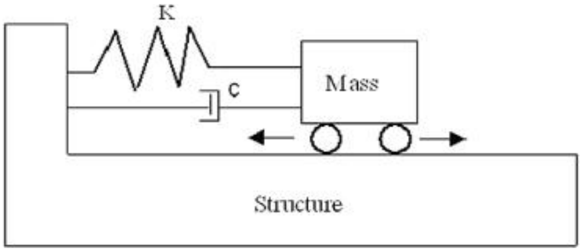

Figure 3 – Tuned Mass Damper model (N1)

3. Seismic Data

The Eurocode 8 requirements were applied but the maximum value of soil acceleration was defined as 4 m/s^2. Structural damping was considered as 5%.

4. Case Study

4. 1 Bridge Description

The case study is a Cable-Stayed bridge developed by José Oliveira Pedro as an alternative study for the conception of the Vasco da Gama Bridge in Lisbon (Figure 4).

The bridge structure is similar to the one constructed for Vasco da Gama Bridge. The main difference is the material adopted for the deck (Figures 5 and 6). The original structure has a pre-stressed concrete deck and the case study a composite steel-concrete one.

The bridge has two towers of 150m high (Figure 7), one central span and two side spans. The solution in this case consists of a central span of 420 m and two side spans of 194.7m, reaching a total length of 829 m. The deck is completely independent from the towers. Regarding the Cable-Stayed system case study is similar to Vasco da Gama Bridge. The system is a vertical group of stays located in each one of the main deck beams. As said deck is a composite steel-concrete element. The concrete is C45/55 class and the reinforcements made of S500 NR. The structural steel class is S355 NL Towers and intermediate piers are made of reinforced concrete also (C40/50 and S500 NR for reinforcements).The modulus of elasticity of the stays was considered 195 GPa (constant). For the stays was used high-resistance stainless steel.


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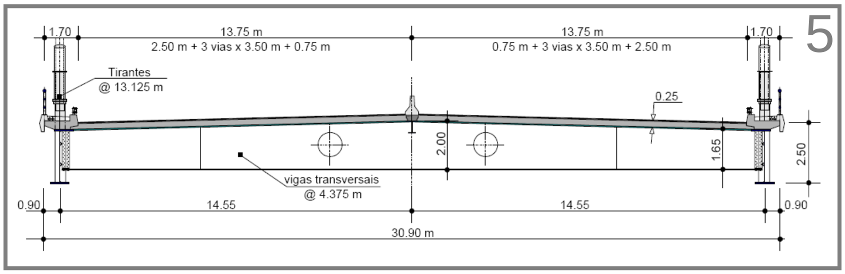
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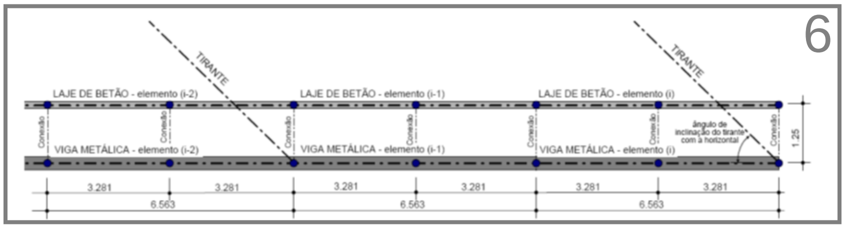
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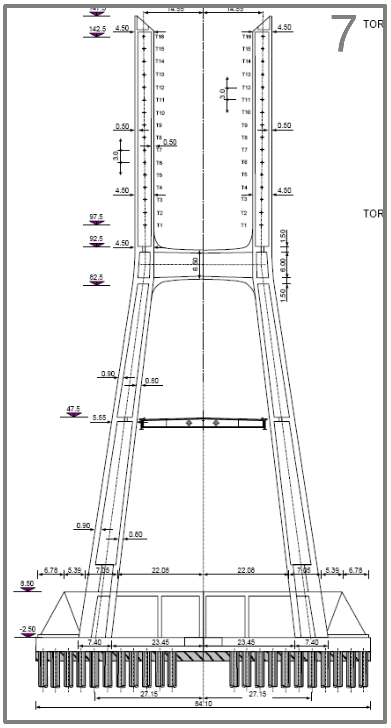
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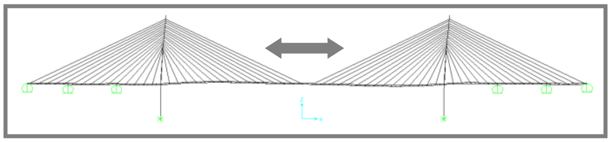
Figure 4 – General view of Vasco da Gama Bridge (N2) ; Figure 5 - Transversal section of the Deck (Oliveira Pedro, 2007) ; Figure 6 - Modeling detail of the composite section (Oliveira Pedro, 2007) Figure 7 – Tower (Gattel, 1999)

The next step was the dynamic analysis of the fixed base structure. The mass of the structure is divided in the following way (half bridge):

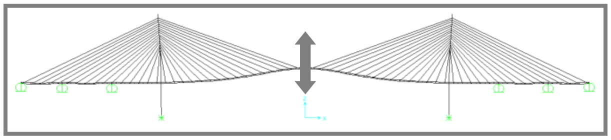
Table 1 – Structure´s Mass by element

	Mass [ton]	% Structure´s Mass
Beam	2661	9%
Deck	11799	42%
Stays	577	2%
Towers	13152	47%
Total	28190	100%

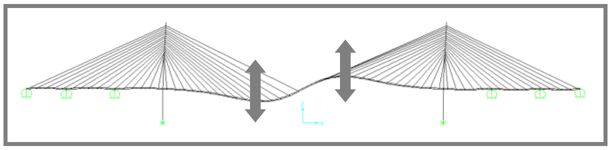
Modal dynamic analysis demonstrated that the bridge is characterized by a fundamental frequency of 0,18 Hz. This fundamental frequency corresponds to the longitudinal mode.



1st Mode f=0,18 Hz



2nd Mode f=0,32 Hz



3rd Mode f=0,41 Hz

Figure 8 – Fundamental vibration modes of the bridge

This is the confirmation that the structure is in fact very flexible due to longitudinal horizontal displacement. The seismic analysis was made for 10 artificial earthquakes generated according to the mentioned conditions. As expected the bridge without any seismic protection device leads to important longitudinal displacements (Table 2). The displacements were monitored in three different points. These points are the top of the tower (Top), the point of the tower at deck height (Tower) and a point of the deck (Deck). The deck oscillates as a rigid body so all his points have the same displacements.

The displacements presented are the linear combination of the maximum value obtained for each earthquake.

Table 2 – Displacements for free structure

Point	Disp. [m]
Top	0,59
Deck	0,52
Tower	0,05
Relative Deck-Tower	0,47

The deck presents considerable displacements of average value of 0,52 m. Unexpectedly the top of the tower presents displacements even bigger than the deck. It is important to understand if the deck and the top oscillate always together or if they are moving out of phase. The tower remains almost at the same position and so there is a big relative motion between it and the deck. Here is the opportunity to install some seismic protection devices such as viscous and hysteretic dampers. In figure 9 is possible to compare different point displacements during an earthquake.

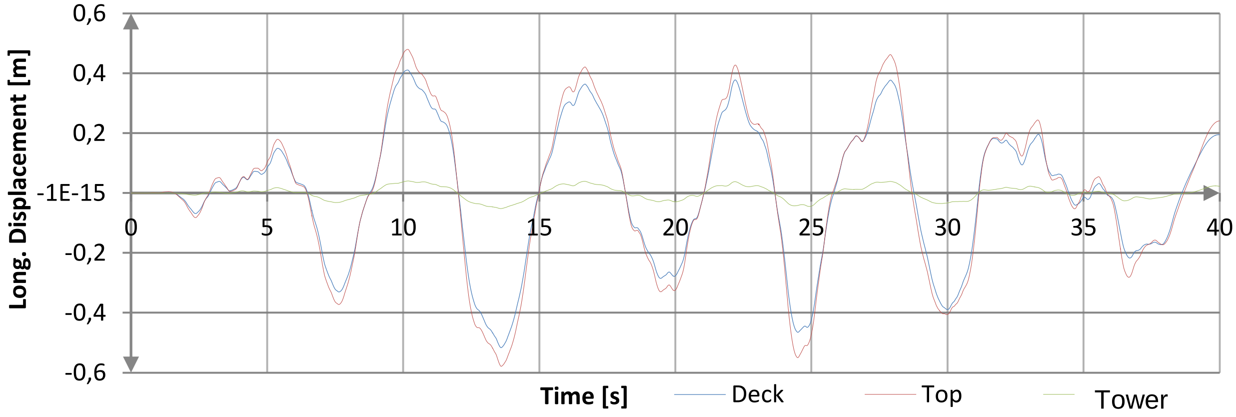


Figure 9 – Free structure response to an earthquake

Deck and top move in fact together. It will be interesting to discover if it is possible to decrease deck displacements by decreasing the top ones. Although is more likely the top follows the deck instead of the opposite.

4.2 Viscous Damper

It was decided that the bridge would have four dampers per tower. So the Viscous Damper modeled for each tower corresponds to two real dampers. This happens because the computational model was built for half of the bridge. The optimization of the Viscous Damper coefficients was made initializing the system with the following values:

$$C = \frac{0{,}1\times 12000}{2}\, tonf = 6000\,\frac{kN}{m/s}$$

$$K = \frac{6000\,kN}{10^{-5}\,m} = 6\times 10^{8}\,\frac{kN}{m}$$

Table 3 – Initial Viscous Damper results

Force [kN]	Deck Disp. [m]
5115	0,18

The results for this initial Viscous Damper were quite interesting. It was achieved a decrease of deck displacement of 66%. Of course this results lead to a force in the damper that is transmitted to the structure. Values of the coefficient C between 0 and 8000 $\frac{kN}{m/s}$ were considered in the optimization process. The stiffness remained the same. The results obtained are in figure 10.

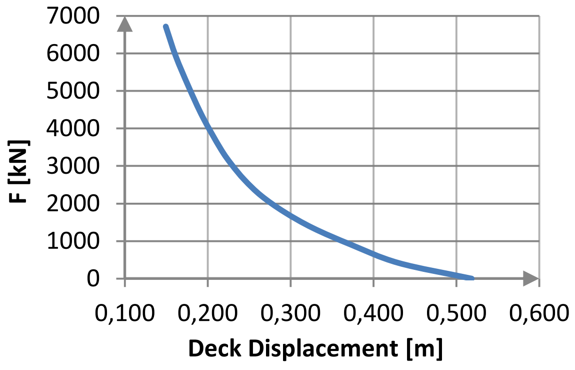


Figure 10 – Maximum forces transmitted to the towers and maximum deck displacements for different C coefficients

The deck displacements decrease when the forces transmitted to the towers increase.

In spite of this the relation between the two things is not linear. In fact for small forces the decrease of deck displacement is considerable but for bigger forces is quite small. The optimized damper should be the one where the decrease of displacement compensates increase of forces. To make this analysis was built a graphic where is possible to relate deck displacement and force transmitted to the bridge for each value of C.

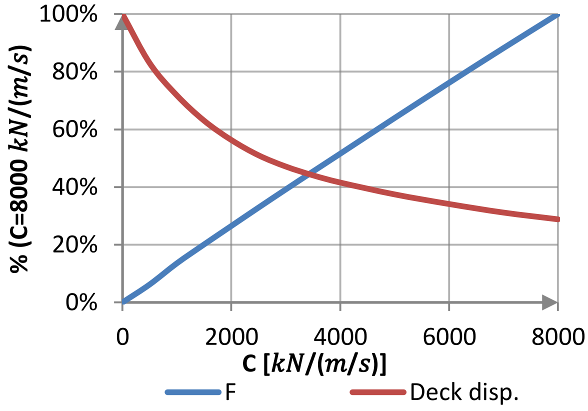


Figure 11 – Influence of coefficient C in the maximum forces transmitted to the towers and maximum deck displacements

The optimal Viscous Damper due to the criteria defined is C=3500 $\frac{kN}{m/s}$ .It was suggested by the intersection of the curves in figure 11.
$K = 6\times 10^{8}\,\frac{kN}{m}$ and α=0,2 were values already fixed.

The main goal of this paper is to reduce seismic response by energy dissipation. So it is important to analyze the hysteresis loop of the Damper designed (Figure 12)

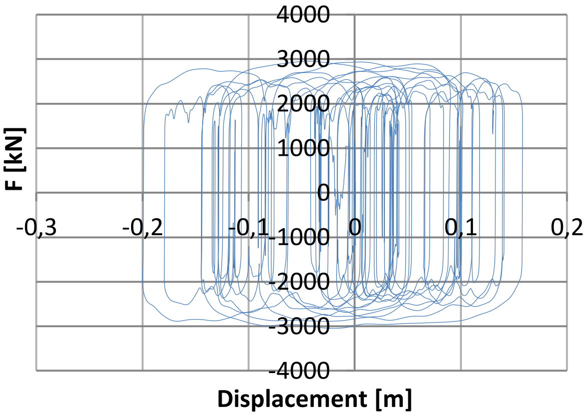


Figure 12 – Optimized Viscous Damper hysteresis loop

Deck displacement obtained for the optimized Viscous Damper was 0,23m. This is a reduction of 56% in deck displacement. The force transmitted to the tower was 3048 kN. The hysteresis loop correspondent to this solution (Figure 12) indicates the expected energy dissipation.

4.3 Hysteretic Damper

The optimization of the Hysteretic Damper was made knowing already the results for the optimized Viscous Damper. The rules defined to initialize the design were used but starting already from the previous results.

$$K_1 = \frac{F_y}{Max\ Elastic\ Disp.} = \frac{3000kN}{0.12m} = 250000\ \frac{kN}{m}$$

$$\frac{\mathrm{K}_2}{\mathrm{K}_1} = 1\%$$

$$F_y = 3000\ kN$$

As mentioned this study pretends to obtain equivalent hysteresis loops for both viscous and hysteretic dampers. At this stage the comparison between the two loops was made (Figure 13).

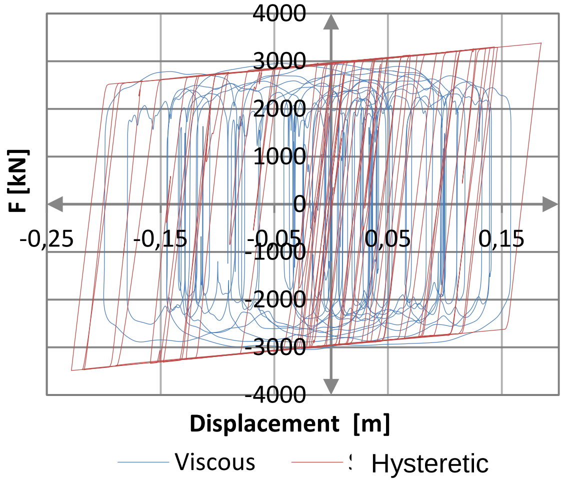


Figure 13 – Comparison between Optimized Viscous Damper and Initial Hysteretic Damper hysteresis loops

The two loops obtained in figure 13 show that energy dissipation is equivalent in the two Dampers. So it is possible to conclude that the initial rules defined for the design of the Hysteretic Damper were correct.

Of course knowing the results from the Viscous damper was a big help. Just as said before this study aims to achieve the optimization of the hysteretic damper. The results obtained for this initial solution were the ones presented in table 3.

Table 3 – Initial Hysteretic Damper results

Force [kN]	Deck Disp. [m]
3553	0,25

The initial results show a reduction of deck displacement of 52%. These results were considered good. In spite of that the optimized hysteretic damper was still the goal to achieve.

To understand the influence of the damper stiffness and yielding force in deck displacement their values were changed. The results were analyzed always taking into account the force transmitted to the towers. The ratio $\frac{\mathrm{K}_2}{\mathrm{K}_1} = 1\%$ was considered as a fixed value.

The first analysis was made considering a fixed stiffness of 250000 $\frac{kN}{m}$ and yielding forces between 0 and 4000 kN. The maximum forces transmitted to the towers were assumed as being very close to F_y values in each case. So figure 14 is the influence of yielding force in maximum deck displacement. Of course yielding force is representing the maximum force transmitted to the towers.

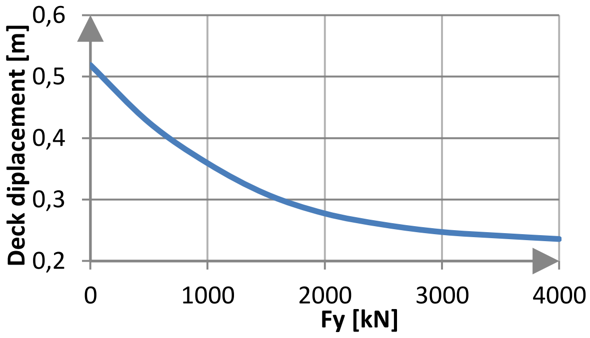


Figure 14 – Influence of yielding force in the maximum deck displacements

Once more the reduction of deck displacement is achieved by increasing structure´s forces. The relation between these two parameters is not linear. At first the increase of yielding force is very attractive but then it is causing less and less deck displacement reduction.

Understanding the most effective value of F_y is needed. For that was produced the graphic (Figure 15), where force transmitted to the structure and deck displacement were plotted for every F_y value.

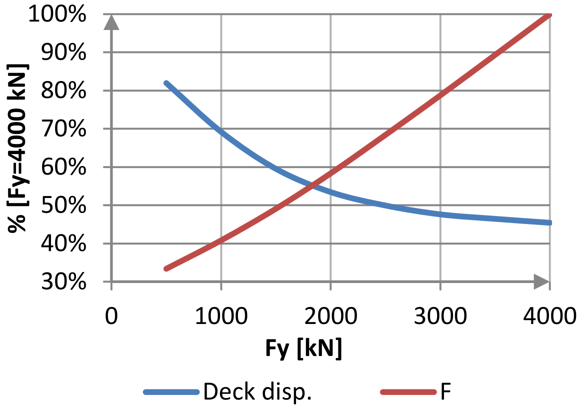


Figure 15 - Influence of yielding force F_y in the maximum forces transmitted to the towers and maximum deck displacements

The optimized Hysteretic Damper due to the criteria defined is F_y=2000 kN. It was suggested by the intersection of the curves in figure 15.

Beyond this moment F_y value was fixed. As mentioned the next step was to considered different values of stiffness K_1. Stiffness was considered between 50000 and 1000000 $\frac{kN}{m}$.

The forces transmitted to the structure were very increased by the increase of stiffness. On the other hand deck displacement didn´t suffer a lot with this modification. In figure 16 is possible to conclude that changes in stiffness value are not important.

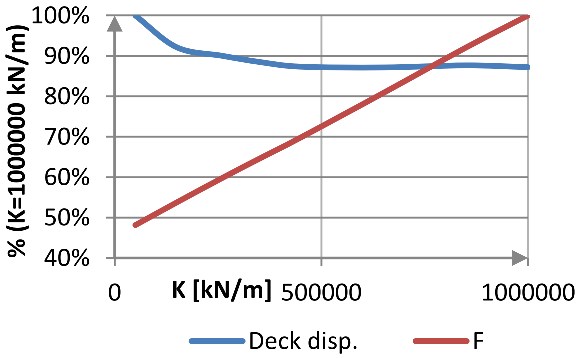


Figure 16 - Influence of stiffness K_1 in the maximum forces transmitted to the towers and maximum deck displacements

Deck displacement is very little influenced by the stiffness of the damper. In fact deck displacement is almost constant over the entire range of stiffness tested. The adequate stiffness remains the initial one.

Due to the criteria defined for yielding force and stiffness the optimized hysteretic damper is characterized by F_y=2000 kN and K_1=250000 $\frac{kN}{m}$. $\frac{K_2}{K_1} = 1\%$ was an equation already fixed.

The hysteretic loop obtained for this Damper is presented in figure 17.

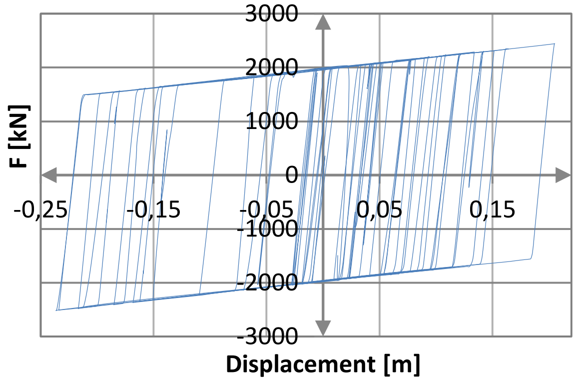


Figure 17 – Optimized Hysteretic Damper hysteresis loop

The deck displacement obtained for the optimized Hysteretic Damper was 0,28m. This is a reduction of 47% in deck displacement. The force transmitted to the tower was 2634 kN. The hysteresis loop correspondent to this solution (Figure 17) indicates the expected energy dissipation.

4.4 Tuned Mass Damper

The research project on "Seismic Protection on Cable-Stayed Bridges" (Freire, 2014) includes, as mentioned, the case study response for viscous and hysteretic dampers but also the response for a Tuned Mass Damper. In this research project is proved that TMD`s are not effective for seismic protection on cable-stayed bridges. The tests include a TMD attached to the deck and also one positioned in the top of each tower. None of them is effective. In the study is also proved that the TMD is not effective in this case because the seismic action is not harmonic. In case the action considered was harmonic the TMD attached to the bridge´s deck would have been as much effective as any of the dampers tested. This paper does not include the complete TMD analysis study. For that is suggested that the research project is consulted. Anyway is interesting to make the comparison between the seismic and the harmonic action. So it is presented the deck displacement for a seismic and an harmonic action (sine). The case presented (Figure 18) is the bridge attached with a TMD in its deck.

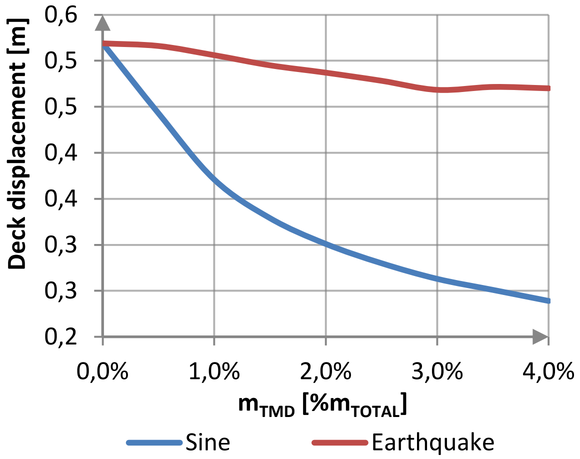


Figure 18 – Structure with TMD response to seismic and harmonic action

5. Comparative analysis

In this section is made a brief comparison between the viscous damper and the hysteretic damper. Both solutions are analyzed as possible protection systems for a cable-stayed bridge. In section 4.4 the TMD was excluded from the valid options.

The optimization process led to two devices with very good results in the decreasing of deck displacements. These two devices also assure that the forces transmitted to the structure are not exaggerated. The devices this study elects are presented in table 4.

Table 4 – Elected Devices

Hysteretic Damper	Viscous Damper
n=20 $K_1 = 250000 \frac{kN}{m}$ $\frac{K_2}{K_1} = 1\%$ $F_y = 2000\ kN$	α=0,2 $C = 3500 \frac{kN}{m/s}$ $K = 6 \times 10^8 \frac{kN}{m}$

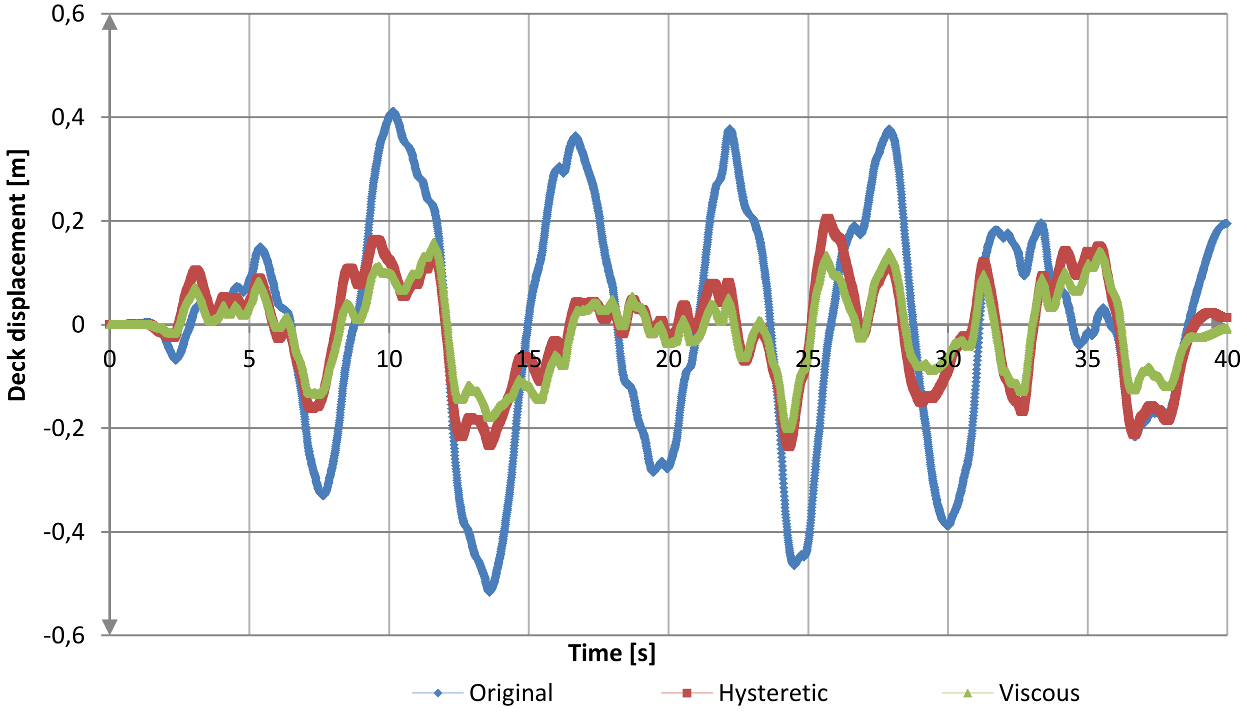


Figure 19 – Deck displacement during an earthquake for original and protected structure (optimized)

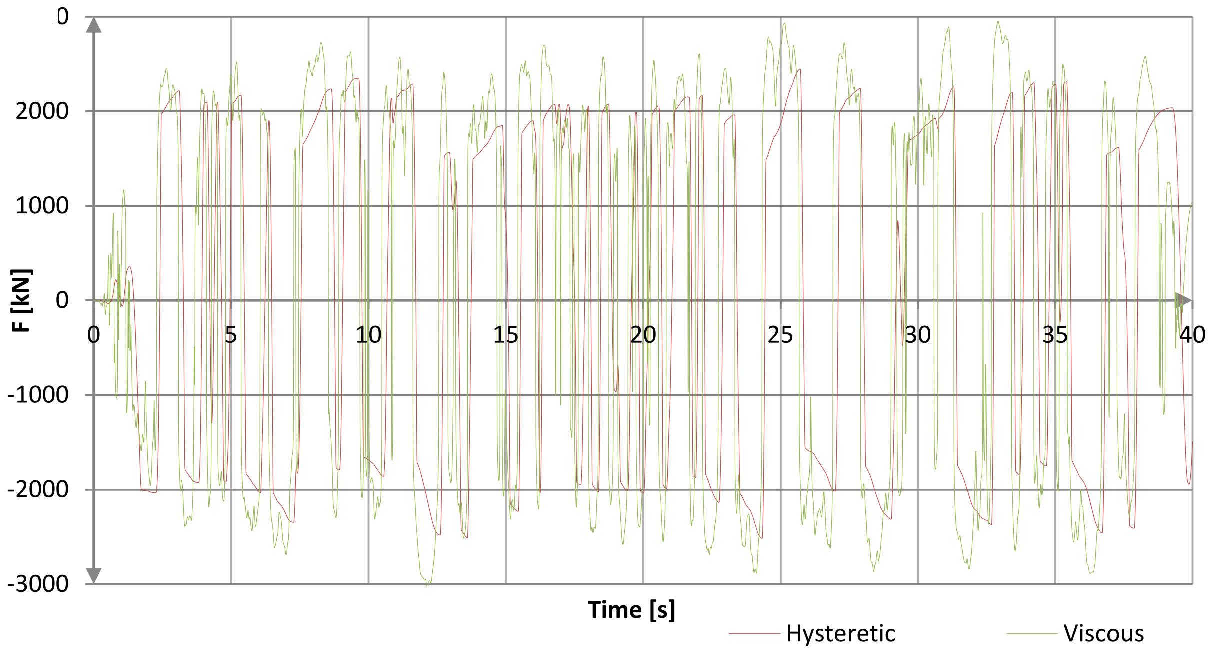


Figure 20 – Force in optimized dampers during an earthquake

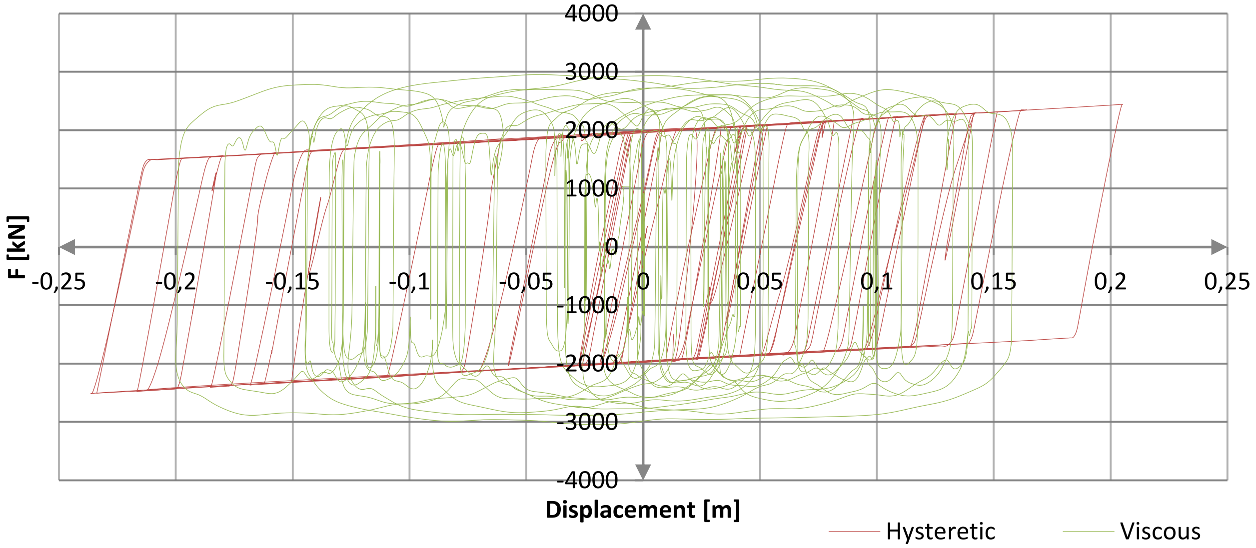


Figure 21 – Hysteresis loop for optimized dampers

In figure 19 the deck displacement is compared during an earthquake in the original structure and also in the structure protected with the optimized dampers. In figure 20 is plotted the force in the optimized dampers and in figure 21 the hysteresis loop during the seismic action. Displacements and forces are very similar in the two dampers. Hysteresis loops are almost equivalent in area as required. The shape of the hysteresis loop is of course different in the two dampers because they have different behavior equations.

A summary of the results in terms of forces transmitted to the structure and displacements is provided in table 5.

At first glance it may seem that the viscous damper is more effective than the hysteretic one. In fact it is not true because the optimization process doesn´t have the detail to confirm that at this level of differences. Furthermore this study doesn´t take in account the economic factor. The consideration of this factor can bring a lot of interesting questions to this field of study.

Tabela 5 – Optimized results

	Viscous Damper	Hysteretic Damper
Deck displacement [m]	0,23	0,28
Deck displacement reduction	56%	47%
Force transmitted to the structure [kN]	3048	2634

6. Conclusions

In this type of bridges the towers deform. It is not true that the deck oscillates anchored in the tower. The deck is so flexible and long that the top of the two towers follow its movement. The deck displacement without any seismic protection device is very high. It is mandatory to reduce this displacement. In other case the designer will have to think in large joints to accommodate these movements. It is considered appropriate that in future developments, seismic protection and joint design for these type of bridges are done together.

Viscous and Hysteretic Dampers were elected as the ones capable of decreasing the deck displacement for cable-stayed bridges. Tuned Mass Dampers are not effective in this field of study.

The follow up of this research project can be the analysis of different case studies and also the inclusion of several devices on the same bridge. Testing new positioning for the devices can also be interesting.

The choice of a seismic protection system should be guided by several variables. Some of them were not considered in this paper. In fact the choice of a device of this type should be an integrated process that include longitudinal displacement, force transmitted to the structure, displacement in other directions, devices cost, devices installation cost, joints cost and maintenance cost of everything involved during the lifetime cycle of a cable-stayed bridge.

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