Base Isolation of Bridges
Analysis of the Effects of the Devices Post-Yielding Stiffness

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SUMMARY

The main goal of the present study is the analysis of hysteretic dampers properties influence, when applied to bridges, namely the yield strength, elastic stiffness and post-yielding stiffness. The aim of this report is to describe the relationship between post-yielding stiffness of the device, and the lateral restoring capability of the structure, an essential function of an isolated system, that allows the structure to recover its initial position after a seismic event.

1 INTRODUCTION

In recent years, technologies for seismic protection have been developed, in order to design structures in areas with highly seismic hazard. One of the most interesting solutions applied in bridges are passive energy dissipation systems. These systems can be steel hysteretic dampers or viscous dampers. The main goal of the present study is the analysis of the properties of hysteretic dampers, on the seismic behaviour of bridges. These devices exhibit a non-linear behaviour associated with the capability for energy dissipation. Therefore, they can reduce the seismic forces transmitted to the structures, in a very efficient way. However, energy dissipation and lateral restoring capability are two antithetic functions. The purpose of the lateral restoring capability requirement is not so much to limit residual displacement at the end of a seismic phenomenon, as to prevent cumulative displacements during the seismic event. These study aims to evaluate some characteristic parameters of the hysteretic dampers, such as the post-yielding stiffness, in terms of its effect on lateral restoring capability.

2 PARAMETRIC STUDY

Hysteretic dampers take advantage of plastic deformation of metallic elements, usually made of steel. In these systems, the force depends on the deformation of the steel device, and the control parameters are elastic stiffness ($K_1$), post-yielding stiffness ($K_2$) and yielding force ($F_y$). These parameters can be defined based on a set of vibration frequencies of the structure, such as:

- $f$ – vibration frequency of the structure without a hysteretic damper [Hz]
- $f_1$ – vibration frequency of the structure before the device’s yielding [Hz]
- $f_2$ – vibration frequency of the structure after the device’s yielding [Hz]
- $F_y$ – yielding force of the device [kN]

The structure can be considered a system of one-degree-of-freedom. For that reason, the global stiffness of the structure without hysteretic dampers ($K_{Piers}$) is calculated based on a linear elastic analysis. The yielding force is considered as function of the weight of the structure, $W$. The table below sets the case studies considered.
In the five first case studies, the structure presents a first mode vibration frequency of 0.2 Hz. In Study 6, the stiffness was reduced so that the frequency is 0.05 Hz in this particular case. These two kinds of case analysis aim to evaluate the importance of the piers as an integrant part of the isolation system in order to control superstructure’s displacements. The following table presents the properties of the isolated system which take into account the properties of the hysteretic damper and the piers.

<table>
<thead>
<tr>
<th>Study</th>
<th>( f ) [Hz]</th>
<th>( f_1 ) [Hz]</th>
<th>( f_2 ) [Hz]</th>
<th>( F_y ) [kN]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.2</td>
<td>0.5</td>
<td>0.21</td>
<td>1.25% W</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2.50% W</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5.00% W</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>7.50% W</td>
</tr>
<tr>
<td>2</td>
<td>0.2</td>
<td>0.5</td>
<td>0.2</td>
<td>1.25% W</td>
</tr>
<tr>
<td>3</td>
<td>0.2</td>
<td>0.5</td>
<td>0.3</td>
<td>1.25% W</td>
</tr>
<tr>
<td>4</td>
<td>0.2</td>
<td>0.3</td>
<td>0.21</td>
<td>1.25% W</td>
</tr>
<tr>
<td>5</td>
<td>0.2</td>
<td>0.7</td>
<td>0.21</td>
<td>1.25% W</td>
</tr>
<tr>
<td>6</td>
<td>0.05</td>
<td>0.5</td>
<td>0.06</td>
<td>1.25% W</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2.50% W</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5.00% W</td>
</tr>
</tbody>
</table>

In the parametric study, a non-linear time-history analysis was considered because these systems are characterized by a bilinear behaviour. Therefore, seismic action is mandatorily simulated by series of accelerations.

### 2.1 Study 1

For the present study, four different yielding forces of the hysteretic damper \((F_y)\) were considered, keeping the stiffness properties constant. The main goal of Study 1 is to compare the bridge’s behaviour when the device’s yielding force is changed, analyzing maximum and residual displacements.
As it was already referred, the re-centering capability is an extremely important property of the isolation systems. In order to evaluate this capability, residual displacements after seismic events were analyzed. The figure 1 shows the course throughout time of a point of the deck (Study 1.1) excited by a series of accelerations (Loureiro, 2008). According to the figure, the structure has a residual displacement close to 1cm, after the seismic event.

In figure 2, the average of maximum and residual displacements observed for each one of the Studies 1.i is presented, in comparison with the maximum displacement observed for the structure without the hysteretic damper.

It is evident that, to an increase of the damper’s yielding force, corresponds an increase of the maximum displacement observed. This situation is justified by the fact that, the higher the yielding force, the longer the system will remain with an elastic behaviour and, therefore, subject to greater accelerations (greater dynamic response) and, consequently, has larger displacements. It is also concluded that, the higher the maximum displacement of the deck, the higher the residual displacement is, and that both will increase with the increase of the hysteretic damper’s yielding force.
2.2 Study 2 and 3

The present analysis serves to compare the structure’s response when its post-yielding stiffness property \( (K_2) \) is modified, as elastic stiffness and yielding force remain constant.
In Study 2, the damper presents an elastic-perfectly plastic behaviour, and in Study 3 the damper’s post-yielding stiffness is increased relatively to Study 1.
In table 3, some of the results obtained for these two studies are presented, in comparison with the ones obtained in Study 1.1.
Its analysis allows to conclude that the post-yielding hysteretic damper’s stiffness modification does not significantly affect the structure’s displacements, without apparent problems with the structures capability to recover its original position (small residual displacements), following any dynamic action, such as seismic action.
The higher the post-yielding stiffness ratio \( \eta = K_p/K_e \), the smaller the damping \( \zeta \), introduced by the device in the structure. It can be therefore concluded that the increase of the post-yielding hysteretic damper’s stiffness brings no advantage to the structure in an energy dissipation level.

2.3 Study 4 and 5

The present analysis serves to compare the structure’s response when the elastic stiffness is modified \( (K_1) \), as post-yielding stiffness and yielding force remains constant.
In Study 4, elastic stiffness is diminished, while in Study 5 it is increased.
In table 3, some of the results obtained for these two studies are also presented.
The modifications of the hysteretic damper’s elastic stiffness have an effect on structure displacements. Given that all damper properties remain unaltered except for elastic stiffness, it is natural that structures with higher elastic stiffness present minor yielding displacements and, therefore, minor maximum displacements.
Once again, registered residual displacements are not important.

<table>
<thead>
<tr>
<th>Study</th>
<th>( d_{Max} ) [cm]</th>
<th>( d_{Residual} ) [cm]</th>
<th>( \eta = K_p/K_e )</th>
<th>Damping, ( \xi )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>7.11</td>
<td>0.632</td>
<td>17.64%</td>
<td>26%</td>
</tr>
<tr>
<td>2</td>
<td>7.19</td>
<td>0.651</td>
<td>16.00%</td>
<td>27%</td>
</tr>
<tr>
<td>3</td>
<td>7.01</td>
<td>0.597</td>
<td>36.00%</td>
<td>14%</td>
</tr>
<tr>
<td>4</td>
<td>10.34</td>
<td>1.438</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>6.21</td>
<td>0.327</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2.4 Study 6

In this study it is intended to analyze a situation where the contribution of the piers to the stiffness of the ensemble is very low, with deck displacements controlled, almost exclusively, by the hysteretic damper placed in one of the abutments of the bridge.
The purpose is to simulate a great loss of stiffness of the structure due to any problem, like high level of cracking.
Only in the case of a bridge where the deck is practically “loose” from its piers will the lateral restoring capability be a determinant and limitative factor in the dimensioning of the energy dissipation device.
As it can be seen in figure 3, residual displacements observed in the three Studies 6.i are in the range between 3.0cm and 5.0cm. These values are far superior to the ones observed in any of the previous cases, where the residual displacement was never higher than 1.5cm, despite similar maximum deck displacements.

![Figure 3 – Comparison between maximum displacements and residual displacements, Study 6](image)

From the analysis of the registered residual displacements, it is concluded that the lateral restoring capability of the structures is not guaranteed, that is, the superstructure when subject to a seismic action does not resume its original position. For a better understanding of this capability, in figure 4 it is presented the displacement time-history of a point of the deck (Study 6.1) when subject to a series of accelerations (Loureiro, 2008). This structure does not present lateral restoring capability because, at the end of the seismic event, the deck is 7.7cm away from its original position.

![Figure 4 - Residual deck displacement throughout time, Study 6.1](image)

Another conclusion that can be taken from this study is that, when the deck is too “loose” from its piers, that is, when the piers, allow for great displacements of the superstructure, the placement of an hysteretic damper is very effective in the control of maximum displacements ($d_{Max}$ without damper = 48.07cm).
3 CODE ANALYSIS

The lateral restoring capability is identified by the majority of existing codes, as a fundamental characteristic of isolated systems (AASHTO 2000, EN1998-2, IBC2000, NEHRP 2000, and others). However, the evaluation of lateral restoring capability is based not on theoretical fundamentals but in empirical approximations.

In the present chapter, it is intended to make the normative verification for the cases analyzed in the parametric study, comparing and commenting the results obtained.

The code used to verify the lateral restoring capability of the structure was the Eurocode 8 – Part 2: Bridges, in three distinct proposals for the chapter 7.7.1 Lateral restoring capability, presented by chronological order:

- prEN 1998-2:2003;

The present chapter serves essentially to show that normative documents have evolved in a logical sense, in what respects the requirement of lateral restoring capability. From this evolution, the best example is the exclusion of the \(W_d\) parameter (weight of the structure) from the conditions to verify.

This parameter, present in the two first codes, made practically impossible the verification of the lateral restoring capability of any isolation system based on hysteretic devices (see Loureiro, 2008).

Next it will be presented an evaluation at the level of lateral restoring capability of the presented studies, using the Revised Proposal of Clause 7.7.1 of EN 1998-2:2005.

Given that the code is not very clear, an attempt was made to simplify the analysis of the expressions through the development of graphics where any of the two present variables (vertical and horizontal axis), are parameters of easy perception.

In accordance to the characteristics of a system with a bilinear hysteretic behaviour (figure 5), it is intended to create a graphic that relates the parameters \(\eta = Kp/Ke\), with the ductility \(m = d_{cd}/d_y\), of the structure.

\[ F_y \]

\[ k_p = \eta \cdot k_x \]

\[ d_y \]

\[ d = m \cdot d_y \]

**Figure 5** – Characteristics of a system with a bilinear hysteretic behaviour
In Table 4 is presented the ductility, $m$, and the ratio $\eta = K_p/K_e$ for all studies.

<table>
<thead>
<tr>
<th>Study 1</th>
<th>Study 2</th>
<th>Study 3</th>
<th>Study 4</th>
<th>Study 5</th>
<th>Study 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>1.2</td>
<td>1.3</td>
<td>1.4</td>
<td>1.5</td>
<td>1.6</td>
</tr>
<tr>
<td>Ductility $m$</td>
<td>4.81</td>
<td>2.46</td>
<td>1.61</td>
<td>1.20</td>
<td>4.86</td>
</tr>
<tr>
<td>$\eta$ (%)</td>
<td>17.64</td>
<td>17.64</td>
<td>17.64</td>
<td>17.64</td>
<td>16.00</td>
</tr>
</tbody>
</table>

According to the Revised Proposal of Clause 7.7.1 of EN 1998-2:2005, a system presents self-restoring capability, when the following condition is verified:

$$\frac{d_{cd}}{d_r} \geq \delta = 0.5$$

Where,
- $d_{cd}$ - is the design displacement of the isolating system in the examined direction;
- $d_r$ - is the static residual displacement of the isolating system in the same direction. For systems with bilinear behaviour, $d_r$ is given as, $d_r = F_0/K_p$;
- $\delta$ – is a numerical value $\delta = 0.5$ (recommended value).

As is shown in detail in Loureiro, 2008, it is possible to construct a graphic representative of the code expression (1), relating the ratio, $\eta$, between the post-yielding stiffness, $K_p$, and the elastic stiffness, $K_e$, with the ductility of the structure, $m$, that corresponds to the ratio between the design displacement and the yielding displacement.

The expression that translates this graphic is as follows,

$$\eta = \frac{1}{1 + \frac{m}{0.5}}$$

In figure 6 is presented the graphic that shows the area where there is lateral restoring capability.

As it was observed in the parametric study, the systems defined as 2, 3, 4, and 5 present lateral restoring capability.

It is concluded that, either for the Study 1.1, as for the Study 1.2, the system presents re-centering capability, since it presented small residual displacements.

In relation to the Studies 1.3 e 1.4, it is necessary to verify the other condition proposed on the code, to be able to claim if they possess lateral restoring capability or not.

As expected, none of the Studies 6 respects the proposed condition.
For Studies 1.4, 1.3, 6.1, 6.2, and 6.3, it is necessary to verify the other proposed condition that, if verified, will guaranty lateral restoring capability to the system.

The relation to verify is as follows,

\[
d_{mi} \geq d_{oi} + \gamma_{du} d_{bi,d} \rho_d
\]  \tag{3}

where,

\[
\rho_d = 1 + 1.35 \cdot \frac{1 - (d_y / d_{cd})^{0.6}}{1 + 80(d_{cd} / d_r)^{1.5}}
\]  \tag{4}

and,

- \(d_{mi}\) - is the displacement capability of the isolator \(i\) in the considered direction;
- \(d_{bi,d}\) - is the design displacement of isolator \(i\) in the examined direction;
- \(d_{oi}\) - is the non-seismic offset displacement of isolator \(i\);
- \(d_y\) - is the yield displacement of the equivalent bilinear system;
- \(\gamma_{du}\) - is a numerical coefficient reflecting uncertainties in the estimation of design displacements \(\gamma_{du} = 1.2\) (recommended value).

Assuming that for the equation (3), \(d_{mi} = 1.5 \cdot d_{bi,d}\), a value recommended by the EN 1998-2:2005 code, and that the displacement in the hysteretic damper by the effect of non-seismic actions on the deck, \(d_{oi}\), is represented by a percentage, \(\alpha\), of the design displacement, \(d_{bi,d}\), we reach the following relation, demonstrated in detail in, Loureiro, 2008.

\[
1.5 \geq \alpha + 1.2 \times \left(1 + 1.35 \cdot \frac{1 - (1/m)^{0.6}}{1 + 80(\eta / (1-\eta)m)^{1.5}}\right)
\]  \tag{5}

With this expression it is possible to interpret the code expression (3) in a graphic having, taken into account only the ductility of the system, \(m\), the relation \(\eta = Kp/Ke\) and the parameter \(\alpha\).

\[\text{\footnotesize{\textsuperscript{1}} d_{bi,d} = d_{cd}}\]
For the Studies 1.3 and 1.4, it is plausible to assume that $\alpha = 10\%$, because the design displacements registered are, in both cases, approximately ten times superior to the displacement caused by the non-seismic actions on the deck. For any of the Studies 6, $\alpha = 1\%$.

**Figure 7** - Graphic representation of the code expression (3) and Studies 1.3 and 1.4

**Figure 8** - Graphic representation of the code expression (3) and Studies 6.1

As seen by the analysis of figure 7, Studies 1.4 and 1.3 present lateral restoring capability. By analyzing figure 8, we realize that only the structure defined as Study 6.1 reveals, according to the EN 1998-2:2005 – A code, a sufficient displacement capability in order to accommodate, with adequate reliability, the accumulation of residual displacements. This means that the structures portrayed by Studies 6.2 and 6.3 do not verify the code in analysis.

4 CONCLUSIONS

According to the results obtained, Studies 1, 2, 3, 4, and 5 do not appear to present lateral restoring capability problems, since they show small residual displacement. This conclusion is supported by code verification, where all these Studies (1 to 5) satisfy the re-centering capability requirements.

The cases where residual displacement is higher, 1.3 e 1.4, are the ones that do not meet the condition $d_{cd}/d_r \geq 0.5$, but that present enough displacement capability to accommodate, with adequate restitution, the accumulation of residual displacements.

The key parameter describing lateral restoring capability of isolated systems subject to seismic action is the relation $d_{cd}/d_r$, where $d_{cd}$ is the design’s seismic displacement, and $d_r$ is the
maximum possible static residual displacement. For bilinear behavior systems, such as hysteretic dampers, \( d_r = \frac{F_0}{K_p} \), where \( K_p \) is the post-yielding stiffness, and \( F_0 \) is the characteristic force (force at zero displacement of hysteresis loops), the lateral restoring capability increases as the relation \( d_c/d_r \) increases.

In table 5 the values of \( d_c/d_r \) for Studies 6.1, 6.2 and 6.3 are presented, demonstrating that, the Study 6.1 is the only one, among the three, to present lateral restoring capability.

Another parameter that affects the re-centering capability is the relation, \( d_y/d_r \). Its value for all studies is presented on table 6.

<table>
<thead>
<tr>
<th>Study</th>
<th>Study 6.1</th>
<th>Study 6.2</th>
<th>Study 6.3</th>
</tr>
</thead>
<tbody>
<tr>
<td>( d_c/d_r )</td>
<td>0.115</td>
<td>0.046</td>
<td>0.031</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Study</th>
<th>Study 1</th>
<th>Study 2</th>
<th>Study 3</th>
<th>Study 4</th>
<th>Study 5</th>
<th>Study 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>( d_y/d_r )</td>
<td>0.21</td>
<td>0.19</td>
<td>0.56</td>
<td>0.49</td>
<td>0.1</td>
<td>0.01</td>
</tr>
</tbody>
</table>

It is easily perceived that the lateral restoring capability increases as the relation \( d_y/d_r \) increases.

The conditions present in EN 1998-2:2005 – A allow for the verification, in terms of lateral restoring capability, of the majority of hysteretic dampers designed for bridges with regular design. It is understood by regular a bridge in which the displacements are controlled, in its vast majority, by the piers. However, in Study 6.1 it is shown that lateral restoring capability can be verified (EN 1998-2:2005 – A) even for a bridge where the deck is practically “loose” from its piers.

It must be referred that with the new code, the re-centering capability verification problem does not occur in the majority of designed bridges, as could happen with the old codes. The proposed code (EN 1998-2:2005 - A) makes coherent the special requirement, 7.7.1 Lateral restoring capability.

As a final comment, it is suggested to the designers to ponder about the participation of structural elements in the seismic isolation global solution, given that characteristics such as lateral restoring capability are an intrinsic part of the entire structural system and not of each component.

REFERENCES

