INVESTIGATION OF DAMPER EFFECT ON STRUCTURAL RESPONSES OF LONG-SPAN CABLE-STAYED BRIDGES UNDER MULTI SUPPORT EXCITATION AND TRAFFIC LOADS

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ABSTRACT

Because bridges have great importance in transportation networks, their safety after seismic excitation should be controlled. Especially, when the span length of the bridge increases, the complexity of seismic control will be higher. In such long-span bridges, factors like traffic loads and dampers may considerably affect the structural responses of the bridge. In addition, the variation of earthquake waves due to their propagation through the ground should be accounted for in the seismic control of long-span bridges by the multi support excitation analysis method. This research deals with the analysis of the seismic behavior of long-span cable-stayed bridges equipped with nonlinear viscous dampers when subjected to multi support seismic excitation and traffic loads, and it focuses on the comparison of viscous dampers’ effectiveness under conditions in which a long-span cable-stayed bridge is subjected to multi support excitation and uniform support excitation. For this purpose, the Vasco da Gama cable-stayed bridge is examined via a numerical study. Generally, the effectiveness of nonlinear viscous dampers increased under multi support excitation in comparison with uniform support excitation.

Keywords: Cable-stayed bridge, Multi Support Excitation, Traffic load, viscous damper.


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1. INTRODUCTION

There are so many situations in which designing a bridge with the usual span length is impossible, due to the limitations of projects. However, seismic design of long-span cable-stayed bridges has a higher complexity level than the usual ones. Construction of long-span cable bridges is always one of the conventional alternatives.

To determine the effects of earthquake load on structures, a well-known idealization in engineering practice is to suppose that the structure is entirely excited from uniform earthquake ground motions. However, earthquake spectra change while traveling, but the variation level of earthquake spectra in structures that are not long are negligible. This assumption is generally accurate for structures small in plan, such as buildings and short-span bridges. Based on this assumption, the dynamic analysis method in which the structure is excited uniformly, i.e., uniform support excitation (USE), has been used.

Because the variation levels of earthquake spectra in long structures, such as long-span bridges, are considerable, designers should consider in detail their effects. Multi support Multi support excitation (MSE) should be employed by designers for dynamic analyses of long-span bridges, because it will result in more-realistic designs.

Dampers have been extensively used to confront earthquake forces in cable-stayed bridges. However, although much research about dampers’ effects on structural responses of cable-stayed bridges and their optimization has been published, the dampers’ response under MSE of the bridge has not been investigated.

In 1992, Nazmy and Abdel-Ghaffar studied the effects of ground motion spatial variability on the response of cable-stayed bridges. They compared a bridge’s response to non-uniform ground motion with its response to uniform input [1]. In 2004, Soyluk researched the spatial variability effects of ground motions on the dynamic behavior of long-span bridges, by a random-vibration-based spectral-analysis approach and two response spectrum methods. Random-vibration analyses were performed on two deck-type arch bridges and a cable-stayed bridge model. The investigation led to the discovery that the structural responses for each random vibration analysis depend largely on the intensity and frequency contents of power spectral density functions [2]. In 2016, Apaydin et al. investigated the structural behavior of the Fatih Sultan Mehmet Suspension Bridge under multipoint earthquake excitations and determined the earthquake performance of the bridge [3]. In 2017, Zhong et al. studied the seismic vulnerability of cable-stayed bridges by fragility analysis and using spatially variable ground motions. The results indicate that the incoherency and site-response effects significantly affect the demands and corresponding component fragilities [4]. Also, in 2017, Bas et al. investigated the effects of multi-support earthquake excitation on the seismic performance of the Bosphorus bridge. Based on the results from the MSE of the bridge, the tensile force of the main and side span cables noticeably increased under the MSE compared with the uniform support and retrofit project. It is noteworthy that none of these researches considered the damper effect in its results [5].

Like the dampers’ effect, traffic load has been neglected in related research, whereas it may affect the structural response of bridges that receive high vehicular traffic. Considering traffic loads will result in even more-realistic structural responses.

In 2012, Kartal and Soyluk studied the effects of earthquake and traffic loadings on the dynamic behavior of cable-stayed bridges. They showed that the combined effect of the earthquake and traffic loadings should be considered for the realistic design of cable-stayed bridges [6].
The authors intend to illustrate the significance of the dampers’ use and their effectiveness under MSE. For this purpose, in this article, basic concepts are reviewed first. Then, through a numerical study, the effects of MSE are investigated, and the dampers’ effects on structural responses of long-span cable-stayed bridges under MSE and USE conditions are compared. Finally, the results are analyzed, and a general judgment is derived as a conclusion.

2. BRIEF REVIEW OF BASIC CONCEPTS

2.1. MSE

Because of the span length of cable-stayed bridges, each support experiences different ground motions when these bridges are subjected to earthquakes. Therefore, it is of paramount importance to include the effect of MSE in cable-stayed-bridge design.

2.1.1. MSE equations

Total structural displacement (\(v\)) that results from the ground motion excitation can be expressed as the sum of two components. One of these components is the result of differential ground motions (pseudostatic displacements), and the other one is the result of inertia forces. The pseudostatic displacement is caused by the nonuniform motion of the supporting points at any time instant.

\[
v = v_s + v_d
\]

where \(\{v\}, \{v_s\}, \{v_d\}\) are the total, pseudostatic, and dynamic displacement vectors, respectively. The dynamic displacement vector is defined as

\[
\{v_d\} = \sum_i \{\phi_i\} Y_i(t)
\]

where \(\{\phi_i\}\) is the \(i\)-th modal vector, and \(Y_i(t)\) is the \(i\)-th modal amplitude with respect to time. The pseudostatic displacement vector is defined as

\[
v_s = r_1 v_{1_g}(\tau_1,t) + r_2 v_{2_g}(\tau_2,t)
\]

where \(\{r_i\}\) is the shape vector of ground displacement, \(\{v_{ig}\}\) is the displacement vector of ground acceleration, \(t\) is time, and \(\{\tau_i\}\) is the time of arrival of ground acceleration to the point of support \(i\) or to the area beginning from a certain reference point [7].

The interpretation of the above equations, especially Eq. 1, will prove the necessity of applying MSE to the bridge; therefore, it is supposed that MSE may increase the seismic response of long-span bridges when compared with USE. Consequently, designers should be regardful of the effects of MSE.

2.1.2. MSE application

By different excitations of bridge supports connected to the ground, MSE will be achieved. One significant aspect of applying MSE is the consideration of the variation level of excitations. In other words, the difference of those excitations should not be excessive and exaggerated.

Therefore, the most appropriate method for MSE application is exciting the bridge support by distinct records of a single earthquake recorded from nearby seismograph stations. In cable-stayed bridges, MSE should be applied to pylons.
2.2. Viscous Damper
Using viscous dampers is a common way to induce energy dissipation to the lateral system of a bridge. The seismic performance of the viscous dampers is mainly determined by the values of damping parameters $C$ and $\alpha$. By considering nonlinearity, the force in the damper will be achieved as in Equation 4.

$$F = CV^\alpha$$

where $\alpha$ is velocity index, which is usually in the range of 0.2–2.0, and $C$ is the damping coefficient, which ranges between 1000 and 20,000 KN.(s/m)$^\alpha$ [8].

3. NUMERICAL STUDY
As a numerical study, the Vasco da Gama cable-stayed bridge in Lisbon was modeled; the model was presented by Pedro and Reis in 2010 [9]. Maleki and Shabestari, in 2016, modeled this bridge and investigated the response modification factor [10]. The bridge was modeled by the CSI Bridge 2017 v.20.0.0 software, manufactured by Computers and Structures Inc. [11].

The results of this numerical study should be interpreted from two aspects:

- Comparison of the viscous damper’s effect on structural responses in MSE and USE conditions.
- Investigation of the necessity of MSE application on long-span cable-stayed bridges

3.1. Modeling

3.1.1. Model characteristics
According to Figure 2, the bridge has three spans. The length of the main span is 300 m, with two 120-m side spans.
The bridge deck width is 22 m. The pylons in the bridge are H-shaped and have a 135-m height. At the level of the deck, there is a main transverse beam as a connection between each pylon and the deck.

A semifan cable arrangement system was used in this bridge. There are 56 cables attached to each pylon in two planes, one on the left side of the deck and the other on the right side. In the main span, the spacing of the cables is 10 m, but in the side spans, this spacing is 8 m.

3.1.2. Seismic loading specifications

Records from the 1999 Chi Chi-Taiwan earthquake were used in this study as earthquake ground motions that were applied to the Vasco da Gama Bridge. Medium soil condition was selected. To consider the MSE analysis, records 1234 and 1206 (RSS NO.), which are close recordings of Chi Chi earthquake ground accelerations, were used. Pylons 1 and 2 were excited by 1234 and 1206, respectively, with the purpose of achieving an MSE condition. These recordings were obtained from the University of California, Berkeley, Pacific Earthquake Engineering Research (PEER) Strong Motion Database [12]. The specifications of the records are presented below.

**Table 1** Record specifications. a) Peak ground acceleration, b) peak ground velocity, and c) peak ground displacement

<table>
<thead>
<tr>
<th>Name</th>
<th>earthquake (PEER records)</th>
<th>PGA (g)</th>
<th>PGV (cm/sec)</th>
<th>PGD (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>E</td>
<td>N</td>
<td>V</td>
</tr>
<tr>
<td></td>
<td></td>
<td>amount</td>
<td>time</td>
<td>amount</td>
</tr>
<tr>
<td>A</td>
<td>1234</td>
<td>0.201</td>
<td>39.6</td>
<td>0.411</td>
</tr>
<tr>
<td></td>
<td>1206</td>
<td>0.199</td>
<td>38.26</td>
<td>0.133</td>
</tr>
<tr>
<td>B</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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The records were filtered for small amounts of accelerations, so time histories are presented from \( t = 20 \) s to \( t = 90 \) s. The acceleration time histories were then converted into the associated displacement time histories to perform MSE analysis.

### Figure 3
Displacement time history record for 1206 and 1234 PEER records (from left to right)

### Figure 4
Acceleration time history record for 1206 and 1234 PEER records (from left to right)

#### 3.1.3. Traffic-loading specifications
Traffic loads were considered in all models due to the results of Kartal and Soyluk [6]. For applying traffic load to the Vasco da Gama cable-stayed bridge, a moving load model was considered by using the heavy truck H20-44 defined in AASHTO [13]. Vasco da Gama Bridge is a four-lane bridge with two lanes in each direction. The speed of vehicles was assumed to be 80 km/h, and the time interval of vehicles was assumed to be 1.5 s. The distance between two vehicles was 33 m, which is acceptable according to AASHTO [13]. The duration after which the bridge was full of vehicles was 24.5 s. It is worth mentioning that the dynamic effects of traffic loading were considered.

#### 3.1.4. Cable prestress forces
In cable-stayed bridges, the bridge has a predetermined longitudinal profile. Therefore, the cable tension on these bridges is determined accordingly. For this purpose, the deck of the bridge was modeled as a beam, whose supports were roller-aligned with the alignment of cables. Then, dead loads were applied to this beam; after analysis of this beam, the forces of the cables were obtained. Based on these forces, the basic specifications for cables were considered. Then, by the method of trial and error, cable forces changed until the deflection profiles under dead loads were close enough to the predetermined desired state.
3.1.5. Damper
Hereafter, when the bridge is modeled with dampers, two nonlinear viscous dampers are located between the pylon and the deck. According to Equation 4, the parameter $\alpha$ is equal to 0.5, but the damping coefficient $C$ was optimized between $C = 1000, 2000, $ and $10,000\text{ KN(s/m)}^\alpha$. Finally, $C = 2000 \text{ KN(s/m)}^\alpha$ was chosen, due to the satisfaction of maximum displacements determined in AASHTO.

4. RESULTS AND FIGURES

4.1. Structural response figures
In this section, figures are presented from two aspects:
- Illustrating the effect of applying MSE
- Comparison of damper effect in MSE and USE conditions

4.1.1. Effect of applying MSE
In Figure 5, structural responses of the bridge are shown in two conditions. First, the bridge was modeled with traffic load and dampers, and then MSE was applied to it. Second, the bridge was modeled with traffic load and dampers, and then USE was applied to it. A comparison will indicate the effect of the application of MSE to the bridge.

![Figure 5](image_url)

**Figure 5** Comparison of structural responses between MSE and USE conditions: a) input energy, b) damper energy, c) displacement of top of Pylon 1, and d) displacement of top of Pylon 2
As shown in Figure 5(a), the input energy of the structure increased in MSE conditions, because of the nonsymmetric excitation of pylons in MSE conditions in comparison with the USE condition. Also, due to the increase of relative velocity variation at two ends of the dampers, dissipated energy by dampers increased in MSE conditions. The displacements of the top of Pylon 1 in MSE and USE conditions are almost the same, and minor differences between them are the result of distinct excitation of the other pylon in those conditions. However, as expected, the differences of displacement at the top of Pylon 2 were greater than those of Pylon 1. In the below table, the proportions of maximum responses of the bridge in MSE and USE conditions are presented.

<table>
<thead>
<tr>
<th></th>
<th>Input energy</th>
<th>Damper energy</th>
<th>Disp. top Pylon 1</th>
<th>Disp. top Pylon 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSE/USE</td>
<td>1.093</td>
<td>1.151</td>
<td>0.934</td>
<td>0.886</td>
</tr>
</tbody>
</table>

4.1.2. Comparison of damper effect in MSE and USE conditions

In Figures 6 and 7, the structural responses of the bridge are shown in conditions with and without dampers. In one set of them, traffic load and MSE are applied to the bridge, and, in the other, traffic load and USE are applied to the bridge. The effect of the dampers on the maximum responses of the modeled bridge is presented in Table 1.

Figure 6 Damper effect on structural responses under MSE conditions: a) input energy, b) displacement of top of Pylon 1, and c) displacement of top of Pylon 2
As shown in Figure 6 and 7a, the input energy of the structure increased in the bridge modeled with dampers. The displacement of the top of Pylons 1 and 2 in MSE and USE conditions decreased in the bridge modeled with dampers in comparison with that modeled without dampers. In the below table, the proportion of maximum responses of the bridge in conditions with and without dampers are presented.

Table 3 Proportion of maximum structural responses of the cable-stayed bridge with and without dampers under MSE and USE

<table>
<thead>
<tr>
<th></th>
<th>Excitation</th>
<th>Input energy</th>
<th>Disp. top Pylon 1</th>
<th>Disp. top Pylon 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>With damper</td>
<td>MSE</td>
<td>1.203</td>
<td>0.716</td>
<td>0.730</td>
</tr>
<tr>
<td>Without damper</td>
<td>USE</td>
<td>1.199</td>
<td>0.859</td>
<td>0.846</td>
</tr>
</tbody>
</table>

Table 2 shows that the damper was more effective in MSE conditions than in USE conditions. Dampers decreased the displacement of top of Pylon 1 by 29% and 14% in MSE and USE conditions, respectively. They decreased the displacement of top of Pylon 2 by 27% and 15% in MSE and USE conditions, respectively. Because MSE conditions are closer to real excitation of a long-span bridge, higher damper effectiveness in the MSE conditions than what the designers expected (USE condition) is promising.

5. CONCLUSION
The main intention of this study is to illustrate the influence of MSE on the effectiveness of viscous dampers. In this study, the Vasco da Gama cable-stayed bridge is used for a numerical study. MSE and USE effects on structural responses of cable-stayed bridges are investigated, and numerical results show that MSE effects on the responses of the bridge are not major.

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However, the effectiveness of the nonlinear viscous damper located between the pylon and the deck increases considerably under MSE, in comparison with USE conditions. Because the safety of bridges after an earthquake is vital, applying MSE condition to long-span cases is necessary, and designers should be regarded.

REFERENCES