Seismic Analysis of a Cable-Stayed Bridge Using the Finite Element Method.

Ali L. Abass¹, Zaid S. Hammoudi², and Haneen A. Mahmood²

¹ Department of Civil Engineering, University of Diyala, College of Engineering, Iraq
², ³ Department of Mechanical Engineering, University of Diyala, College of Engineering, Iraq

E-Mail: enghaneenamer@gmail.com

Abstract. In this paper, a cable-stayed bridge is modelled and analysed using the finite element method on Ansys. The damping effect is studied in the vertical and inclined directions as an earthquake effect is applied on the cable-stayed bridge in the longitudinal and lateral directions with changes to the number, direction, and value of the damping coefficient (c) of the dampers. The results show that increments in the number of dampers and damping coefficient in inclined dampers were more effective than changes to vertical dampers in longitudinal and lateral earthquakes.

1. Introduction

Cables are widely used as an element in structures capable of carrying tensile forces; however, cables may experience vibration problems as a result of their low damping levels. Problems caused by cable vibrations are critical to bridge design, as cable-stayed bridges can be exposed to vibrations due to wind, rain, traffic, and earthquakes. These unwanted vibrations thus require minimisation. The simplest way to control this situation is by using a base isolation technique by providing portable insulation and supporting the deck in all locations subject to vibration. In the past, a very limited number of practical research projects have taken place studying the seismic efficiency of cable-stayed bridges [1-3]. These studies have shown that isolation in cable-stayed bridges can minimise the induced forces of earthquakes on the bridge’s tower, but that it also leads to increases in the response of deck displacement. This can create a comfortable status for traffic, but as a result of the large displacement response of the deck, it becomes harder to prepare seismic gaps in the edges of the deck in the longitudinal direction. In such cases, additional damping alongside insulators can greatly help to minimise the spikes in the slabs and towers of suspended bridges. There are many types of passive energy dissipation devices that can be used to control the dynamic response of such structures. Most developments in the application of additional damping in bridges and buildings has occurred in the form of viscous fluid dampers, and the main approach is to maximise the high power dissipation capacity of the dampers [4]. However, there are many research models for the analytical and practical seismic isolation of buildings and bridges with viscous fluid dampers, and many studies have been carried out to illustrate reduction of bearing displacement and force, creating stronger structures [5-9]. The effectiveness of passive linear dampers and semi active structures used to control the earthquake response of cable-stayed bridges was investigated in [10]. In addition, semi active and similar approaches to the protection of bridges and buildings from earthquakes were illustrated in [11–16]. These included static ambient and dynamic field...
tests and observations of the long span Nissibi cable-stayed bridge. The results obtained from the ambient vibration, static, and dynamic loading tests were compared with the analytical results of the bridge. The effect of load number on the system response was also investigated [11]. The shape memory alloy (SMA) damping effect was studied in two facilities. SMA dampers also elastically minimise the maximum oscillation amplitude prompt by simulated action, as discussed in [17]. The single concave friction pendulum bearings (SCFP) damping effect on reducing earthquake effects on cable-stayed bridges was investigated in [14]. Seismic damping performance of the near fault NF seismic limiter referred to as a Roll-N- Cage (RNC) isolator was discussed in [15]. A new passive seismic control device for cable-stayed bridges made with SMAs and its performance was discussed in [16]. Non-linear NL-RHA and static pushover procedures available to cope with earthquakes, and their advantages, disadvantages and application in the non-linear seismic behaviours of cable-stayed bridges were studied in [17]. Magneto-Rheological (MR) dampers, used in a semi active Fazzy control technique to promote the seismic performance of cable-stayed bridges, were discussed in [18]. A device used for passive supplemental energy dispersion, a form of viscous fluid damper (VFD) used in association with elastomeric sliding isolation systems to form a passive hybrid control system was studied in [19]. A taut cable problem and its solution was discussed in terms of using an adaptable fluid damper as dictated by Maxwell model in [20]. A hybrid fibre reinforced polymer (FRP) cable with a theoretical damping model with smart damper design in a long span cable-stayed bridge was chosen for evaluation of its damping ratio in terms of the equations discussed in [13]. To improve the response of the structure in its longitudinal direction, the possibility of modifying the original bridge with different passive supplemental damping and seismic isolation systems was submitted and estimated for this purpose and an element model of the bridge and seismic analysis offered in [12].

The current authors note that earthquakes have begun to increase in frequency in Iraq, and the number of cable-stayed bridges there has also begun to increase. Two bridges were built and opened in 2017 in Al-Emara and Al-Basra, for example. Based on these factors, this research presents an analysis of a cable-stayed bridge using the Finite Element Method. By inserting earthquake effects in the longitudinal and transverse direction, the effects of damping using different types of dampers with varying damping coefficients and location will be investigated.

2. Description of Cable-Stayed Bridge

Cable-stayed bridges can be divided into four primary parts: cables, pylons, the bridge deck, and the boundary conditions. The Quincy Bayview Bridge consists of 56 cables in two planes along the bridge deck. The bridge is symmetrical about the y (vertical) axis. The mid span of the bridge is 274 m, and it is fringed by two side spans of 134 m each. The towers of the bridge are of 53.7 m height above the deck and reach 17 m below the deck. Two H type pylons support the bridge deck and the cables. The lower end of the cables supports the bridge deck, and the upper end of the cables connects at the top of pylon in a fan type connection. The pylons are supported by the piers, which are based under the water level. The ends of the bridge deck are supported by anchor piers.

3. Finite Element Modelling of Cable-Stayed Bridge

The case study used in this paper is the Quincy Bayview Bridge crossing the Mississippi river at Quincy, Illinois. The bridge consists of two H-shaped concrete towers with double plane semi harp type cables. The deck of the bridge is made of composite concrete and two I-steel girders. Further bridge description can be found in detail in Wilson and Gravelle [14]. For analysis purpose, the deck was divided into 30 elements, and the bridge tower was divided into 10 elements. Based on their geometry, the towers were divided into three parts. The finite element model of the towers is shown in figure 1b; the total number of cables is 28, distributed as follows: 14 cables to support the mid span and 7 to support each side span. The cables are spaced equally at 2.75 m c/c at the top part of tower. The relevant properties of the cables are given in Table (1). The finite element model of the Quincy Bayview Bridge was modelled with three different types of elements: shell element, truss element, and beam element. The cables were modelled as truss and beam elements with and without modified modulus of elasticity. The pylons were modelled as beam elements. The bridge deck was modelled as a composite structure, which consisted of shell and
beam elements. Figure 1 represents an overview of the finite element model of the Cable-Stayed Bridge. Figure 2a shows the three-dimensional modelling of the cable-stayed bridge.

![Figure 1. Details of cable-stayed bridge](image)

3.1. **Deck**
The floor of the bridge deck was modelled as four node shell elements. Each node of the element had six degrees of freedom with translations in the x, y, and z-direction as well as rotations about the x, y, and z-axes. The parapets and stringers, as well as the composite girders, were modelled as three-dimensional beam elements which also had six degrees of freedom in translation and rotation. Figure 2(a) represents the finite element model of the typical cross section of the bridge deck. In order to accurately model the structure, an equivalent cross section of the bridge was made.

3.2. **Tower**
Each pylon consists of two columns and two struts which were modelled as three-dimensional beam elements. The geometry of the pylons was divided into three different sections. In order to make a more accurate model, three cross sections of the geometric property were applied to the columns and one cross section of the geometric property was applied to the struts. Three-dimensional modelling of the towers is shown in Figure 2(b).

3.3. **Cables**
The cables of the Quincy Bayview Bridge were modelled as truss elements. A single truss element is a tension-only member. The elements have three degrees of freedom of translation in the x, y, and z-directions. Cables were modelled as 6-beam 181 elements with pre-stressed cables. The cross-section area of a link cable is shown in Table 1, where beam cables had areas the same as the link cable area.

| Cables number | Cross-sectional area (m²) | Young’s modulus (MPa) | Cable weight (N/m) |
|---------------|--------------------------|-----------------------|--------------------|
| 1             | 0.018                    | 205000                | 1765.80            |
| 2             | 0.0135                   | 205000                | 1324.35            |
| 3             | 0.0107                   | 205000                | 1049.67            |
| 4             | 0.007                    | 205000                | 686.70             |
4. **Boundary Condition**

The boundary conditions of a finite element model are always very difficult to make exactly the same as those in real structures. Thus, estimated boundary conditions were considered in this model. The connection between the piers and the pylons was considered as a fixed connection, and the connection between the cables and the bridge deck was also considered to be fixed. Based on the Engineering Drawing of Quincy Bayview Bridge, the connection between the bridge deck and the cables was allowed to rotate in certain conditions. The three-dimensional truss elements had no rotational resistances. Therefore, the difference between the fixed connection and the pinned connection can be ignored for modal analysis of this type of structure.

The base of the towers (in contact with the ground) was considered as fixed in all directions. Earthquake conditions were entered as acceleration to all nodes of the bridge. Figure 3b shows the boundary conditions of a cable-stayed bridge with cables modelled as 6-beam elements, while Figure 3c shows the boundary conditions of a cable-stayed bridge with cables modelled as single link elements.
5. Results and Discussion

Cable-stayed bridges were analysed statically by applying gravity loads onto the bridge models. The free vibration analysis of the bridges was thus studied. In this paper, the Mississippi bridge's dynamic analyses were studied in terms of two considerations. In the first, the cables were modelled as single link element, and in the second, the cables were modelled as 6-beam elements. The El Centro earthquake data was used for dynamic analysis, with the earthquake considered as acceleration on all nodes in a specified direction. The earthquake was applied first in the longitudinal direction, then in the lateral direction, as shown in Figures 4, 5, 18, and 19. Three nodes on deck were selected: node 1 in the middle.
of the first span, node 2 in the middle of the middle span, and node 3 in middle of the third span. The effect of the dampers on displacement in the x, y, and z directions for all three nodes was studied. Figure 4 shows the displacements (ux, uy, and uz) of the three nodes in the link element type cables of a cable-stayed bridge affected by applying an earthquake longitudinally without damping. The earthquake was inserted laterally on the link element cables, as shown in Figure 5. Figures 18 and 19 show how the earthquake was inserted on multi-beam element type cables of a cable-stayed bridge longitudinally and laterally, respectively.

In this study, viscoelastic dampers were used for damping with a base damping coefficient C=50,000 N.m/s, K=10,000 N/m. By changing the damping coefficient values ±50%, several types of dampers were studied.

Table 3 shows the damping effect of two vertical dampers between the deck and tower in a longitudinal earthquake, as seen in Figure 6, compared with that seen in Figure 4. The displacement (ux) of node 1 showed a clear damping effect, but as seen in Figure 9, uy and uz showed little damping. Figure 11 shows a clear damping effect on ux at node 3 with two vertical dampers. Figure 7 shows that the damping effect of two vertical dampers was clear on the uy of all three nodes, with no damping effect seen for a 12,500 N.m/s damping coefficient. Figure 9 shows that the damping effect of vertical dampers on the uy of node 2 was greater with a 50,000 N.m/s damping coefficient, as compared to the results in Figure 5. By increasing the damping coefficient to 75,000 N.m/s, the damping effect N.m/s on uy of node 2 became clear, as shown in Figure 11.

Table 4 shows the results of an analysis of link and beam cables with four lateral dampers in a longitudinal earthquake. In comparison with Figure 1, link cable without damping, Figures 12, 14, and 16 show that the damping effect of four inclined dampers with multi values of damping coefficient (25,000, 50,000, and 75000 N.m/s) have a small damping effect on ux and uy in all nodes. Figures 13, 15, and 17, as seen in Table 4 and when compared with Figure 5, show that four inclined dampers have a small damping effect on the ux of the three nodes at the varying types of damping coefficient (12,500, 50,000, 75,000 N.m/s), but that the damping effect of the dampers was clear on the uz of node 2 as shown in Figures 13, 15, and 17.

Table 5 shows the damping effect of two vertical dampers in link and beam element type cables with application of a lateral earthquake. Two vertical dampers with damping coefficient values 12,500, 50,000, and 75,000 N.m/s have little effect on the ux and uz of nodes 1, 2, and 3 compared with the results seen in Figure 18. In multi-beam element type cables, two vertical dampers have a small damping effect on the ux, uy and uz of all nodes as shown in Figures 20, 22, and 24.

Table 6 shows the damping effect of four inclined dampers with multi damping coefficient values for link and beam cables with a lateral earthquake. For link element type cables, four inclined dampers have a clear damping effect on the uy of nodes 1 and 3, as shown in Figures 21, 23, and 25. This effect can be seen in Figure 18. The damping effect of four inclined dampers was not clear on the ux in all nodes, as shown in Figures 24, 26, and 28; however, the effect of changing damping coefficient of dampers (12,500, 50,000 and 75,000 N.m/s) was clear on their uy. Four inclined dampers have a clear damping effect on uy and uz, as shown in Figures 25, 27, and 29.

Figure 32 shows the damping effect of two vertical dampers between the deck and towers with a damping coefficient 50,000 N.m/s on the mid span of the deck at node 413.
### Table 2. Damping effect of two vertical dampers on cable-stayed bridge with lateral earthquake.

|                      | One element of link cable damping | Multi-Beam element of beam cable damping |
|----------------------|-----------------------------------|-----------------------------------------|
| **Figure (4)**       | ![link cable longitudinal earthquake without damping](image1) | ![beam cable longitudinal earthquake without damping](image2) |
| **Figure (6)**       | ![25000 damping](image3)          | ![25000 damping](image4)                |
| **Figure (8)**       | ![50000 damping](image5)          | ![50000 damping](image6)                |
Table 3. Damping effect of four inclined dampers on cable-stayed bridge with longitudinal earthquake.

One element of link cable damping  Multi-Beam element of beam cable damping
Table 4. Damping effect of two vertical dampers on cable-stayed bridge with lateral earthquake.
Table 5. Damping effect of four inclined dampers on cable-stayed bridge with lateral earthquake.

| One element of link cable damping | Multi-Beam element of beam cable damping |
|----------------------------------|-----------------------------------------|

Figure (24) 75000 damping

Figure (25) 75000 damping

Figure (18) link cable lateral earthquake without damping

Figure (19) beam cable lateral earthquake without damping

Figure (26) 25000 damping

Figure (27) 25000 damping
Figure 4. Damping effect of dampers on mid span

6. Conclusions
In this research, a 3D cable-stayed bridge was modelled using Ansys 15.0 software, and an earthquake inserted longitudinally and laterally for beam and link element type cables without damping, with two vertical dampers, and with four inclined dampers using different values of damping coefficient. The results showed that four inclined dampers had a clear effect on the beam element type cables of cable-stayed bridges, and that dampers with damping coefficient 75,000 N.m/s had more effect on bridges those with other damping coefficient values.
The response of the deck to earthquakes with and without damping was discussed in terms of three spans. The results showed that the effects of damping systems depended on the type of dampers (damping coefficient value), direction of dampers (vertical or inclined) and the position of dampers (between deck and tower, in anchorage, and in cables). In addition, modelling of the bridge was discussed in terms of the element types of cables. The results showed that dampers have more effect on beam element type cables than link element type cables. These factors have a clear effect on cable-stayed bridges in terms of earthquake damping.

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