Seismic Behaviour of Cable-Stayed Bridges: A State-of-the-Art Review

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ABSTRACT

Bridges are civil works for which is required their structural integrity and accessibility after the occurrence of an earthquake. However, it is known that these systems are very vulnerable, as it was demonstrated after the occurrence of the earthquake events of San Fernando (1971), Loma Prieta (1989), Northridge (1994), Kobe (1995) and Taiwan (1999). Considering the existent typologies, cable-stayed bridges are, without question, a very important alternative, since they can be used for long-spans and they are, together with suspended bridges, the most impressive engineering works. Because of their importance, for span-lengths exceeding 200 m, a conservative design is desirable, being common to require an elastic or almost elastic structural response for the design earthquake of very low occurrence probability. Hence, requiring an elastic response and additional energy dissipation on the structural elements, it is possible to use active or passive devices for energy dissipation and seismic control. Born for military use, energy dissipation and base isolation devices began their incursion in the civil world quickly, improving the seismic behaviour of constructions and becoming with active control the new tendencies in seismic protection of any kind of bridges. This paper corresponds to an actualized state-of-the-art review about the seismic behaviour of cable-stayed bridges with special attention in the non-linear seismic behaviour, tower response and spatial variability effects. Incorporation of additional systems of passive protection and the use of new intelligent strategies based on hybrid and semi-active systems are the final part of this work.

Keywords: Cable-Stayed Bridges, Seismic Behaviour, Non-Linear Seismic Response, Tower Response, Spatial Variability Effects, Passive Protection, Semi-Active Protection, Hybrid Protection.

INTRODUCTION

Most of the damage done by earthquakes consists in the interruption of communication ways and other life lines. For this reason, it is very important that the security of life lines be high. Bridges are very vulnerable structures in that way, and essential for transportation systems, consequently the understanding of their seismic behaviour is fundamental. Cable-stayed bridges, due to their large dimensions and flexibility, usually experience very long fundamental periods, which is an aspect that differentiates them from other structures, and of course, that affects their dynamic behaviour. However, the flexibility and dynamic characteristics of that kind of bridges depend on several parameters such as the main span length, stay system and their layout, support conditions and many other things. This structural typology is complex, consisting on several structural components with different individual
stiffness and damping properties. They experience more flexibility than normal girder bridges, and consequently, need a detailed dynamic analysis for their seismic design. Thus, on cable-stayed bridges it is very important to accurately evaluate their periods, modal shapes and damping characteristics.

In general terms, the seismic behaviour of cable-stayed bridges has been very satisfactory, as collapses or severe damage have not been reported in the last years. The main damage reason has been differential motion at the supports, when the earthquake acts in the longitudinal or traverse direction, conforming today a special problem called spatial variability effects.

The application of the Vibration Control Theory on cable-stayed bridges began more than 20 years ago, with the incorporation of the first seismic isolation devices. Since then, their improvement has not stopped, but the incorporation of this technology to cable-stayed bridges has been slow. Many control devices have been tested applying analytic and/or experimental methodologies, but from a seismic point of view, only a few cable-stayed bridges include advanced protection systems, maybe due to their satisfactory performance during recent earthquakes and the lack of specific regulations for their design and construction. Thus, new passive protection technologies, introducing seismic isolation and energy dissipation devices, began to be used with seismic purposes only a few years ago, as in the Cape Girardeau Bridge (USA) and the Rion – Antirion Bridge (Greece). In fact, constant research and experimentation has allowed a great progress for the new seismic devices whose performance characteristics are better known, with more capabilities to be employed on large structures, according to the new tendencies. The application of semi-active and hybrid protection technologies to cable-stayed bridges has recently begun, mainly with studies and investigations related to the mitigation of cable vibrations. The improvement of Vibration Control has increased in the last years, and it is expected to continue growing.

SEISMIC RESPONSE OF CABLE-STAYED BRIDGES

General Dynamic Characterization

In general terms, cable-stayed bridges do not show much sensitivity to seismic excitations. However, it is clear that the main problems come at deck level with horizontal motion [Walter, 1999]. The vertical component has a great importance in the analysis and design of pylons and cables, but not for the deck, since in modern bridges it is supported by the cables that obviously constitute a lot of elastic supports.

Modal analysis results on cable-stayed bridges are discussed in many papers, with emphasis on the seismic behaviour. First vibration modes show a very long period, in the order of several seconds, and they are fundamentally deck modes. They are followed by cable vibration modes, coupled with the deck. The tower modes are usually higher-order vibration ones, which can be coupled with the deck depending on the support conditions. The obtained modes are classified according to their action direction: longitudinal, transverse and torsional direction, taking into account that one of them is predominant. Undoubtedly, the modes are very difficult to separate when they are sufficiently coupled [Morgenthal, 1999]. For typical cable-stayed bridges there are strong coupled modes (like bending and torsion) in the three orthogonal directions. This coupled motion makes the difference regarding suspension bridges, in which exists pure vertical, lateral and torsional motion, very easy to recognize. That implies carrying out a three-dimensional system modelling [Wethyavivorn and Fleming, 1987].

An exact analysis of natural frequencies and modal shapes on cable-stayed bridges is very important, not only for the study of the seismic response, but also for wind action and traffic loads. In general terms, cables are idealized as truss elements in a traditional finite element analysis. This method is simple but inadequate for a more accurate dynamic analysis of a cable-stayed bridge, because it does not consider the transverse vibration of the cables. Numeric and experimental results show that modelling of cables has a significant effect in the prediction of the dynamic characteristics of cable-stayed bridges. The discretization of each cable in series of single elements can help to predict an adequate vibration of them, as can be found in the work by Au et al (2001). Likewise, there is an
analytical study about the evaluation of natural frequencies at long-span cable-stayed bridges with “H” and “A” type towers, and considering different cable modelling [Bruno and Leonardi, 1997]. In this work, the strong dependency of the natural frequencies regarding geometric parameters is clear.

**Non-Linear Seismic Behaviour**

Due to their nature, long-span cable-stayed bridges have a predominant non-linear behaviour. The static non-linear analysis under dead loads is essential as a starting point for the non-linear seismic analysis, taking the deformed state for dead load in the bridge to analyze [Abdel Ghaffar, 1991]. For main span bridges longer than 600 m, geometric and material non-linear analyses are necessary when the structures are subjected to strong motions. Those material nonlinearities depend on the specific structure, but geometric nonlinearities are present in almost all cable-stayed bridges, especially in the stay cable sag effect, the compressive action in deck and towers, and the large deflections effect due to the flexibility of this kind of structures [Morgenthal, 1999]. In fact, the investigation developed by Ren (1999) gives a good analysis of the effects and importance of both kinds of nonlinearities on cable-stayed bridges.

At the present time, a lot of finite element software that takes into account nonlinearities in this kind of structures can be found. Thus, it is possible to consider the non-linear behaviour of cables by using *Ernst’s formula* or applying multi-cable element formulations. Non-linear behaviour of towers and girders, due to bending or compressive forces, can also be considered, keeping in mind the axial and bending stiffness. The complete change of the bridge geometry, as a third source of geometric non-linearity, can be considered through an incremental process, in which the structure stiffness is calculated starting from the previous nodal coordinates.

Material nonlinearities, which are very important in a push-over analysis, can be nowadays considered starting from the knowledge of material constitutive laws, and that of the hysteretic behaviour at the energy dissipation zones, in which new behaviour models based on load tests are continually proposed. The newest finite element software includes the possibility of considering this kind of analysis.

Ren and Obata (1999) have investigated the elastic-plastic seismic behaviour of long-span cable-stayed bridges using finite element modelling. They have considered the geometric nonlinearities coming from the stay cable sag effect, axial force-bending moment interaction and large displacements. Material nonlinearity arises when the stiffening steel girder yields. For the above-mentioned, the example bridge was a cable-stayed one with a main span length of 605 m, using in the analysis three strong earthquake records. The evaluation of the residual elastic-plastic seismic response was considered defining a new kind of seismic damage index called the *Maximum Equivalent Plastic Strain Ratio*. The results showed that the elastic-plastic effect tends to reduce the seismic response of long-span cable-stayed bridges. The elastic and elastic-plastic seismic response behaviour depends highly on the characteristics of the input earthquake records. Also, it is shown that geometric nonlinearity has little influence in the seismic response behaviour, even under strong earthquake record inputs. Fig. 1 is an example of a response comparison under the Higashi – Kobe earthquake.

![Figure 1. Comparison between Elastic and Elastic-Plastic Responses under the Higashi - Kobe Record](image-url)
Seismic Response of the Towers

The purpose of the towers is to support the cable system and transfer forces to the foundations. They are loaded with high compressions and bending moments that depend on the stay cable layout and the deck-tower support conditions. Towers can be made of steel or concrete, being the latter generally more economic considering similar stiffness conditions. However, their self-weight is generally higher than that of steel, which implies keeping in mind local soil conditions and construction speed when using concrete. Thus, the seismic response of the towers will be conditioned by several aspects, and in addition to the previous idea, the geometric shape of the towers, which depends on the applied loads, cable-stay system and aesthetic conditions, is a very important aspect. It is necessary to emphasize in the fact that concrete design is undoubtedly heavier, inducing higher seismic forces.

Hayashikawa et al (2000) have studied the non-linear dynamic behaviour and seismic isolation of steel towers of cable-stayed bridges under three-dimensional great earthquake ground motion. They have considered both material and geometric nonlinearities, using the tangent-stiffness iterative procedure to obtain the non-linear seismic response. They presented some numerical examples for three different tower shapes: A - type, H - type and gate – type models. Fig. 2 shows a general view of the chosen modelling and the applied tower typologies.

Figure 2. General View and Modelling of the Selected Towers

Natural periods, maximum displacements at the tower-top for the longitudinal direction and maximum curvatures show a tendency to decrease as longitudinal cable stiffness increases. Fig. 3 is an example of the above-mentioned.

Figure 3. Relationships between Natural Period, Maximum Displacement and Maximum Curvature with Spring Coefficient

Continuing with this investigation and based on vertical motion with friction, the effect of including a passive control device for the towers was studied (Fig. 4). Natural periods increased, mainly in the H and gate – type models. Defining \( L1 \) as the longitudinal direction and \( H1 \) as the transverse direction, a comparison of the natural periods, with and without energy dissipation, can be observed in Table 1.

Figure 4. Tower with Passive Control Device by Moving Vertically
Table 1. Calculated Natural Periods (sec) with Dissipation and Without Energy Dissipation

<table>
<thead>
<tr>
<th>Mode</th>
<th>System with dissipation</th>
<th>System without dissipation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Type A</td>
<td>Type H</td>
</tr>
<tr>
<td>L1</td>
<td>0.3229</td>
<td>0.3228</td>
</tr>
<tr>
<td>H1</td>
<td>1.0355</td>
<td>1.2535</td>
</tr>
</tbody>
</table>

The results of this investigation, with the incorporation of friction passive isolation, showed the effectiveness of reducing the reaction forces of the tower bases. The use of passive control in the towers shows a significant reduction of the induced forces if compared to the non-isolated case.

Similar studies, without seismic isolation, based on parametric investigations on the dynamic behaviour of cable-stayed bridges with type-H steel towers, investigated by Abdel Raheem and Hayashikawa (2003), have shown the individual influence of different design aspects, such as damping mechanism, input ground motion, tower modal shapes and the incidence of initial construction imperfections. The results showed that the horizontal beam height and length and the low yield energy dissipation system significantly affect the tower structural behaviour. The initial imperfections within design range have slight detrimental effects on the tower seismic response, but these effects grow rapidly beyond the design range.

Although construction of cable-stayed bridges using steel towers has currently become somehow obsolete, the selection of this tower-type cannot be only a structural decision but also aesthetic. Detailed studies taking place during the constructive phase have shown that steel towers are more expensive than those made of concrete. The metallic solution can be the answer in structures with central suspension, when the minimum required deck width is the factor that governs the bridge economy [Walter, 1999].

Spatial Variability Effects

Spatial variability of the ground motion is a well-known phenomenon, for which exists an extensive literature. This phenomenon has a special importance for long-structures, such as pipelines, bridges and tunnels; and it consists basically in a non-synchronous support motion condition, which is usually ignored. In a traditional analysis, employing seismic records or spectra, identical at all the support points, the situation is not important for the shortest structures, but becomes important when the structure is long, as occurs with long-span cable-stayed bridges. Spatial variability effects involve several mechanisms that have been identified: wave-passage effect, incoherence effect, site-response effect, attenuation effects of wave amplitudes with distance and seismic source extension effect. Considering all these phenomena, the three first ones are the most important effects, since it is known that the attenuation affect and geometric spreading of half-space, as well as the seismic source extension, have a low incidence on the spatial variability of long-span bridges [Ettouney et al., 2001].

In the case of long-span cable-stayed bridges, the studies began with the research developed by Abdel-Ghaffar in the early 80s. Regarding cable-stayed bridges, the multiple-support problem begins when the bridge is long with regard to the wave-lengths of the input motion in the frequency range of importance to its earthquake response, and then, different parts of the bridge may be subjected to significantly different excitations, which is a problem normally not important for buildings, with a complicated correlation of the motion at the support points [Abdel-Ghaffar, 1991]. In fact, in the case of a bridge with two supports, for example, 12 different soil motion components will be considered if the spatial variability effect is included, but if the analysis is done considering uniform motion, only 3 components will be included. Soyluk and Dumanoglu (2004) studied the spatial variability effects of ground motion on cable-stayed bridges using stochastic analysis. The ground motion was described by the power spectral density function (PSD), and the spatial variability was considered keeping in mind the wave-passage effect, site-response effects and the incoherence effect. Investigation results confirmed, once again, that spatial variability and propagation effects of ground motion have important effects in the dynamic behaviour of cable-stayed bridges and variability of the ground
motion should be included in the stochastic analysis. It was also observed that the wave velocity influences notably on the seismic response. On the other hand, total bridge displacements are governed by the dynamic motion component, as long as the pseudo-static component has an important influence on the spatial variability of the ground motion. Figures 5 and 6 show bending moments at the deck considering general excitation and uniform motion.

![Figure 5. Normalized Moment Variances of the Deck: (a) General Excitation, (b) Uniform Ground Motion](image1)

![Figure 6. Mean of Maximum Total Deck Bending Moments for Different Wave Velocities – General Excitation](image2)

Lin et al (2004) investigated the seismic spatial effects for long-span bridges using the Pseudo Excitation Method, applying this strategy to cable-stayed bridges, and considering the spatial variability through the wave-passage and incoherence effects, showing that wave-passage effect has a singular importance. Recently, Soyluk et al (2004) carried out a comparative study of several analysis strategies considering non-synchronous motion. They included different random vibration methods to evaluate the dynamic behaviour of cable-stayed bridges for a variety of ground motion wave velocities. The analyses results suggested that the structural response usually shows important amplifications, depending on the decreasing ground motion wave velocities.

**APPLICATION OF PASSIVE SYSTEMS**

The first studies about passive control on cable-stayed bridges began with Ali and Abdel-Ghaffar (1991). In these incursions, they proposed the use of lead rubber bearings (LRB devices) as passive control systems on cable-stayed bridges. The results of these investigations showed the convenience of using passive control devices such as those proposed; however, enhancement of the structural flexibility increases the displacements notably. The effect of having a lead core at the rubber supports (LRB) is like providing additional damping. Likewise, they concluded that distribution of seismic forces transmitted to towers, deck and cables depends on the position of the devices. In the same way, the arrangement of these supports at the abutments reduces the seismic forces on the towers. In 1995, the same authors carried out a similar research to the one done in 1991. In this new investigation, they proposed two different bridge models with double-plane harp and fan-type cables with incorporation of LRB and extrusion dampers as passive devices. A four-node isoparametric cable element was introduced and proposed for the idealization of cables, to take into account both in-plane and out-of-plane responses. In addition, the cable element takes into consideration the pretension effect, which is one of the features of cable-stayed bridges. For the deck and towers, four-node isoparametric beam elements were proposed, being formulated for general symmetric sections including multi-vent box sections, plate sections and cut-off corner tower sections, allowing large displacements, shear
deformations and curved configurations, with reduction of degrees of freedom associated with some deck types, such as box sections, where one beam element can represent the main girder. The general conclusion was that significant reduction in earthquake induced forces along the bridge can be achieved with energy dissipation devices in comparison with conventional connections. They also concluded that shorter span bridges are better candidates for a more effective application of the devices.

Niihara et al (1994) investigated the improvements in earthquake resistance of long-span prestressed concrete cable-stayed bridges by hysteresis dampers using time history response analysis. In this research, reductions in the displacement of the deck and the bending moments in the towers and piers were discussed, from the point of view of the stay cable arrangement and span length. They analyzed two stay cable layouts: semi-harp and harp-type. The analytic models, for the 400 m-span length bridge are shown in Fig. 7, while the shear force - displacement characteristics of the damper are shown in Fig. 8.

Results of this investigation showed that a semi-harp cable layout is more effective than the harp shape configuration for long-span PC cable-stayed bridges with hysteresis dampers. The latter increase the seismic resistance regardless of the span length. Fig. 9 is an example of the comparative results for the deck response considering the semi-harp and harp layouts, and for three support conditions of the deck: floating, fixed and damper type. It is evident a minor response when additional hysteresis dampers are added. The introduction of hysteresis dampers is clearly helpful for long-span bridges.

A more recent investigation done by Vader and McDaniel (2004), studied the influence of energy dissipating systems on the seismic response of cable supported bridges, by use of viscous and friction dampers inserted between the vertical shafts of the suspension tower, in models of the San Francisco – Oakland Bay Bridge main span for two bridge proposals: suspended bridge and cable-stayed one. Their performance in protecting the bridge under seismic loading was compared to that of the new shear link protection system. The effect of forward directivity was monitored to discover if pulse motion reduced the functionality of the dampers.
Friction and viscous dampers improved upon performance of the shear links at different tower protection configuration. Results suggested that forward directivity reduces performance slightly, but bridge tower top restraint has a larger effect on performance. Fig. 10 shows the results of the seismic response of the tower, considering the cable-stayed bridge proposal for the two proposed devices (viscous and friction damper), compared with the shear link, and taking into account two possible configurations: diagonal and toggle-braced.

The results of this research showed that friction dampers, considering diagonal configuration, work efficiently in the cable-stayed bridge model, even though, they generate very high shear forces, and therefore, viscous dampers are the best solution in this case. These last ones reduce bending moments and relative displacements in the tower. At the same time, they keep base shear forces near levels for the bridge considering the incorporation of shear link devices.

HYBRID AND SEMI-ACTIVE PROTECTION

Although active control on cable-stayed bridges was proposed for the first time in the late 70s, studies and applications began more than one decade ago, mainly focusing on the application of strategies to mitigate the effect of cable vibrations, due to aerodynamic effects, earthquake actions or loads induced by traffic (nowadays known as Active Tendon Control).

The first analytic and experimental studies on the application of active systems on cable-stayed bridges were realized by Schemmann and Smith (1996, 1998). The first study consisted in the realization of an experimental/analytic model of an actively controlled cable-stayed bridge, developed as part of an interdisciplinary and inter-institutional investigation project to investigate the effects of the active control on cable-stayed bridges under seismic action. The second work, based on the Jindo Bridge, South-Korea, studied some complexities associated with the modelling of cable-stayed bridges, such as non-linear behaviour and contribution of coupled higher modes with regard to the effectiveness of active control. The investigation was divided into two parts: the first one studied some modelling aspects, and the second part, some analysis issues. The results of the research showed significant reductions for the maximum internal forces, and by testing some possible configurations for the actuators, they concluded that actuators located near the mid-span were the best configuration.

The study showed that only the first order modes need to be controlled to reduce the displacement response; however, higher order modes are very important to reduce forces. On the other hand, control of coupled modes can increase the seismic response, and, specifically, forces. Fig. 11 shows some results for lateral displacements at the mid-span, under uniform seismic action.
Other recent strategies about the active control on cable-stayed bridges were proposed by Li et al. (2001) and Helduser and Bonefeld (2001). The first research studied the application of Active Mass Dampers (AMD), using the classical algorithm of linear control and applying it to the second Nanjing Yangtze Bridge, China; showing its effectiveness in reducing seismic forces, mainly due to the fact that it is enough to control the first mode to reduce lateral displacements significantly. The second work, introduced the use of electro-hydraulic actuators as a strategy for the active protection of cable-stayed bridges.

Actually, one of the most interesting semi-active control strategies on cable-stayed bridges is, without question, the application of controllable fluids. In relation to this, the employ of Magnetorheological Dampers (MRD) has a very promising future, because of the low operational energy required, as well as their good performance.

![Figure 12. MR Dampers on the Dongting Lake Bridge](image)

The work exposed by Chen et al. (2003) shows the only well-known practical application of these devices on cable-stayed bridges. MR dampers were applied to the Dongting Lake Bridge (China) as a solution to the wind-rain vibration (Fig. 12). The installation concluded in June 2002, constituting the first application to cable-stayed bridges. Actually, a lot of investigations with regard to MR dampers are being conducted, mainly to study their effectiveness on real structures and the best control algorithms.

CONCLUSIONS

Although several recent investigations have contributed to the earthquake-response analysis and design of cable-stayed bridges, it is still essential that more research be conducted on the subject to study other aspects of the problem. From the point of view of the investigation carried out, some conclusions and recommendations should be taken into account:

1. Until now, there exist a few investigations regarding the seismic response analysis of towers of cable-stayed bridges. The tower seismic response will depend, among other things, on its geometry and materiality. Parametric studies would be very interesting and well accepted by the scientific community, as well as comparative studies between steel and concrete typologies.

2. There is a lack of studies with regard to the vertical response of cable-stayed bridges. At the moment, there are some general investigations about the vertical seismic response of traditional highway bridges, but specific studies about cable-stayed bridges are inexistent. In fact, available data on near-field earthquakes indicate that vertical seismic motion can be greater than the horizontal one, and both jointly can become more than three or more times the design values. This denies the general recommendation that considers as maximum vertical effective acceleration, 2/3 of the maximum horizontal effective acceleration.

3. With regard to the passive protection of cable-stayed bridges, it seems that the effectiveness of the employed system strongly depends on the device used and its configuration, bridge geometry, earthquake nature and source distance. Aspects such as damping, effect of cable vibrations, influence of support conditions, soil-structure interaction and site-conditions, spatial variability effects and the seismic input are very important to the global response. The use of fluid viscous dampers, LRB devices and sliding dampers can be the future in relation to passive seismic protection. However, it is strongly recommended a major investigation with regard to their
behaviour, depending on the configuration and source distances, especially when they are located in high seismicity zones and the near-source effects are important.

4. The use of active devices is an attractive and interesting strategy for the seismic control of cable-stayed bridges. However, it is necessary a better comprehension of their behaviour and performance, specially their hysteretic characteristics and non-linear behaviour. In fact, the key for an adequate response is to benefit from a good control algorithm, low energy requirements and enough robustness. In this sense, it seems that MR dampers can be the future of active protection. Nevertheless, because of their inherent simplicity, robustness and better-known properties, passive devices are more frequently used.

REFERENCES


