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Eccomas Proceedia COMPDYN (2017) 2171-2180

ECCOMAS
Proceedia

COMPDYN 2017
6th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, M. Fragiadakis (eds.)
Rhodes Island, Greece, 15–17 June, 2017

THE EFFECT OF MULTI-ANGLE, SPATIALLY VARIABLE SEISMIC MOTIONS ON CABLE-STAYED BRIDGES.

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Keywords: Spatial Variability, Cable-stayed Bridges, Incidence Angle, Non-linear Seismic Behaviour

Abstract. *The spatial variability of the ground motion can be a key factor to the design of cable-stayed bridges to resist seismic actions due to the critical effect of the asynchronous movement that it introduces between the towers. Cable-stayed bridges are landmark structures consisting key parts of transportation networks and their integrity must be ensured even under extreme seismic events. This work examines the effect that spatially variable ground motions have on the towers of a cable-stayed bridge with 200 m main span. Two different orientations of the structure are examined in an attempt to shed light into the orientation-dependent seismic response of the towers. Additionally, three different propagation velocities of the seismic waves are adopted and the results are compared to those obtained under synchronous ground motions.*

Peer-review under responsibility of the organizing committee of COMPDYN 2017.
doi: 10.7712/120117.5558.17235

1 INTRODUCTION

Cable-stayed bridges present unique features in terms of interactions among their key structural components and modal couplings. They are flexible structures with long fundamental periods that fall in the region of low spectral accelerations and combined with their reduced number of supports, they are considered good candidates to resist the ground motion. However, their reduced damping [1] and their reduced mass compared to other types of bridges, makes them susceptible to seismic actions. Cable-stayed bridges have been associated with the social and economic growth of the surrounding areas and consequently their design must ensure adequate performance even against extreme seismic events. This is particularly important for the towers of these structures because the deck is isolated by the cable-system and the inertia forces developed during the earthquake are concentrated in these members. In fact, the design of the towers in bridges located in seismic-prone regions is usually governed by the ground motion [2].

One of the most critical and unpredictable characteristics of earthquakes is that seismic waves do not remain constant as they travel away from the fault. Their frequency content and amplitude are altered as they pass through successive soil media, and eventually they reach consecutive supports of long structures having a variable pattern, introducing this way differential movements to the supports of such structures [3]. This phenomenon is most commonly referred to as the spatial variability of the ground motion (SVGM) and has been extensively studied by many researchers; [4, 5, 6, 7, 8], among others. Spatially variable motions result from the combination of four important aspects [7, 9]:

- *Wave passage effect*, which refers to the difference in arrival times of the seismic waves to different stations and is accounted for by considering a finite value of the wave propagation velocity.

- *Incoherence effect*, referring to the loss of coherence of the ground motion due to several reflections and refractions of the seismic waves in heterogeneous soil media. It is expressed through the coherency function.

- *Local soil effect*, which is due to the local soil conditions and their effect on the amplitude and the frequency content of the ground motion. It is accounted for by assuming different soils at the supports.

- *Attenuation effect*, referring to the gradual decay of the amplitude of the seismic waves with distance as they travel away from the fault. This effect is deemed insignificant for the scale of man-made structures and is often ignored.

The SVGM is known to affect the internal forces of multiply supported structures but this effect has not been possible to predict beforehand [4, 9] due to the high unpredictability of the input ground motion. The differential movement of the supports can change the inertial forces in the structure and at the same time, additional pseudo-static forces are generated that are not present when synchronous motion of the supports is assumed [10]. Traditionally, the SVGM has been considered important only in longer structures and to this end, international code provisions such as Eurocode 8 - part 2 [11] provide critical lengths beyond which the SVGM should be considered. However, Nazmy and Abdel-Ghaffar [12] demonstrated that the SVGM can have a greater impact in relatively short cable-stayed bridges because of their increased stiffness in comparison to longer-span structures. Recently Efthymiou and Camara [13] compared the response of cable-stayed bridges with H-shaped towers and different span lengths under a set of completely coherent ground motions that only consider the time lag between supports (wave passage effect). Again, the results showed that the towers of short-to-medium-span bridges (200-400 m main span) may be more sensitive to the SVGM rather than the towers of longer bridges (600 m main span). This finding can be associated with the pseudo-static forces caused by the differential movement of the towers which are more pronounced in stiffer structures [14], questioning the code-based approach of considering only the length of the bridges and not their vibration modes when distinguishing which structures are sensitive to the SVGM. In addition, the asynchronism of the ground motion may be linked with the increased contribution of higher-order modes to the response [15], these modes being mainly antisymmetric [16] and with no relevant contribution to the response of the bridge under completely synchronous motions [17]. In fact, a recent study on a continuously monitored cable-stayed bridge with H-shaped towers and a 215 m main span, showed that dominant vibration modes that are excited under the assumption of uniform motion are de-amplified when non-uniform motions are considered [18]. Another aspect of the propagating seismic motions is the incidence angle of the seismic waves with respect to the structure. A number of studies have been conducted on the influence of this incidence angle on the response of bridges. Allam and Datta [19] studied the orientation of a cable-stayed bridge under uncorrelated ground motions parallel to the three principal directions and observed that maximum displacements were not obtained when the axis of the bridge was parallel or perpendicular to the seismic fault. This is also verified by Khan [20] who examined the effect of the incidence angle on the structural reliability of cable-stayed bridges. More recently, Taskari and Sextos [21] examined the effect of the direction of the wave propagation on the fragility curves of the piers of a constructed highway bridge and concluded that the seismic performance of this bridge is strongly influenced by its orientation with respect to the fault.

This paper presents a study on the effect of the SVGM on the towers of a cable-stayed bridge with H-shaped towers and a main span of 200 m. Two different orientations of the bridge are considered, parallel and perpendicular to the seismic fault, in an attempt to shed light into the non-linear response of the towers of such structures.

2 DESCRIPTION OF THE STUDIED BRIDGES AND THE SEISMIC ACTION

2.1 Geometry and modelling assumptions

The parametric models of cable-stayed bridges employed in this study are based on the work of Camara *et al.* [22]. The bridges are formed of two concrete towers with H-shape, a composite deck and two lateral cable planes in a semi-harp configuration. Intermediate piers are placed in the side spans to constrain the deck vertically. The complete bridge, including the sections of the towers, deck and cables are defined as functions of the main span length (L_P). This distance defines the length of the main span (L_S) and the height of the tower above deck level (H). The parametrisation process is summarised in figure 1. The width of the deck is 25 m and it is formed of two longitudinal I-shaped girders at the edges, connected by transverse I beams at fixed intervals to ensure the overall stability of the deck, and a 25 cm thick concrete slab on top. The deck is constrained vertically at the abutments and at the intermediate piers, it is restrained in the Y direction (perpendicular to the traffic flow) at the abutments and the towers and it is released both in the longitudinal (X) and the vertical (Z) directions.

Strong longitudinal and transverse reinforcement ratios of 2.4% and 0.8% respectively are assumed in the towers to ensure adequate concrete confinement. Regarding the properties of the materials used in this work, the concrete has a characteristic strength of 40 MPa, the structural and reinforcement steel has a yielding stress of 552 MPa and the prestressing steel has an ultimate stress of 1770 MPa. The elasticity moduli of the concrete, reinforcement/structural steel and prestressing steel are 35, 210 and 195 GPa respectively.

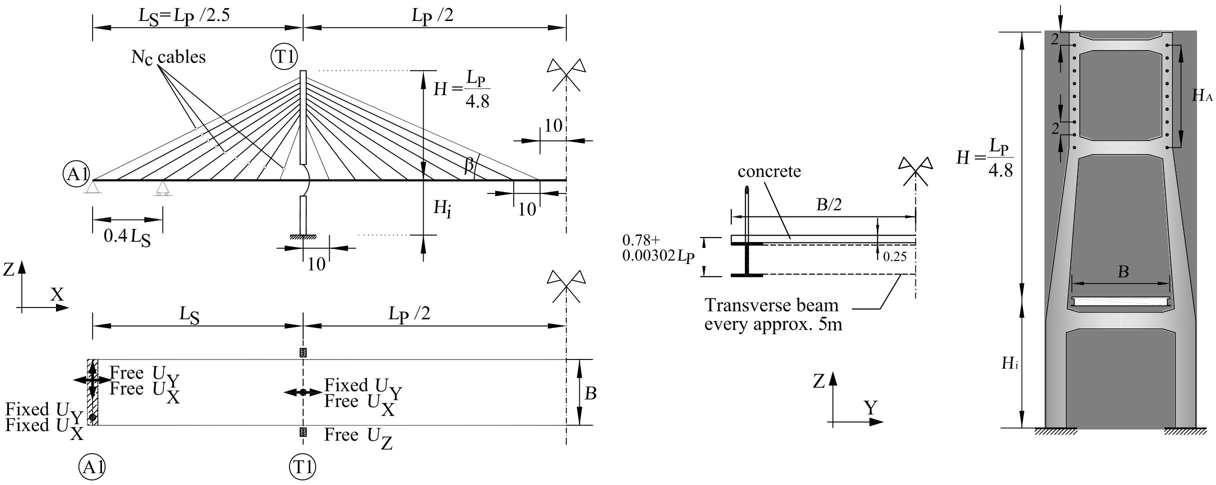

Figure 1: Parametric definition of the cable-stayed bridges.

The bridges are modelled using the FE software package Abaqus [23]. The deck is modelled with 'beam'-type elements through the centre of gravity of an idealised section that accounts for the properties of all the individual components forming the deck section, i.e. the longitudinal steel girders, the transverse steel beams, the concrete slab and the non-structural elements (cable anchors, railings etc.) (Figure 2). This 'simplified' deck section is adopted in order to reduce the computational cost of the analysis.

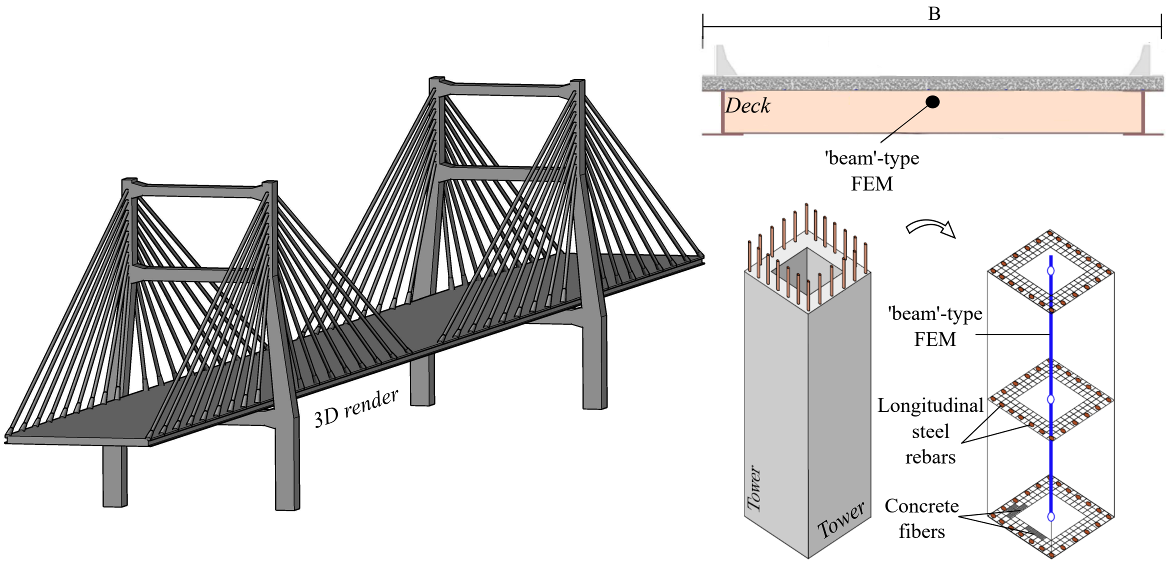

Figure 2: 3D model of the bridge and FE modelling of the deck and towers.

The towers are modelled with 'beam'-type elements through the centre of gravity of the section. The 'fiber-section' approach is adopted for each node of the tower's FEM, represented by concrete fibers and discrete rebars as shown in Figure 2. This consideration applies for the total of members composing the towers, the two legs and the transverse struts connecting them at multiple heights of the tower. For the cable system, each cable is represented by one element. Finally, the flexibility of the tower foundations is simulated with translational springs in the X, Y and Z directions. The springs' stiffness is assumed constant during the analysis and it is estimated by considering the foundation soil equivalent to Eurocode's 8 [24] Type D. The rotation of the towers is completely constrained.

For the analyses, the system of equations of dynamics is integrated step-by-step, using the direct implicit HHT algorithm [25]. The initial and at the same maximum time-step is 0.01 s, whilst it can be reduced down to 1e-12 s to achieve convergence. The structural damping is defined by using the Rayleigh theory, assuming a damping ratio ξ=2% to account for the reduced structural dissipation of cable-stayed bridges in the elastic range [1]. The damping factor is fixed for the first and last vibration frequencies of interest: 0.50 and 20 Hz respectively.

2.2 Seismic action

The seismic action is applied to the foundations of the bridges by means of ten sets of independent two-directional, horizontal acceleration histories. These are generated synthetically to match Eurocode's 8 [24] type 1 design spectrum for soft soil conditions (TD). To account for the two principal components of the earthquake, namely '*Fault Parallel*' (FP) and '*Fault Normal*' (FN) components, a reduced design spectrum by 70% is considered for the FP component [26]. The PGA is equal to a_g=0.5g and a reduced damping factor of ξ=2% has been assumed for the definition of the target spectra. Two different orientations of the bridges are considered; the bridge axis being $\{1\}$ parallel (θ=0°) and $\{2\}$ perpendicular (θ=90°) to the fault. For the SVGM, the wave passage effect is considered by assuming different wave propagation velocities in the range 250-2000 m/s to account for the propagation in different soils, and the incoherence effect is considered by employing the loss of coherency model of Harichandran and Vanmarcke [27]. The methodology proposed by Deodatis [28] is adopted for the generation of the spatially variable, independent sets of accelerations. Finally, each acceleration set consists of four two-directional accelerograms, that are applied to the four horizontally constrained supports of the bridge (abutments and towers).

3 DISCUSSION OF RESULTS

The results presented herein are post-processed to obtain the peak average seismic forces in the towers, excluding the self-weight. The results are presented in Figure 3 in terms of the peak seismic longitudinal and the peak transverse bending moments along the lateral legs of the towers. In each plot the black solid line represents the peak average seismic response from the synchronous motion of the supports, the coloured band around it shows one standard deviation centred in the average synchronous response and the remaining coloured dotted lines represent the peak seismic response from the different wave propagation velocities that are considered equal to; 250, 1000 and 2000 m/s. In this figure, the peak seismic longitudinal and transverse response is presented for the two towers of the bridge and for two different orientations of the bridge with respect to the seismic fault.

First of all, in can be noticed that the overall effect of SVGM on the response values is more pronounced in the longitudinal direction and not so critical in the transverse direction, which can be explained by the presence of the cable-system that connects the deck to the towers and hence, results in an increased stiffness in the longitudinal direction. Another observation is that the lowest propagation velocity (250 m/s) typically results in the most critical response when

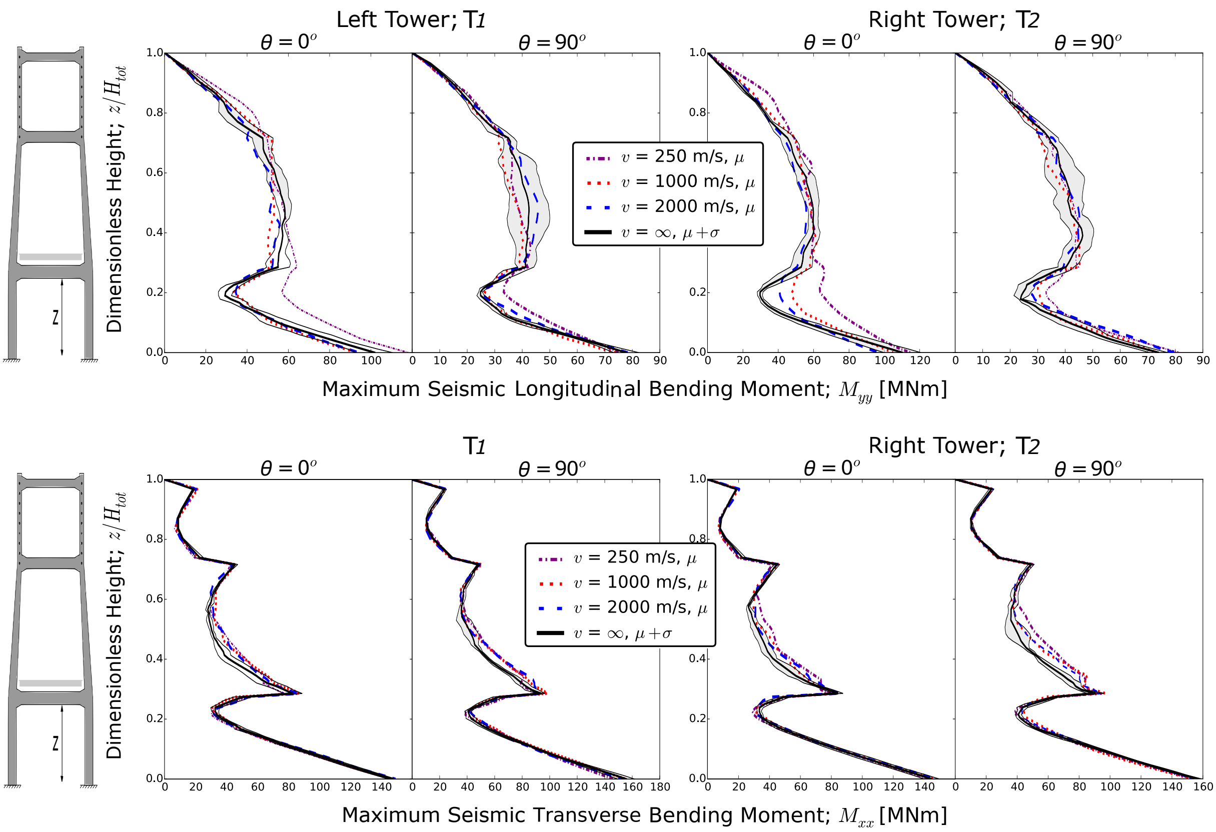

Figure 3: Peak seismic longitudinal (top) and transverse (bottom) bending moment along the left and right towers of the bridge with main span of 200 m. The moments are presented for three different wave propagation velocities and for two different orientations of the bridge with respect to the fault.

compared to the results from the synchronous motion. This can be attributed to the fact that for lower values of the wave propagation velocity the time lag between subsequent supports increases and, as a result, the differential movement of the two towers is more pronounced leading in the pseudo-static forces dominating the response. Additionally, it can be noticed that the effect of the wave-propagation velocity, and in a broader sense the effect of the SVGM, changes along the height of the legs. In the top row of this figure it can be seen that effect of the asynchronous motion is critical for the response at the level of the deck, but at the area of the legs above the deck level it is beneficial to the response. This verifies the unpredictable effect of the SVGM on the structures and it also suggests that different areas of the towers should be examined under the impact of spatially variable motions.

Looking at the different orientations of the bridge, it is noticed that in the longitudinal direction (top row) the seismic bending moment is maximised for θ=0° (i.e. the bridge being parallel to the seismic fault), whereas in the transverse direction the bending moment is maximised for θ=90°, verifying that the response is orientation-dependent.

When assessing the effect of SVGM on the response of the bridge, it can be seen that mostly in the longitudinal direction, the right tower; $T2$ (second tower to receive the seismic action) is more prone to receive damage from spatially variable motions. However, this is not the case in the transverse direction where the response between the two towers is almost symmetrical. This can be attributed to the cable-system which triggers movement in the second tower due to the longitudinal movements of the previous supports and before the earthquake has actually reached this tower. In the transverse direction the towers are not directly constrained by the cable-system and are free to oscillate independently.

In Figure 4 the peak deformation (positive in tension and negative in compression) of the longitudinal reinforcement bars in the tower during an earthquake is presented for the different wave propagation velocities and the different orientations of the bridge that are adopted herein. The maximum compression is recorded at the corners of the concrete and the maximum tension is obtained at the corner reinforcement bars. The elastic limits of compression and tension of the concrete and the reinforcement respectively are also presented in this figure. Cracking in the concrete is not admissible if the reinforcement yields in tension (i.e $\varepsilon_{tot} > 0.26\%$). It is noticed that the most critical sections in terms of yielding of the longitudinal reinforcement, are the base of the tower and the lower area of the cable system where the transverse strut is placed. From the viewpoint of the orientation of the bridge, the cracking is more severe for θ=90°. Finally, as far as the influence of the SVGM is concerned, the different propagation velocities result in different peak deformations compared to the results form the synchronous case. These, can be higher or lower than the deformation values from the synchronous motion case, depending not only on the value of the velocity, but also on the orientation of the bridge. It is interesting to note that for θ=0° (Figure 4, left plot), the SVGM results in higher deformations at the level of cable-system and with increasing velocities, the deformation tends to match the resulting values from the synchronous motion case, whereas for θ=90° (Figure 4, right plot) this pattern is not observed and in fact the deformation from c=2000 m/s is lower than the one recorded from the synchronous case.

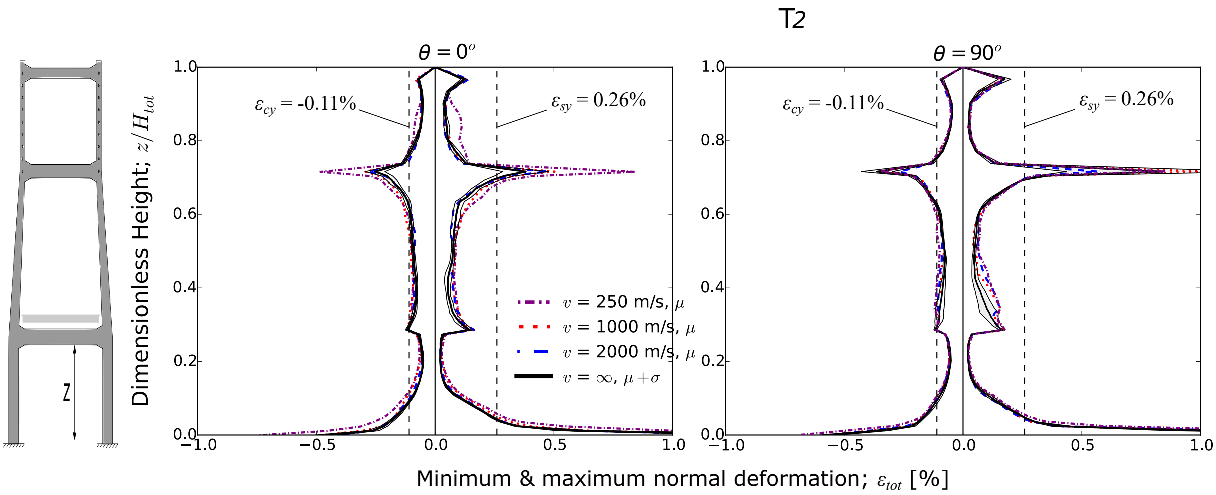

Figure 4: Peak deformation of the longitudinal reinforcement bars along the tower height. The deformations are presented for three different wave propagation velocities and for two different orientations of the bridge with respect to the fault.

4 CONCLUSIONS

For this paper, the non-linear seismic response of the towers of a cable-stayed bridge with H-shaped towers and main span of 200 m under the effect of spatially variable motions has been assessed. Different values of the propagation velocity of the seismic waves have been considered to account for the propagation in different soils along with two different orientations of the bridge with respect to fault. The main findings of this research can be summarised in the following:

- The wave propagation velocity is an important factor and may define whether the effect of the SVGM is beneficial or detrimental to the towers.
- The orientation of the bridge should be considered because different orientations results in different response values being maximised.
- The effect of the SVGM is more critical in the longitudinal direction due to the presence of the cable-system, and usually the second tower to receive the earthquake is the most critical between the two.
- The effect of the SVGM may differ significantly in different parts of the towers and hence the most critical sections should be examined when assessing the overall effect of the SVGM on the tower.
- The SVGM results in a different amount of damage in the tower that is dependent on the assumed value of the wave propagation velocity and also on the orientation of the bridge with respect to the fault.

ACKNOWLEDGEMENTS

The authors would like to deeply thank the Research Centre for Civil Engineering Structures and the Department of Civil Engineering at City, University of London.

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