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3D FINITE ELEMENT MODELING OF A HIGHWAY BRIDGE CONSIDERING THE EFFECT OF SOIL AND FOUNDATION

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Abstract. *It has been already shown through scientific research worldwide that the effect of soil-structure interaction should be investigated especially in the case of bridges with great importance or specific soil and structural characteristics. The most efficient way available nowadays to account for this phenomenon is by modeling the performance of soil, structure and foundation as a whole in the time domain. On the other hand, especially for the case of long, curved bridges, the issue of deciding a 'reasonable' incoming wavefield angle of incidence has not yet been scrutinized. Along these lines, the scope of this paper is to investigate the potential influence of the excitation direction of seismic motion in the case of such long, curved bridges, using the most refined finite element model practically affordable in terms of computational cost. For this purpose, the long (640m) and curved (R=488m) Krystallopigi Bridge is chosen and modeled using the general finite element program ANSYS accounting for soil-superstructure interaction (SSI) both at the location of piers and abutments. The parametric study of different ground motion scenarios performed, highlights the complexity of the phenomenon and the difficulty in determining a 'critical' angle of excitation for all response quantities and all piers at the same time especially in the light of soil-structure interaction. Moreover, the dispersion of the results obtained indicates that the impact of ignoring the influence of the direction of seismic excitation and the role played by SSI effects may be significant under certain circumstances.*

1 INTRODUCTION

The way in which the response of a structure, its foundation type and presence of the surrounding soil and the characteristics of the incoming earthquake input motion, are coupled during a strong seismic event is an extensively studied and complex physical problem of major practical interest. It is indeed widely known that soil-structure interaction (SSI) may modify significantly the dynamic characteristics of a system leading to a completely different (elastic or inelastic) dynamic response behavior compared to the one anticipated when considering fixed support conditions. Consequently, the particular phenomenon cannot be easily ignored in advance in the case of bridges with great importance or specific structural characteristics especially since a large number of damage cases reported worldwide can be attributed, at least to some extent, to the compliance and additional radiation and material damping at the soil-foundation interface.

Due to the complexity of the problem, the most common approach to take soil-structure interaction into consideration is through the uncoupling of the two main components of interaction, i.e. kinematic and inertial, and their subsequent superpositioning. Within this framework the foundation and the surrounding soil are replaced with appropriate for each stage springs and dashpots [1-2] while the response of the foundation itself is considered as the input motion for the (similarly supported) superstructure. It is noted that the same approach was also used by Sextos et al. for the case of the bridge that is studied herein [3] as it will be described in the following. On the other hand, modeling of the performance of soil, structure and foundation as a whole in the time domain using appropriate finite or boundary elements has always been a tempting approach; however, the inherent uncertainty in the spatial distribution of soil characteristics and earthquake ground motion as well as the computational cost related to modeling the propagation of seismic waves and ensuring appropriate stress distribution around the bridge foundation most often prohibit the development of large-scale finite element models for the study of the particular phenomenon. As a result, only few attempts to analyze the full soil-structure system have been performed so far for large bridge-soil systems (i.e. Humboldt Bay Bridge, [4, 5], Meloland Road Over-crossing Bridge, [6]) while such a 'holistic' finite element approach is still deemed unrealistic for any practical purposed.

Along these lines the scope of this paper is to utilize the currently available computational capabilities to investigate a physical problem that cannot be studied using the commonly made assumption of a fixed-base structure. In particular, to investigate the potential influence of the excitation direction of seismic motion in the case of long, curved bridges in the light of interaction between soil-pier foundation-pier - superstructure as well as soil-abutment-superstrucure. The reason for such an investigation is that despite the fact that numerous researchers have studied the importance of the incidence angle of earthquake excitation in the dynamic response of structures, the effect of soil compliance and damping on the relative sensitivity of a bridge to the direction of its excitation is typically not studied. As a result, the conclusions drawn based on theoretical approaches (such that of Penzien and Watabe [7]) or response spectrum analysis [8-13], linear time history analysis [14] or on nonlinear analysis in the time domain [15-17] cannot be easily extrapolated for the case of large soil-foundation-bridge systems. Torsional sensitivity of a structure is an additional parameter that adds to the complexity of the problem as for some irregular buildings it has been shown [18-20] that the importance of the adopted direction of seismic excitation is strongly coupled with the contribution of the excited torsional modes of vibration and the subsequent nonlinear response of the structure. Moreover, the current seismic design framework (i.e. EC8-Part2 [21] and Greek code E39/99 [22] referring to bridges) is unclear as to the principal axes of excitation especially for the case of curved bridges, hence, the designer cannot easily quantify the uncertainty related to the selection of the 'appropriate' direction of base excitation, which at the end and given the overall uncertainty, is usually assumed parallel and perpendicular to the chord for the two seismic input components respectively.

For this purpose, the long and curved Krystallopigi Bridge described below was adopted for study utilizing a large soil volume and investigating parametrically various scenarios of seismic wave angle of incidence. The description of the bridge configuration as well as the comparative results of the direction of excitation impact ignoring or considering soil-structure interaction as presented in the following.

2 OVERVIEW OF THE BRIDGE STUDIED

The Krystallopigi Bridge is a long curved structure that crosses a valley, as a part of the EGNATIA highway in West Macedonia region in Greece studied in detail by Paraskeva et al. [23] while its response has been also evaluated for spatially variable earthquake ground motions [24]. The structure comprises of two curved but parallel sections; however, this study focuses on the left branch of the bridge which is a twelve span structure of a total length of 640m. The two outer spans of this branch have a 44m length each while the ten inner spans have a 55m length. The curvature radius is equal to 488m and its deck width is 13m. The slope of the structure along the bridge axis varies (from 2.9% to 5.12%) while the deck transverse slope is constant and equal to 6%. A prestressed concrete box girder section is used for the deck while the piers consist of rectangular hollow reinforced concrete sections which in the pier top range are formed as solid rectangular sections for practical reasons (e.g. anchorage of prestressing cables). The structure is supported on eleven piers (M1-M11) of height that varies between 11 and 27m. For the end piers (M1, M2, M3, M9, M10, M11) a bearing type pier-to-deck connection was adopted, allowing movement in the longitudinal direction but restricting movement in the transverse direction, while the interior piers were constructed as monolithically connected to the deck. Foundation soils are in general composed of soft (v_s=250m/sec) to moderate stiffness (v_s=400m/sec) layers, as well as stiff limestone formations (v_s=1800m/sec). A number of piers are supported on groups of piles while others on surface foundations; their configuration and length depends on the foundation soil properties. Specifically, the abutments A1 as well as piers M1-M9 are supported on 1.2m diameter group of piles which cross the surface clay layer up to the level of submerged limestone while abutment A2 is directly founded on the stiff limestone outcrop.

3 MODELING OF THE BRIDGE-SOIL SYSTEM

Both the Krystallopigi Bridge and the near field soil were modeled in 3-Dimensions using the general purpose finite element program ANSYS [25] and the inherent-language APDL (ANSYS Programming Design Language) [26]. The particular programming approach elaborates the reversibility of the finite element model developed and the effective management of the post-processing data resulting from the parametric analyses performed.

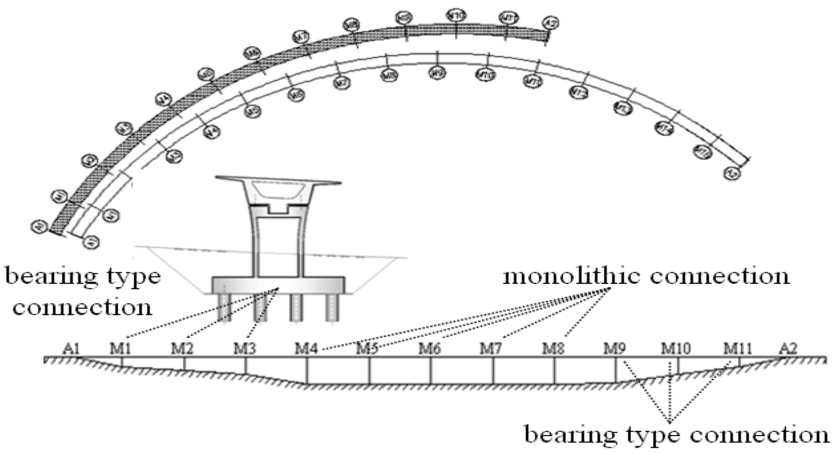

Figure 1. Layout of the bridge configuration

Superstructure

The deck and the piers, which sections vary along the bridge and the piers axis respectively, were modeled with 3-Dimentional beam elements. A dense grid of beam elements was generated at the pier-deck connection range as well as at locations of abrupt deck or pier section dimensions. As a result, 220 beam elements were used for the deck discretization while 8-10 beam elements were used for each middle pier. It is noted that the line (beam) pier elements were connected to the (solid element) supporting pile cap through appropriate coupling equations in order to ensure realistic stress transmition and distribution as illustrated in Figure 2.

Soil domain

As already mentioned, the foundation soil is composed of clay, debris and limestone layers of different height along the bridge. In order to be able to uncouple the relative impact of the direction excitation from the inherent uncertainty related to the variation of soil properties with soil depth and bridge length, the soil domain was simulated as homogenous and characterized by a uniform mean value of modulus of elasticity that was taken equal to 30MPa. A 700mx240m soil domain was generated with depth varying from 2 to 40m depending on the actual topography. The need to incorporate the exact pile group configuration and length below each pier and to model soil –to-pile and pile-to-pile dynamic interaction, essentially determined the finite element mesh geometry at the vicinity of the bridge. As a result, a dense grid of 8-node brick elements (Solid185 ANSYS type, 3 DOF per node) was adopted for an area twice as large the pile group dimensions, gradually leading to a coarse mesh grid of 20-node solid elements (Solid186 ANSYS type, 3 DOF per node).

Foundation and abutments

During the finite element modeling of the system an effort was made to incorporate the effect of embankment-abutment-superstructure interaction since it has been shown both numerically and through measurements from bridges in California that not only the stiffness and damping of the system is strongly affected but also the incoming input motion maybe significantly amplified [27]. Along these lines, the embankment of the left abutment (i.e. A1) was modeled in detail along a critical length of 50m. It is noted that there was no reason to replicate the aforementioned discretization approach for the right abutment (i.e. A2) as well since, according to the geotechnical study available, it was founded on stiff limestone formations. The superstructure to abutment interaction on the other hand, was taken into account with the use of appropriate gap elements (ANSYS type Link10) while full contact was assumed between abutment and embankments. As noted previously, 3-Dimentional beam elements were used for modeling the foundation piles, the length of which essentially coincides with the dimensions of soil mesh at the vicinity of the pile group

Boundary conditions

Appropriate dashpots with values depending on soil characteristics were implemented on the lateral surfaces of the soil domain in order to diminish reflections of waves on the particular boundaries [28] with the exception of the area of abutment A2 due to the aforementioned physical restraint provided by the supporting stiff outcrop. Similarly, the base of the model was also fixed to elaborate uniform acceleration earthquake input of the system for various angles of enforced base excitation.

Analyses type

As it is well known, higher frequencies and mode shapes of the spatially discretized equations generally do not accurately represent the dynamic response of such a complex system in the framework of transient analysis. Moreover, filtering of high frequencies is not always accurately performed while algorithmic damping provided by Newmark's method often leads to a lower level of accuracy [29]. For this reason, the Hilber-Hughes-Taylor integration method was used with an integration constant α=-0.30 in order to obtain an unconditionally stable, second order accurate scheme. Rayleigh damping was also implemented with appropriate constants (a=0.91 and b=0.003) so that the overall system damping in the range of frequencies of interest would vary between 5 and 10%.

Earthquake Input motion

As a means to quantify the effect of seismic motion incidence angle on the dynamic response of the particular bridge studied, two horizontal and perpendicular ground acceleration components were imposed simultaneously along the structure's axes by assuming a gradual rotation of the excitation vector around the z-z (vertical) axis. For this purpose, five different earthquake scenarios were investigated based on the records obtained from the Lefkada, Thessaloniki, Kozani and Athens earthquake and an artificially generated motion compatible with the Eurocode 8 elastic response spectrum as seen in Table 1. The base excitation (i.e. at the base of the soil medium) was computed after appropriate deconvolution and baseline correction process for both the horizontal components. Site response, in terms of the amplitude and frequency amplification of seismic waves as they propagate through the soil medium, were taken into account inherently by the structure of the 3-Dimentional soil domain, hence, no specific analysis had to be performed for this purpose. It is only noted that for simplicity, soil was considered as linear elastic; consequently, as it is shown in the following, it was the relative effect of angle of incidence that was studied and no absolute values of displacements or bending moments were directly compared.

Parametric analyses scheme

Having modeled the particular soil-foundation-structure system and generated the earthquake input motion scenarios a parametric scheme was adopted, employing different angles of base excitation (i.e. 0° to 180° at a step of 15°) for all the aforementioned five seismic scenarios. This procedure was applied twice, one considering the entire soil volume beneath and around the bridge and one assuming fixed base conditions at the bottom of all piers and abutments, as an effort to investigate whether inclusion of soil-structure effects does modify the response patterns observed or the 'critical' (most detrimental) angle by rotating the vector of excitation.

For the sake of comparison, a reference excitation angle (θ=0°) was adopted corresponding to the simultaneous excitation along the chord and the perpendicular to the chord axes of the curved bridge under study. By obtaining the results of the reference analysis which henceforth will be named θ=0 analysis, the analyses are repeated for all scenarios for the alternative cases denoted as θ=i analysis, where i is the incidence angle of earthquake excitation with respect to the reference coordinate system. Based on this assumption, the effect of the direction of excitation is expressed in terms of the orientation effect ratio $r(\theta_i)$ [14] for both the displacements and the member forces. Apparently, the particular ratio is equal to the deck absolute displacement or the pier base bending moment resulting from a θ=i analysis, divided to the deck absolute displacement or the pier base bending moment respectively for the θ=0 analysis:

$$r\left(\theta_i\right) = \frac{max\left|R_{\theta\neq 0}\left(\theta_i, t\right)\right|}{max\left|R_{\theta=0}\left(t\right)\right|} \tag{1}$$

where i=0° to 180° at a step of 15°, $max|R_{\theta\neq 0}(\theta,t)|$ is the maximum response value under θ≠0 excitation and $max|R_{\theta=0}(t)|$ is the maximum response value under θ=0° excitation. A value of this ratio that exceeds 1.0 represents the unfavorable case of displacement or bending moment increase, values that exceed 1.0 are deemed beneficial. After analyzing the five different seismic scenarios for the bridge-soil and the fixed base system, the orientation effect ratios of displacements and member forces were derived. From all the results obtained, which can be found in detail elsewhere [30], the deck displacements which are perpendicular to the curved bridge chord at each pier location as well as the pier base bending moments around the strong and the weak pier section axis are presented and discussed herein.

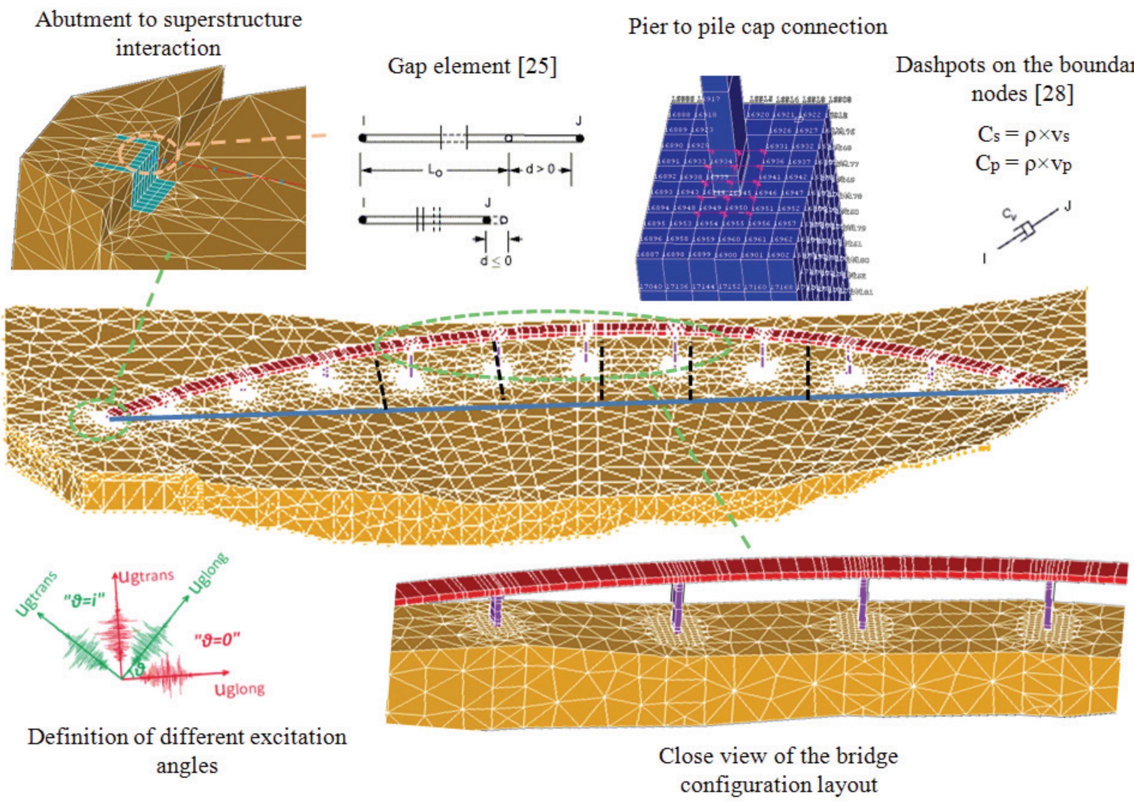

Figure 2. Finite element model of the Krystallopigi Bridge and definition of excitation direction

SCEN	Seismic event	Magnitude	PHA (m/sec^2)
1	Kozani (1995)	5.2Mw	2.05
2	Athens (1999)	6.0Mw	1.58
3	Lefkada (2003)	6.4Mw	4.12
4	Thessaloniki (1978)	5.12Ms	1.43
5	Artificial acc.	-	2.40

Table 1 : Reference seismic excitation scenarios

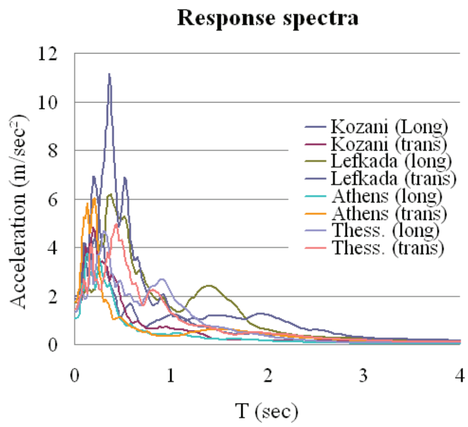

Figure 3. Response spectra of the earthquake records used.

4 ANALYSES RESULTS

Figures 4 to 7 as well as 8 to 11 present the numerical results for the soil-structure and the fixed-base system respectively. Each radar type diagram illustrates the value of the orientation effect ratio $r(\theta_i)$ for the (perpendicular to the bridge chord) deck displacements at the location of the piers and the abutments for each excitation angle studied (i.e. 0° to 180° at a step of 15°). The size of the radar type line essentially reflects the impact of different angles of excitation (further from the center at values larger than 1.0 correspond to detrimental displacement increase) whereas the shape of the polygon shows whether the observed increase is uniform for all angles or occurs for specific directions of base excitation. At first it can be clearly noted that the influence of the direction of excitation is different for each deck point examined but also different depending on the characteristics of the earthquake motion (scenario) studied. For instance (Figures 4-7), the deck displacements at the position of pier M9 due to the Athens earthquake seems to be rather independent of the excitation angle and the reference earthquake used (effect ratio always close to 1.0), whereas displacement of the deck at the location of pier M4 present ratio which exceeds the value of 3.0 for particular excitation directions (i.e. 90°) and specific scenarios (Athens earthquake).

As a consequence, a single value of a 'critical' angle of wave incidence or a 'critical' earthquake frequency content that leads uniformly to a global reduction or increase in displacements cannot be defined. The lack of a stable 'critical' angle of base excitation is clearly shown in Figures 12 and 13 where it can be observed that the most detrimental angle of incidence varies in an unpredictable manner for all piers and all earthquake scenarios studied. This observation is in agreement with previous studies [14] and is also valid for pier base bending moments as it is shown elsewhere [30].

It is interesting to notice that the same conclusion can be drawn for the case of the fixed-base system (Figures 8-11). Again, the orientation effect ration can be grater or lower to unity dependent on the angle of excitation studied, the action effect studied, the earthquake scenario and the location of the bridge. But in contrast to the refined finite element model that accounts for soil-foundation-bridge interaction, the critical combinations that lead to maximum response values are completely different. As reason for such a distinct behavior between the flexibly and rigidly fixed structure is that different dynamic characteristics of the curved bridge lead to different interplay patterns between the structure, the earthquake input and the direction of its application. Other analyses [30] indicate that on average, the covariance of the orientation effect ratio for the fixed-base system (if seen as a gross measure or the error introduced when studying the particular bridge solely on the basis of two horizontal components along the chord and its perpendicular axis, that is ignoring the importance of the direction of excitation) is of the order of 0.20. Similar covariance is observed for the soil-structure system as well; however the individual set of orientation ratio $r(\theta_i)$ values that lead to the (same) covariance present a completely different distribution among the piers. As a result, it is deemed that not only the assumption of a single direction of excitation might hide significant aspects of the complex dynamic response of a curved bridge, but also even a refined approach in terms of direction of excitation that neglects the role played by the soil may be proven a significantly unconservative.

5 CONCLUSIONS

This paper aims to investigate the potential influence of the excitation direction of the seismic motion on the dynamic response of curved bridges (with emphasis in the long and curved in plan Krystallopigi Bridge), using a refined finite element model that accounts for the interaction between the approach embankment, the abutment, the surrounding soil, the foundation and the bridge structure. Through the parametric analysis performed that involved a set of five ground motion scenarios, the following conclusions were drawn:

- The typical analysis approach for the case of curved bridges in the time domain according to which a single direction of base excitation is adopted, may lead to unconservative estimates of seismic demand for specific piers and action effects and hide significant aspects the bridge complex response.
- Excitation of such a curved bridge along the θ=0° or 90° degrees is proven not necessarily the most critical, as one might have anticipated for the longitudinal and the transversal dynamic response respectively; a conclusion also in agreement with other researchers [14, 17].
- The determination of the critical excitation angle that would lead to uniformly detrimental deck displacements or pier stress increase cannot be easily defined (or might even not exist at all) since the distribution of the orientation effect ratio along the piers for various angles of incidence and earthquake characteristics does not follow a predictable manner. However, one might be tempted to notice that this distribution is not completely random since almost all resulting response increase polygons presented in Figures 4-11 essentially resemble a circle with a center that is shifted from the origin. It is therefore feasible to claim that despite the overall problem uncertainty, the gradual modification of the excitation direction leads to equally gradual (and definitely not random) modification of the response.
- In order to obtain an reliable estimate of the maximum member forces and displacements of a curved bridge excited in the time domain, the designer has to perform analyses for various excitation angles between 0 and 180 degrees.
- It is unrealistic to adopt refined procedures regarding the ground motion characteristics and its angle of incidence if soil-structure-interaction effects are not modeled properly.
- It is considered that the effect of the excitation angle should be studied more thoroughly starting from the extrapolation of the parametric scheme described above, for the case of other equally realistic bridge configurations.

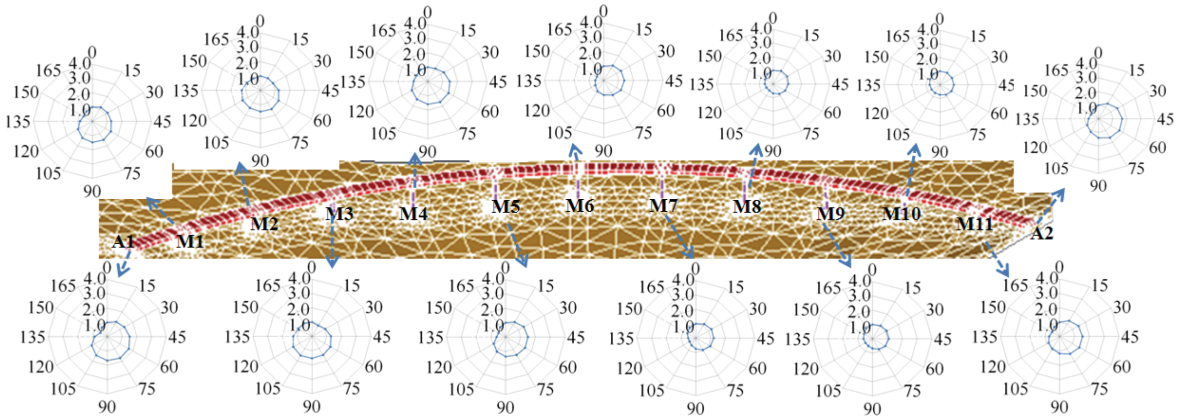

Figure 4. Effect ratios $r(\theta_i)$ of deck displacements-perpendicular to the bridge chord (Kozani earthquake)

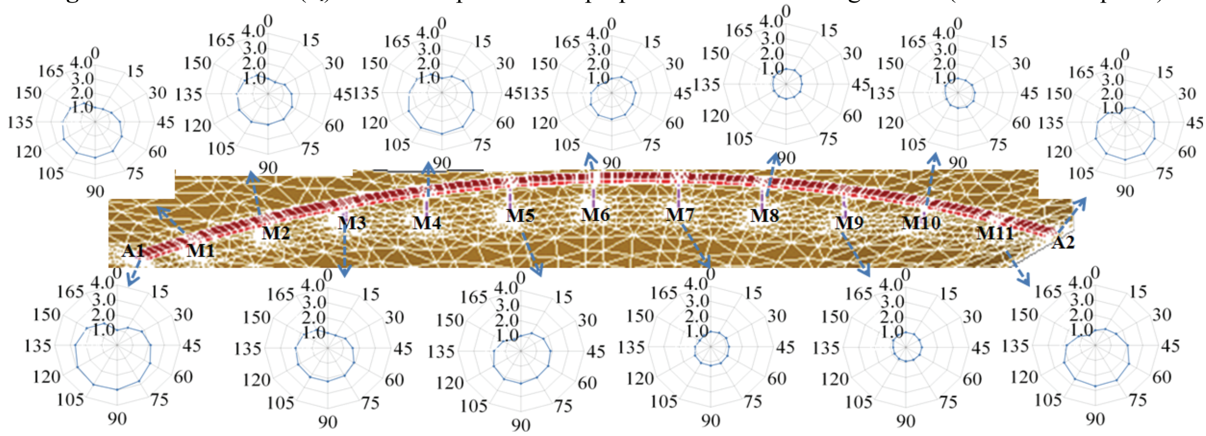

Figure 5. Effect ratios $r(\theta_i)$ of deck displacements-perpendicular to the bridge chord (Athens earthquake)

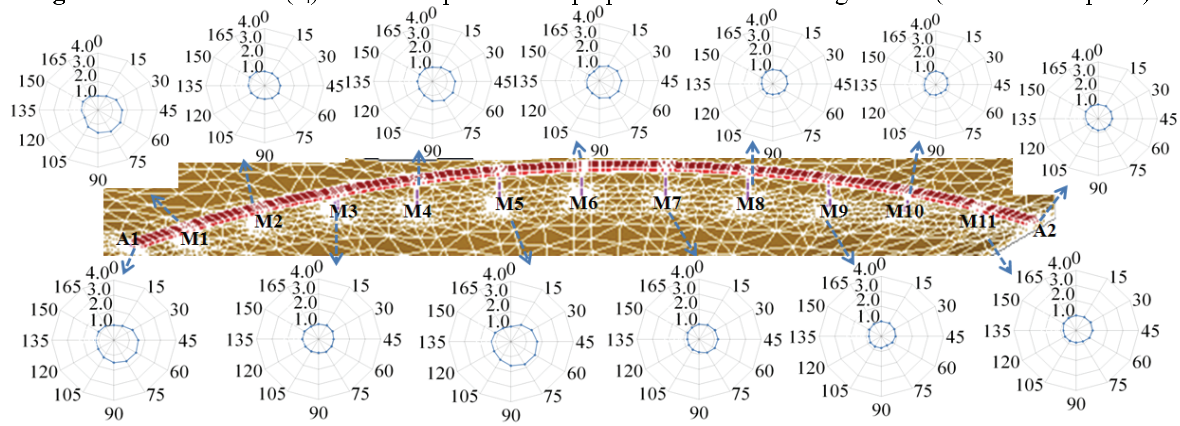

Figure 6. Effect ratios $r(\theta_i)$ of deck displacements-perpendicular to the bridge chord (Lefkada earthquake)

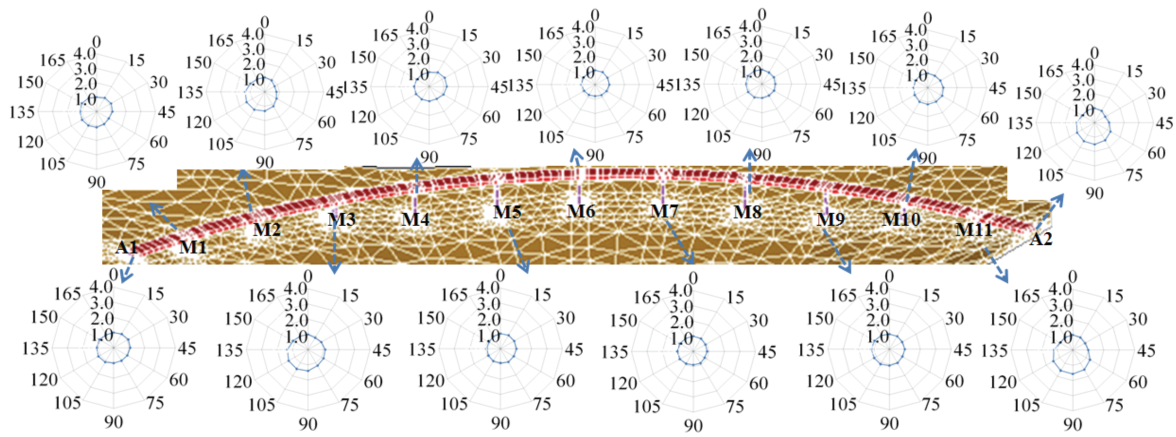

Figure 7. Effect ratios $r(\theta_i)$ of deck displacements-perpendicular to the bridge chord (Thessaloniki earthquake)

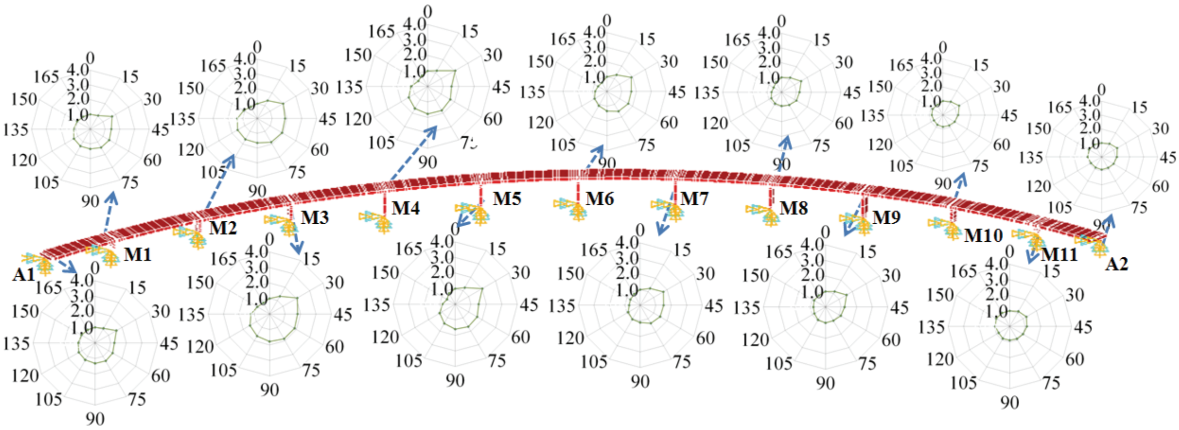

Figure 8. Effect ratios r(θ$_i$) of deck displacements-perpendicular to the bridge chord (Kozani earthquake)

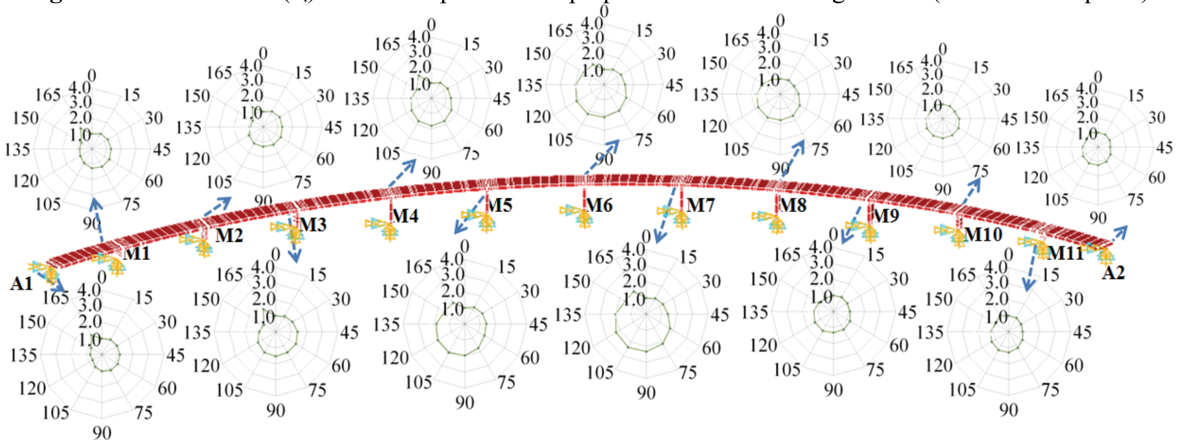

Figure 9. Effect ratios r(θ$_i$) of deck displacements-perpendicular to the bridge chord (Athens earthquake)

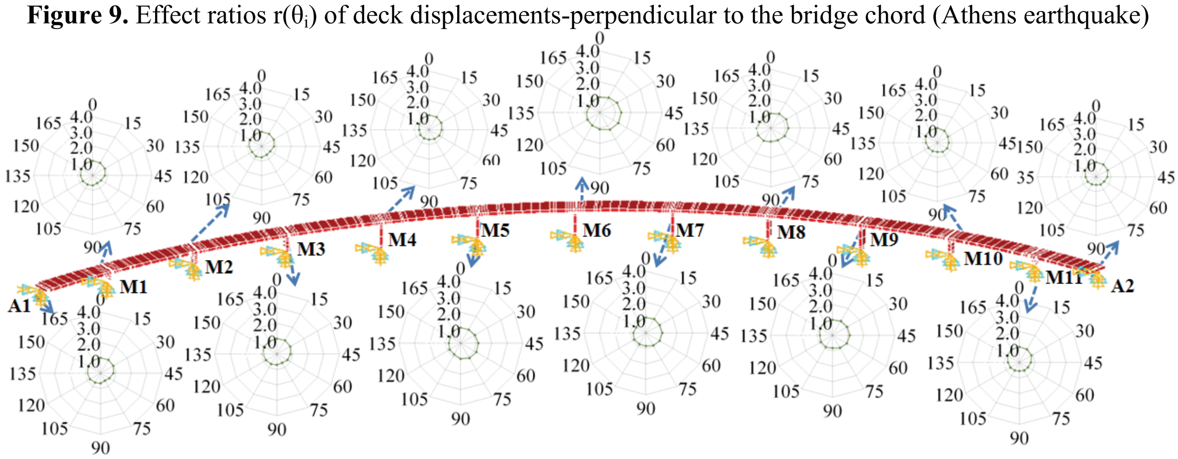

Figure 10. Effect ratios r(θ$_i$) of deck displacements-perpendicular to the bridge chord (Lefkada earthquake)

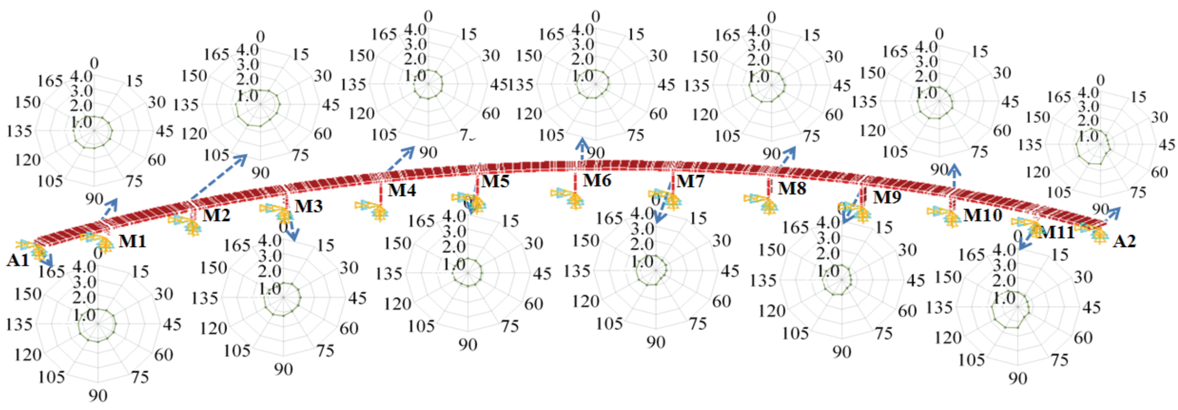

Figure 11. Effect ratios r(θ$_i$) of deck displacements-perpendicular to the bridge chord (Thessaloniki earthquake)

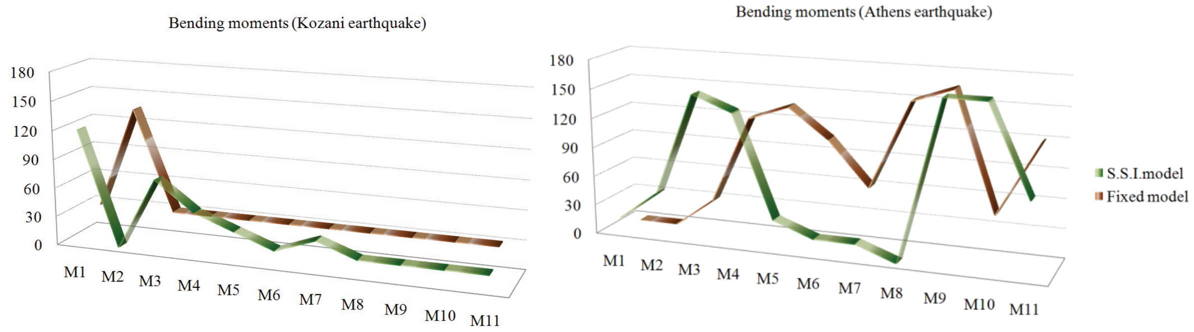

Figure 12. Critical angle of incidence for pier base bending moments (Kozani and Athens earthquake)

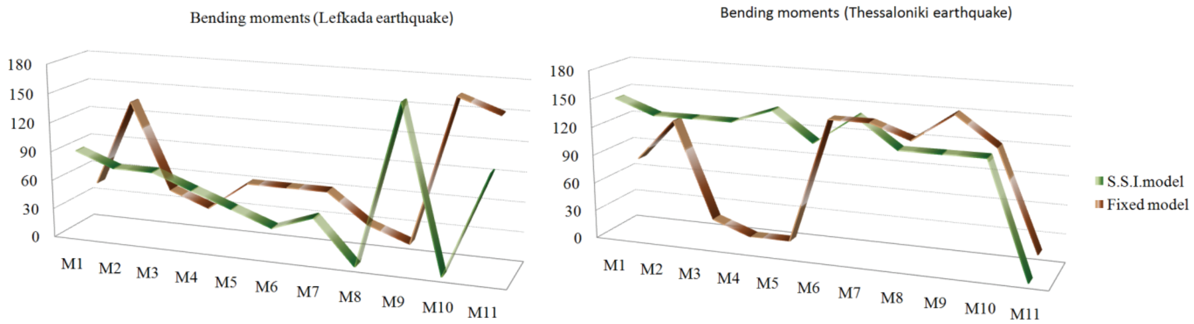

Figure 13. Critical angle incidence for pier base bending moments (Lefkada and Thessaloniki earthquake)

6 ACKNOWLEDGMENTS

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