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Sensitivity of the Seismic Response of Long Medieval Walls to Earthquake and Material Uncertainty

SEXTOS Anastasios[1,a], STYLIANIDIS Kosmas-Athanasios[1,b] and MYKONIOU Konstantinos[1,c]

[1]Aristotle University of Thessaloniki, Thessaloniki, Greece

[a] asextos@civil.auth.gr, [b] kcstyl@civil.auth.gr, [c] mykoniou@civil.auth.gr

Abstract: The scope of this paper is to illustrate a strategy for assessing the seismic performance of medieval city walls with emphasis on the Byzantine Walls of the city of Thessaloniki. Despite the relatively simple structural system of such structures, their response under earthquake excitation in 3D space and in the time domain, has not yet been adequately studied primarily due to the lack of efficient numerical tools, the high computational cost associated and the uncertainty related to the spatial variation of material properties and seismic input motion characteristics. Nowadays, the advances in scientific knowledge and the increase in computational power, the ability to efficiently conduct sensitivity analyses and the deeper knowledge of earthquake engineering aspects, provides the opportunity for a more refined simulation and study; however, such approach still remains heavy enough and as such, unsuitable for all practical purposes. Along these lines, a comprehensive computational framework is established and presented herein that aims at quantifying the relative importance of the uncertainty associated with modeling parameters, structural and soil material properties, as well as the earthquake ground motion selection process and application assumptions, the latter refering to the consideration of different angles of incidence of the incoming seismic wavefield and the spatially variable nature of ground motion that excites asynchronously the particularly long historic structures. It is foressen that this detailed 3D dynamic analysis will assist in identifing the relative impact of earthquake characteristics and material properties, permit justified simplifications and facilitate the overall process undertaken by the authors to assess the seismic history of the city of Thessaloniki through a set of detailed back analyses of well-selected parts of the extended wall cirquit.

Keywords: Byzantine walls, spatial variability of earthquake ground motion, angle of incidence of seismic waves, mechanical property

Introduction

This paper aims to investigate the relation between the dynamic response of a 150m long, irregular in plan Byzantine Walls complex (Fig. 1) located in the city of Thessaloniki in Greece and the direction of propagation of the incoming earthquake motion, taking into account the influence of the spatially variable nature of the incident seismic waves and the inherent uncertaintly of the mechanical properties of the structure. The approach that was followed, involved the conduction of elastic dynamic analyses of a 3-Dimentional Finite Element model of the structure in the time domain, for multiple angles of incidence of the incoming wavefield and simultaneous action of the two seismic motion's horizontal components.

Figure 1: Aspects of the Wall complex under study

Considering the asynchronous excitation, each supporting base point of the computational model was excitated with a distinct ground displacement as a function of time and space along two different axes. This is indeed a particularly multi-parametric and complex physical problem for a number of reasons: (a) first, it has been shown (Sextos and Kappos 2008, Stylianidis and Sextos 2009) that the angle of the seismic waves' incidence affects substantially the elastic dynamic performance in the time domain of irregular in plan Wall circuits, a fact that has been also shown in the case of curved bridges (Burdette et al. 2008), (b) such historic structures are typically stiff (and hence of short fundamental period) a fact that amplifies the importance of the pseudo-static component of their dynamic response and hence it yields them more sensitive to the excitation of higher (primarily antisymmetric) modes (Tubino et al. 2003, Sextos et al. 2003); a phenomenon that is amplified due to the abrupt geometry change of the structure both in plan and height (c) it is difficult to provide a realiable estimate of the mechanical properties of the monument and the spatial variation of its strength and stiffness not only due to its extensive geometry but also due to its layered construction. Along these lines, the scope of this paper is to investigate the relative importance of earthquake motion and material charracteristics on the dynamic response of the specific and similar wall structures, in order to permit the justified simplification of the problem, the reduction of computational demand and the subsequent stochastic treatment of the aforementioned inherent uncertainty. This effort is also considered as part of an overall process which aims at assessing the seismic history of the city of Thessaloniki through a set of detailed back analyses of well-selected parts of the extended wall cirquit.

Mechanical Properties of the Walls

The construction materials of the Wall under study vary substantially along both its length and its various sections since the latter consist of alternate layers of stones and external bricks at both facades, filled with rubbles. In order to obtain a statistical estimate of the variation of material properties, a series of non-destructive tests were performed in situ leading to the assessment of the compressive strength of the (weaker and hence more ctitical) intermediate mortar layer. It was observed that the construction of the Wall complex under study during two clearly distinct historical periods (i.e. Byzantine and Ottoman) had a noticeable impact on the measured mortar strengths. In particular, the more recent parts of masonry construction of the Ottoman era were characteriszed by significantly higher mortar compressive strengths (i.e. mean value of 3,96MPa MPa compared to 1.88MPa of the Byzantine part). Since Eurocodes do not provide any guidance for the case of similar construction, the new Italian structural regulations NTC08 for masonry were used and the corresponding values of stiffness (in terms of the Young's modulus) and unit weight of masonry were obtained for further use in the finite element discretization of the system. In order to compensate for the dispersion of the measured material properties and the overall uncertainty in the definition of the structural strength and stiffness, two bounding sets of values were adopted corresponding to masonry stiffness of (a) 1.1GPa for the Byzantine part and 1.5GPa for the Ottoman part and (b) 1.4GPa and 1.95GPa respectively. A parametric analysis scheme was then developed considering the characteristics of ground motion as will be shown in the following.

Modeling of the Walls

A 3-Dimensional Finite Element model was created with the widely used commercial program ANSYS (ver.10) for the study of the static, modal and transient response of the structure, which was modeled with 7800 higher-order, 20-node, hexahedral solid elements of three (Ux,Uy,Uz) degrees of freedom per node. Due to the complexity of the geometry and the fine discretization, the structure was considered as purely linear elastic and the primary emphasis was given on the macroscopic dynamic response of the system under simultaneous asynchronous excitation along two horizontal axes. Another reason that did not permit inelastic dynamic analysis was the extent of the monument, as well as the lack of reliable material data for the entire length of the structure. Therefore, both local material and geometric non-linearities (inclusive of cracking, crushing and sliding at critical locations) were not considered. The system was also assumed as fully fixed at its base and soil compliance was ignored for simplicity, since static spring values are in any case inadequate to reproduce the interaction between soil and structure and the introduction of (frequency-dependent) point specific spring-dashpot systems would substantially increase the computational cost.

Earthquake Scenario

The two horizontal components of the seismic motion recorded at the city center (Ms=6,5, PGA=0,15g, Ambrasseys et al. 2000) during the earthquake that stroke Thessaloniki in 1978 were taken as the reference motion and were appropriately deconvoluted to the bedrock level at the location where the records were obtained (i.e city center) based on geotechnical data from the Microzoning study of Thessaloniki (Anastasiadis et al. 2001). Further, a non-linear site response analysis was conducted using the computer code Cyclic-1D (Elgamal at al. 2002) for the site of interest, based on the soil stratification data at the location of the Wall. Given the resulting displacement time histories on the free surface, the response of the structure was assessed for an earthquake scenario corresponding to an average return period of 475 years and random angles of incidence of the incoming motion were considered, under the condition of similar frequency content with the chosen ground motion.

Consideration of Spatially Variable Nature of Earthquake Ground Motion

The sources of the spatial and temporal variations of seismic motion have been well identified (Der Kiureghian and Neuenhofer, 1992) as related to the fact that: (a) waves travel at a finite velocity, hence they arrive at consecutive support points with a time delay; (b) waves gradually lose their coherency in terms of statistical dependence and correlation with distance and frequency, due to multiple reflections, refractions, and superpositioning that take place during propagation and (c) local site conditions hence result to wave amplification and alteration of frequency content especially in cases that they vary substantially along the length of the monument. Herein, from the above three factors of the asynchronous ground motion, only the first was explicitly taken into consideration. This was due to the fact that despite the overall length of the Walls under study (i.e. 150m), the projected length along the wave propagation axis was relative small, thus the local site conditions could be safely regarded as uniform. Furthermore, observations made in previous studies (Sextos and Kappos, 2008), primarily focusing on the effect of spatial variability on bridges, came to the conclusion that incoherency is not a critical parameter for the dynamic response of structures with overall length lower than 200m, unless significant soil variations were evident. The excitation of each base node of the structure was therefore derived analytically as shown in equations (1) and (2) for random angle of incidence of the incoming wavefield (Fig. 2) and was programmed internally in ANSYS in order to be considered automatically during analysis runtime. This approach permited the excitation of the finite element model with node- and time-dependent displacement time histories $U_{i,x}$ και $U_{i,y}$, for all the 1850 supporting base points:

$$U_{i,x}(x_i,y_i,z_i,t)= U_{ref,x}(x_{ref},y_{ref},z_{ref},t-(x_i+x_p)/V_{app.})\cdot\cos\theta +U_{ref,y}(x_{ref},y_{ref},z_{ref},t-(x_i+x_p)/V_{app.})\cdot\sin\theta \quad (1)$$

$$U_{i,y}(x_i,y_i,z_i,t)= U_{ref,x}(x_{ref},y_{ref},z_{ref},t-(x_i+x_p)/V_{app.})\cdot\sin\theta+U_{ref,y}(x_{ref},y_{ref},z_{ref},t-(x_i+x_p)/V_{app.})\cdot\cos\theta \quad (2)$$

where x_i, y_i are the coordinates of a given base point i, $U_{ref,x}$, $U_{ref,y}$ the two component seismic motion at the reference point, V_{app} is the apparent velocity of seismic waves, θ is the angle of incidence of the incoming motion and x_{ref}, y_{ref} the coordinates of the reference point which was considered as the earthquake point source (and excited by the surface motion that resulted from the site response analysis and the target earthquake scenario).

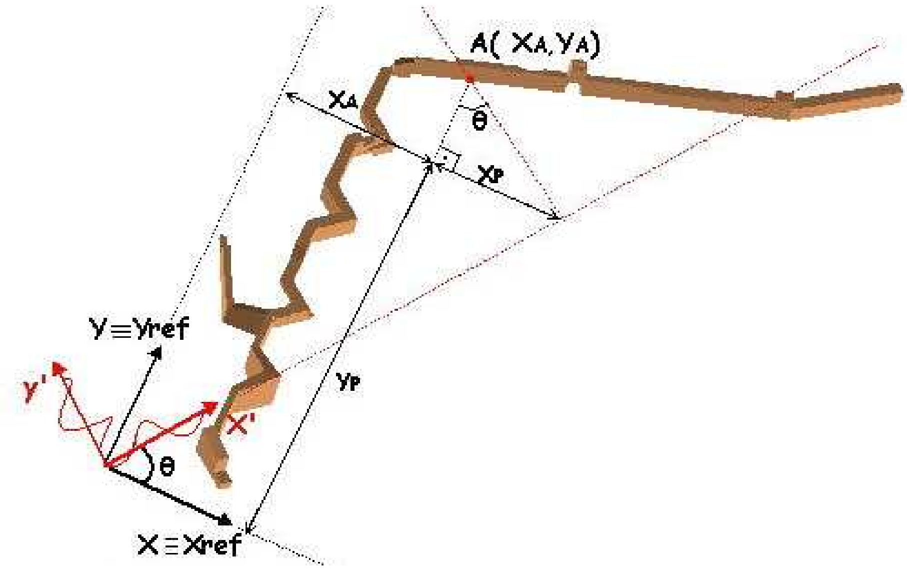

Figure 2: Estimation of the time- and space-dependent earthquake excitation of the structure's base nodes for various angles of seismic wave incidence

In order to visualise the analysis results, the response quantities derived from the analysis (i.e. stresses and displacements) for various angles of seismic waves incidence (θ=j°) were compared to those corresponding to the reference case of excitation at zero angle (analysis θ=0°). It has also to be noted that such diagrams could have been drawn for all the thousant nodes of the finite element model but such an approach was practically unrealistic, hence characteristic nodes were carefully selected in order to belong to the three most critical sections of the masonry structure where the maximum stresses were observed both in space and time. Along these lines, the four characteristic points presented correspond to locations near openings (point 'A'), base of the wall (points 'B' and 'D') as well as of abrupt change of structural geometry (point 'C'). The above procedure was then repeated for the second set of analyses corresponding to the upper bound of the masonry compressive strength (and stiffness). The extreme tensile stresses for multiple angles of incidence of seismic motion (θ=0°-180°) for the two bound values of masonry stiffness (denoted as 'material 1' and 'material 2') are depicted in Fig. 3.

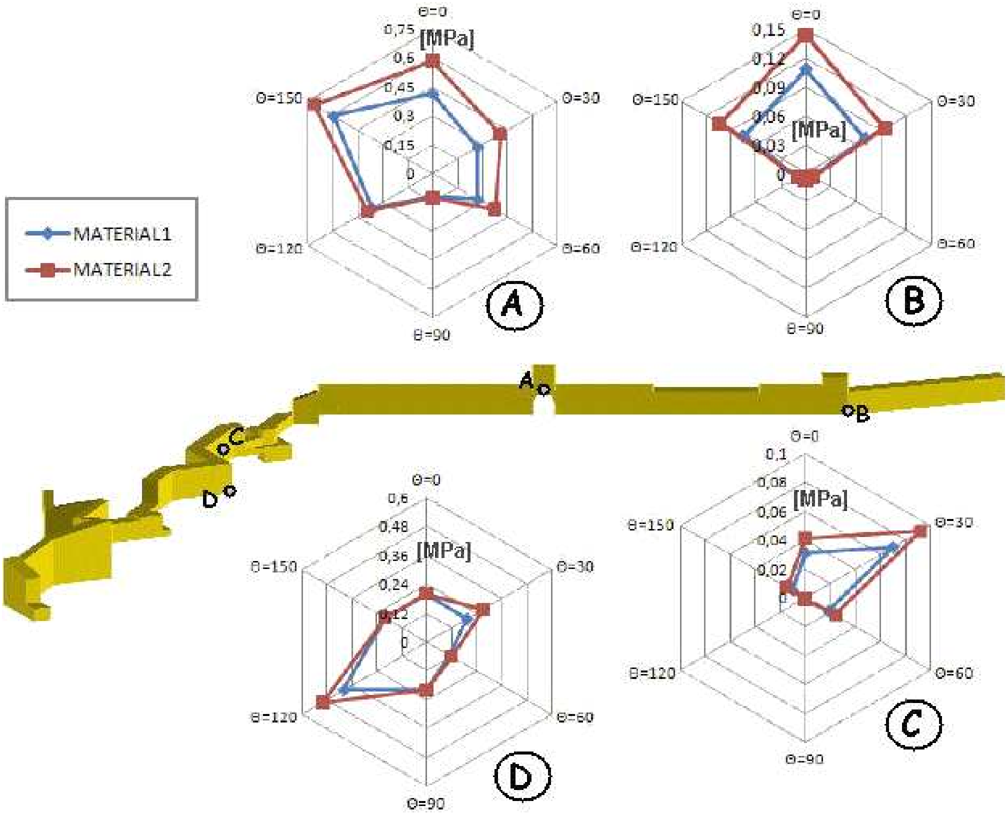

Figure 3: Extreme tensile stresses for multiple angles of incidence of seismic motion (θ=0°-180°) at four characteristic locations for two bound values of masonry stiffness.

From the above figure it is shown that the alteration of seismic wave direction of propagation may lead to up to 100% (points 'C' and 'D') of maximum stress increase compared to the maxima observed for the case of the reference angle. This increase can also be smaller (25%) for the case of point 'A' or not observed at all. On the contrary, significant reductions are also evident compared to the θ=0˚ case (i.e. maximum in time stress values at the most 'favourable' angle correspond to the 25% of the reference ones for point 'A', 10% for point 'B', 90% for point 'C' and 25% for point 'D'). As a result and as also has been observed in the case of seismic response of bridges under excitation at various incident angles, a single, critical angle for which the tensile stresses are uniformly maximized or minimized cannot be defined in advance. At the same time for a *given*, *constant* angle of seismic waves incidence, the reduction of maximum in time stresses when adopting the softer material properties (i.e. 'material 1') compared to the (higher stresses) of the upper stiffness bound case ('material 2') do not exceed 20% on average for all four points under study. Given the above and notwithstanding the limitations of the (unique and undoubtedly specific) case study, as a rough estimate it can be claimed that decisions made regarding the direction of earthquake excitation have a more significant impact on the dynamic response of the particular Wall complex compared to the prediction of the 'exact' material properties. As such, a seismic hazard analysis for defining the most probable direction of excitation given specific active faults is considered necessary for the assessment of the seismic behaviour of similar complex and extended wall structures.

Conclusions

The main conclusions that can be drawn were summarized as follows:

- It is not possible to a-priori define a single critical angle of seismic waves incidence for the assessment of the Walls' seismic response and capacity.
- The elastic dynamic response of the structure shows an intense sensitivity on the selection of the angle of incidence of the incoming wavefield independently of the stiffness assumed.
- In the framework of the process proposed, the spatially variable nature of the incoming seismic waves should not be neglected, since it was shown (as for bridges, pipelines, dams and other stiff and extended structures) that the excitation of higher modes may impose significant pseudo-static forces on the structure that did not develop under synchronous excitation;
- The angle of incidence of the incoming wavefield is a crucial parameter for the system's seismic performance and the coupled effect with asynchronous excitation is difficult to be assessed in advance.
- Further investigation is certainly required as the problem is very complex especially taking into consideration the frequency content variation of different earthquake events, the inelastic response of masonry sections under strong ground motions, the potential for local sliding and yielding and the effect of soil-structure interaction. Such aspects were not explicitly studied herein but are certainly important issues that have to be further investigated.

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