FINITE ELEMENT PREDICTION OF SEISMIC RESPONSE MODIFICATION OF MONUMENTAL STRUCTURES UTILIZING BASE ISOLATION

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ABSTRACT

The analysis of the mechanical behavior of ancient structures is an essential engineering task concerning the preservation of the architectural heritage. As many monuments of classical antiquity are located in regions of earthquake activity, the safety assessment of these structures, as well as the selection of possible restoration interventions, requires numerical models capable of representing correctly their seismic response. The work presented herein was part of a research project in which a better understanding of the dynamics of classical column - architrave structures was sought by means of numerical techniques. In this paper, the seismic behavior of ancient monumental structures with multi-drum classical columns is investigated. In particular, the column - architrave classical structure under strong ground excitations was represented by a finite element method. This approach simulates the individual rock blocks as distinct rigid blocks interconnected with slidelines and incorporates seismic isolation dampers under the basement of the structure. Sliding and rocking motions of individual stone blocks and drums are modeled utilizing nonlinear frictional contact conditions. The seismic isolation is modeled through the application of pad bearings under the basement of the structure. These pads are interpreted by appropriate rubber and steel layers. Time domain analyses were performed, considering the geometric and material non-linear behavior at the joints and the characteristics of pad bearings. The deformation and failure modes of drum columns subject to seismic excitations of various types and intensities were analyzed. The adverse influence of drum imperfections on structural safety was also examined.

INTRODUCTION

Ancient Greek and Roman structures composed of large heavy members that simply lie on top of each other in a perfect-fit construction without the use of connecting mortar are distinctly different from relatively flexible contemporary structures. The colonnade (including free-standing monolithic columns or columns with drums) is the typical structural form of ancient Greek or Roman temples. The columns are connected at the top with the epistyle (entablature), also composed of monolithic orthogonal blocks, spanning the distance between two columns. In classic stone monuments, cooperation between the volumes of marble causes friction forces at the interfaces between the volumes of marble and, in this mode, transfer of static loads. The seismic response mechanisms that develop on this solid block structural system during strong ground motions can include sliding and rocking, thus dissipating the seismic energy in a different way from that of conventional contemporary buildings. The application of dynamic forces involves instant devaluations, rotations, rocks or lift-offs of the marble elements. In this case the frictional forces at the interfaces are eliminated so there is a risk of structural collapse due to loss of balance. The complex process of failure is highly nonlinear and depends on the response and morphology of the construction. Therefore it is necessary to develop special numerical approach that should provide all relevant phenomena.

A basic parameter in the planning of behavior and safe operation of classic monuments against devastating earthquakes is the seismic isolation using bearings to the foundation. The seismic isolation can be passive or dynamic depending on the damping behavior of the data, but can protect the superstructure from the disaster. The bearings absorb seismic vibrations so that the stress of construction is minimal. Usually, the behavior is nonlinear and depends on the response of the structure. Therefore, the linear analysis applied to normal structures using appropriate seismic spectra is not applicable in this case. The design of bearings for seismic isolation of the classical monuments requires the full study of seismic behavior under seismic excitations and study of the eigenfrequency. Therefore appropriate experimental and numerical procedures must be developed and certify their profitability.

In recent years, many investigators examined the problem analytically or experimentally (e.g. References [1; 2]). Experimental studies have been made recently in the NTUA, to determine the stability of simulators of the columns of Parthenon Pronaos [3] which showed that the column may be subjected to large deformations during the vibration. The mathematical model for the minimum value of horizontal acceleration of ground, for a single pulse, which is required to overturn a rectangular solid, has been developed by Housner [4]. The response of a rigid body under the influence of harmonic and seismic excitations has been studied experimentally by Ishiyama [5]. Experimental studies on the response of vertebrate solid objects have been made by researchers Manos and Demosthenous [6]. The impact of use of energy dampers "Shape Memory Alloy Devices" in the dynamic behavior of models of ancient columns and colonnades are studied by Prof. C. Manos and colleagues [7]. The seismic performance bearings in ancient pagodas consisted of five stone parts has been studied on a seismic bank, by J.K. Kim and colleagues [8]. Two types of bearings were used: 1) Friction Pendulum System (FPS) and 2) Pure Friction System with laminated rubber bearing (PF system with LRB).

The purpose of this work is to study the vibrations generated by an actual earthquake excitation (earthquake Aegio 1995) in a single column, initially when it simply relies on the ground and then when between the column and soil mediates a seismic isolator. The comparison of results will lead to the understanding of the need of existence of such isolators and to the selection of the appropriate one. Our target is to design the forms of vibrations for various cases of columns with different elements of isolator. It is clear therefore that we are interested in a dynamic analysis in most parts of the solution. At all stages of this work we used the method of finite elements. In this study we use the package FEA LUSAS.

FORMULATION OF THE MODEL

MODEL OF THE STRUCTURE

A typical section of a temple is reproduced in Figure 1. The number of drums in each column is not constant for all the columns and is controlled by the size of the sound rock that was available in the ancient limestone quarry.

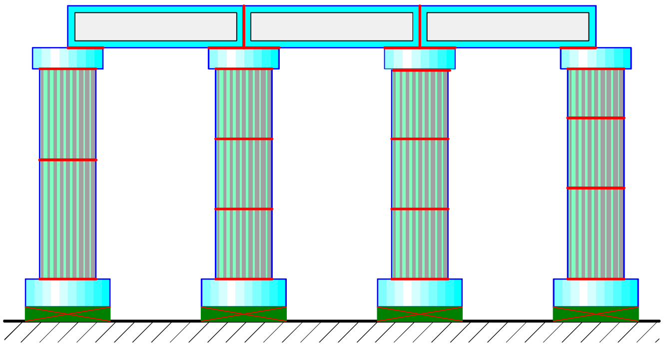

Figure 1: Typical section of a temple

SEISMIC ISOLATION

The base-isolated column is modeled as a shear type supported on various base isolators. The corresponding equation of motion for the base mass under earthquake ground acceleration is expressed by

$$m_b \ddot{x}_b + F_b - k_1 x_1 - c_1 \dot{x}_1 = -m_b \ddot{x}_g \qquad (1)$$

where m_b and F_b are base mass and restoring force developed in the isolation system, respectively; k_1 is the and c_1 is the damping. A system of differential equation of equilibrium for base mass during impact with the adjacent structure is as follows

$$m_b \ddot{x}_b + F_b - k_1 x_1 - c_1 \dot{x}_1 + k_g (|x_b| - d)\mathrm{sgn}(x_b) + c_g \dot{x}_b = -m_b \ddot{x}_g \qquad (2)$$

where k_g and c_g are the stiffness and damping coefficient of the adjacent structure, respectively; and sgn denotes the signum function. The restoring force developed in the isolation systems, F_b depends upon the type of system considered and described for different systems as follows [9].

Laminated rubber bearings

The basic components of laminated rubber bearings (LRB) are steel and rubber plates built in the alternate layers (Figure 2(a)). The dominant feature of LRB system is parallel action of linear spring and damping. The restoring force developed in the bearing, F_b is given by

$$F_b = c_b \dot{x}_b + k_b x_b \qquad (3)$$

Lead-rubber bearings

These bearings are similar to the LRB but a central lead-core is used to provide an additional means of energy dissipation and initial rigidity against minor earthquakes and winds (Figure 2(b)). The energy absorbing capacity by the lead-core reduces the bearing displacement. The N-Z bearings also provide an additional hysteretic damping through the yielding of lead-core. The force–deformation behavior of the N-Z bearing is generally represented by non-linear characteristics. The restoring force developed in the isolation bearing is given by

$$F_b = c_b \dot{x}_b + \alpha k_b x_b + (1-\alpha) F_y Z \qquad (4)$$

where Fy is the yield strength of the bearing; α is an index which represent the ratio of post-to-pre-yielding stiffness, k_b is the initial stiffness of the bearing, c_b is the viscous damping of the bearing and Z is the non-dimensional hysteretic displacement component.

Pure-friction system

The simplest sliding isolation system is the pure-friction (P-F) system based on the mechanism of sliding friction. The horizontal frictional force at the bearing interface offers resistance to motion and dissipates energy. The schematic diagram of P-F system is as shown in Fig. 2(c) which represent typical Coulomb's friction (i.e. friction coefficient, m is considered independent of sliding velocity). The limiting frictional force in the bearing is Fs =μMg (in which μ denotes the friction coefficient). The restoring force, F_b during the sliding phase is expressed by

$$F_b = F_s \operatorname{sgn}(\dot{x}_b) \qquad (5)$$

Friction pendulum system

The concept of sliding bearings used along with notion of a pendulum type response, by means of an articulated slider on spherical concave chrome surface, marks a friction pendulum system (FPS). The system is activated only when the earthquake forces overcome the static value of friction, and coefficient of friction depends upon velocity attained. The FPS develops a lateral force equal to the combination of the mobilized frictional force and the restoring force that develops because of rising of the structure along the spherical surface. The schematic diagram of FPS is shown in Fig. 2(d). The resisting force provided by the system is

$$F_b = k_b x_b + F_x \qquad (6)$$

where k_b is the bearing stiffness provided by virtue of inward gravity action at the concave surface; and F_x is the frictional force. The system is characterized by bearing isolation period (T_b) that depends upon radius of curvature of concave surface and friction coefficient (μ).

Resilient-friction base isolator

Resilient-friction base isolator (R-FBI) system consists of concentric layers of Teflon-coated plates in friction contact with each other and a central rubber core. The schematic diagram of R-FBI is as shown in Fig. 2(e). The bearing force in case of R-FBI system is

$$F_b = c_b \dot{x}_b + k_b x_b + F_x \qquad (7)$$

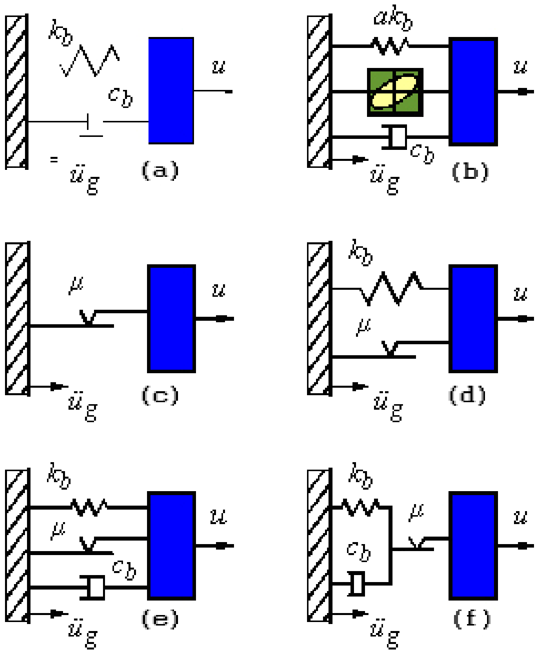

Figure 2: Schematic diagrams for LRB, N-Z, P-F, FPS, R-FBI and EDF systems

Electric de France system

A system is developed under the auspices of "Electric de France" (EDF) standardized for nuclear power plants in region of high seismicity. The schematic model of EDF system is shown in Fig. 2(f). Before sliding takes place, the restoring force is governed by

$$F_b = c_b \dot{x}_b + k_b x_b \qquad (8)$$

When the restoring force exceeds the limiting frictional force Fs the sliding at the top plate of the EDF system takes place. The restoring force during the sliding phase remains constant and given by

$$F_b = F_s \operatorname{sgn}(\dot{x}_b) \qquad (9)$$

FINITE ELEMENT APPROXIMATION

In the finite element method (FEM) framework, the equilibrium equations governing the nonlinear dynamic behavior of the three-dimensional column are

$$M\ddot{U} + C\dot{U} + KU = R \qquad (10)$$

where M, C, and K are the mass, damping, and stiffness matrices, respectively. The time-dependent vectors $\ddot{U}$, $\dot{U}$, U, and R denote the nodal accelerations, velocities, displacements, and external forces, respectively, in terms of a global Cartesian coordinate system x,y,z. Interference conditions associated with partial closing and opening of the contact surfaces were modeled through the slideline facility which is available in some commercial finite element codes. This technique models effectively the contact behavior of two or more bodies with no exact prior knowledge of the contact process even when relative surface deformations with arbitrary contact and separation take place. Slidelines comprised of two nonregular necessarily surfaces which are defined by a number of contact segments corresponding to external faces of elements closest to the surfaces. The nodal constraint slideline treatment allows for adjustment of contact conditions by setting appropriate constraints. Concerning the most important properties of slidelines, the stiffness factor depends on material properties and controls the degree of penetration experienced in the contact zone, and the zonal contact detection radius is a measure of the maximum distance between any two neighboring contact nodes. When relative slipping occurs, this technique incorporates friction forces between sliding surfaces. This requires definition of an additional property of slideline, i.e. the apparent coefficient of friction. At each increment of the procedure, this facility tracks the node pairs being nearly in contact by means of the zonal contact detection radius, and adjusts the contact constraints. This technique does not directly couple nodal degrees of freedom but introduces repellent forces between the penetrating regions of the two surfaces. Coupling of the nodal freedoms in this manner introduces no additional equations into the solution and the technique is sufficiently flexible to be implemented within both explicit and implicit type of finite element codes. The Newton-Raphson iterative scheme, together with the displacement Euclidean norm are adopted for the determination of the exact position of contact zone at each increment. This utility was used to simulate the contact of drums by defining slidelines along contact surfaces.

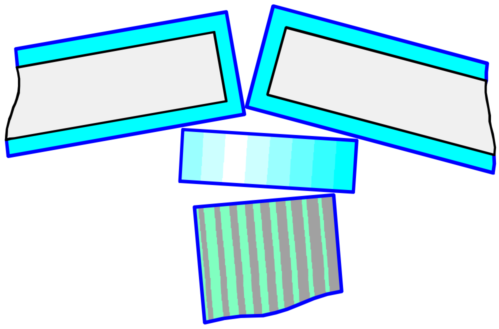

Figure 3: Contact details

The seismic reducer, in fact, is a buffer composed of successive leaves of rubber and steel. In our study it appears with elements that represent springs (joint elements) which will link 12 points, arranged in the territory in the directions Y, Z and freely in the X direction, with 12 specific points in the base of the column. The connection with the column will be made with JNT4 elements where, in our tests, we set the external stimulation. JNT4 are three-dimensional, four-noded elements, each one, connecting two nodes of the model. We will deal with both the linear and the nonlinear analysis to study the behavior of the columns. Linearity / non-linearity enter the problem analysis using linear and nonlinear properties of springs respectively (Element Library JNT4 material properties). In linear analysis, the JNT4 element links two nodes with three springs, one for each dimension. The only parameter that changes the behavior of the element is the constant of spring in each direction (Kx, Ky, Kz) which we define ourselves. In the non-linear analysis, the springs are characterized by a varying constant.

NUMERICAL RESULTS

Seismic response of a base-isolated structure is investigated under real earthquake ground motions during impact with adjacent structure. Numerical study is carried out using analytical model of the base-isolated structure under consideration for calculation of the response quantity in absolute acceleration and in the relative bearing displacement. The above response quantities are important because, floor accelerations developed in the structure are proportional to the forces exerted due to earthquake ground motion and the bearing displacements are crucial in design of isolation systems. The main feature of the columns is that they consist of individual cylinders one over the other presenting high inertia. This led us to design a three-dimensional (quite realistic in appearance) model. There were used three-dimensional elements (solid elements) in order to simulate the inertia of each cylinder (HX8M in Lusas). For the conduct of this study a simplified model of an ancient column was used. Its geometry was defined by assumptions and criteria that do not significantly affect our results. So we accepted that: 1) The stripes and the taper of the ancient columns can be omitted, 2) The local discontinuities and any heterogeneity of the material do not affect the model, 3) The used loads and displacements are clustered (CL) with a fixed measure and address, 4) The diameter and length of the column remain constant, 5) The three drums, which make up the column, link together with slidelines. As it is known the column (pillar) consists of one or more servings (drums) as shown in Figure 4.

Figure 4: Erechtheion Column

The material of ancient columns was mainly marble. The analysis column has a height of six meters and a diameter of one meter. The simulation will take place by using physical properties of stone.

- Mass density : $\rho = 2800 Kgr / m^3$
- Young's modulus : $E = 6 * 10^{10}$ Pa
- Poisson Ratio : $v = 0.15$

For the parametric study the earthquake recorded at Aegio in 1995 was selected. The Aegio accelerogram was recorded near the causative fault of an Ms 6.2 earthquake 18 km away from the epicenter. The peak ground acceleration (PGA) of this earthquake motion was 0.501305g with a time increment of 0.005 seconds. The acceleration spectrum of the above ground motion is shown in Figure 5. The model of a typical column, as shown in Figure 6, was initially analyzed without any seismic isolator at its base. The acceleration spectrum of an upper node was examined for 2.4 seconds in every case. Although the total duration of the earthquake was above 16 seconds shown in Figure 5, we examined only the first 2.4 seconds of it because the usage of such low time increment (0.005 sec.) would not permit us more due to program failing and huge computing time.

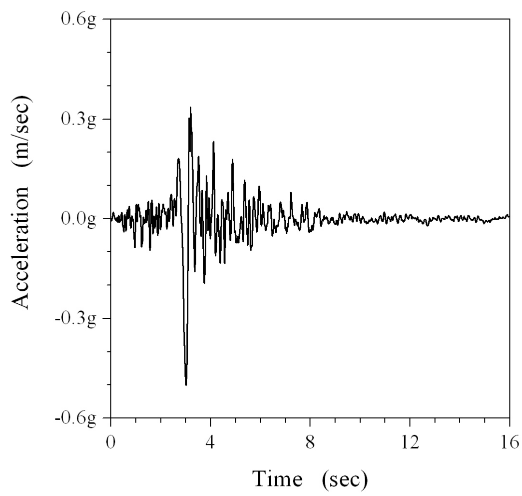

Figure 5: Motion records selected for the analysis

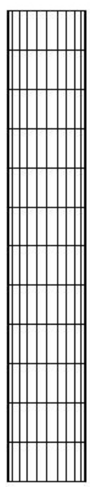

Figure 6: Typical model of the column

During the analysis we try to use a damper simulated by linear joint elements with spring constant K = 1.3E6 N/m and damping ratio c = 0.1. We studied the acceleration of an upper node, same in both models, and formed the following diagram (Figure 7).

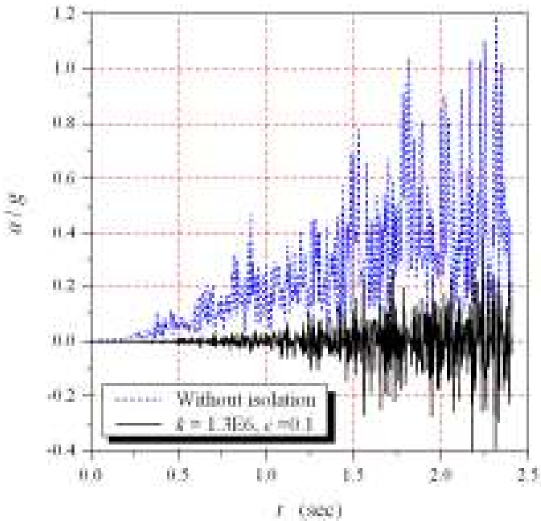

Figure 7: Acceleration of the capital for non-isolated and linearly isolated columns

It is obvious that the acceleration is reduced drastically in the case of the damped column. This is easily observed even from the first moments of the earthquake motion. During the next analysis two differently damped columns were examined (Figure 8). The first column is supported on a damper simulated by linear joint elements with spring constant K = 1.3E6 N/m and damping ratio c = 0.2. On the other hand, the second column is supported by non-linear joints with the same spring constant and lift-off stiffness k=650E3 N/m.

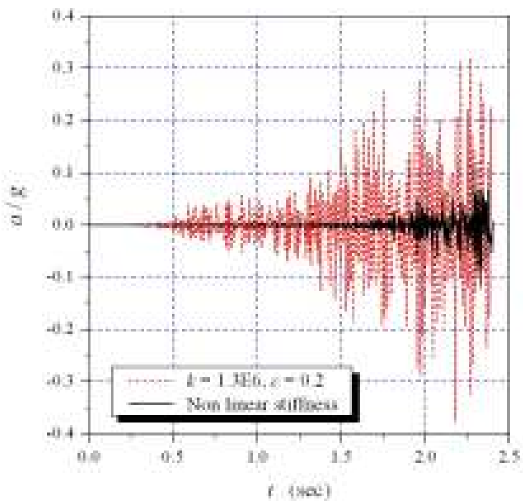

Figure 8: Acceleration of the capital for linearly and non-linearly isolated columns

It is observed that the second method is much more appropriate and reduces the acceleration effectively.

The system of three columns coupled with two architraves is investigated for the model of the temple shown in Figure 9.

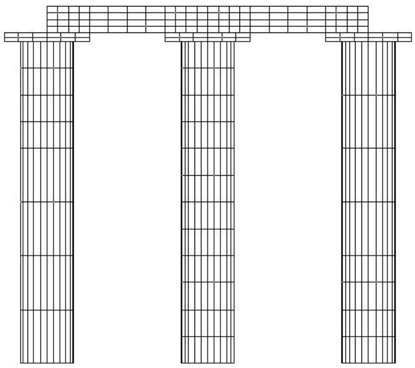

Figure 9: Typical model of the temple

It is evident that the coupling of the columns with an architrave does not alter significantly the stability and it may reduce or increase the chances of failure, depending on the period of the excitation and the characteristics of the structure. From the deformed shape of the temple illustrated in Figure 10, it is obvious that for different sizes of drums, different deformations are observed and that although the presence of the architraves, deformations are perceptible.

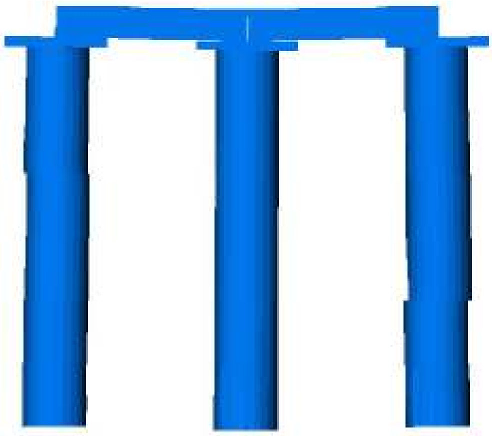

Figure 10: Deformed shape of the temple

CONCLUSIONS

Seismic response of base-isolated columns is investigated. The comparative performance of different isolation systems during impact conditions is studied under real earthquake ground motions. It is found that the method is able to reproduce the key features of the experimentally observed dynamic response of such structures. The slidelines are able to carry out this, fully, non-linear problem and to model right the contact problem of the volumes. The rolling effect was effectually approximated and the columns’ behavior was outright at each study. It seemed that plenty of simulations are necessary to be done in order to find out which isolator should be appropriate for each structure. The analysis seems very simple because, for each model, the only thing that changes is the bearing. Changing the material properties of the joints leads to a completely different isolator with quite different behavior in total. In terms of acceleration reducing, it is observed that the method with the non-linear joints is more effective than the first method with the linear approximation. Although the analysis is simple and computationally efficient, it is also quite time-consuming. This happens because this is a time response problem that requires high computing power and long lasting analyses.

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