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THE USE OF NUMERICAL METHODS TO INVESTIGATE THE SEISMIC RESPONSE OF A LARGE BLOCK MASONRY COLONNADE

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ABSTRACT

Numerical methods, using finite or discrete elements, when properly applied can simulate the seismic structural response of structures made up of complex arrangements of large masonry blocks. By representing each block separately, structures such as colonnades in archeological sites can be modeled exactly with contact surfaces between separate blocks modeled by non penetrating frictional surfaces. The colonnades at the temple of Jupiter in Baalbeck are modeled using finite element and discrete element approaches and the seismic response and level of structural damage are assessed as a function of the seismic even characteristics. A comparison of the different modeling possibilities and their implications as to the prediction of the risk of structural collapse under earthquake loads is presented. The information extracted from the analyses can be used for the preservation of existing structures as well as for archeo-seismological studies.

Introduction

Seismic events represent one of the major hazards that endanger the conservation of large masonry structures such as encountered in archeological and historical sites. These represent an important part of the world cultural and historical heritage requiring protection. Lebanon is particularly rich in these heritage sites such as Baalbeck, Tyr, Saida, Tripoli, and Byblos. In return the study of the damage and structural collapse caused to these archeological structures by historically recorded seismic events can help estimate the magnitude and nature of these events through the reverse approach of archeo-seismology.

Single and stacked rigid block dynamics is an active field of research and the mathematics involved are relatively complex, see Zhang and Makris (2001) and Spanos et al., (2001) for example. For harmonic excitations some closed form solutions can be derived while for random excitations the rigid blocks' response can be chaotic with a strange attractor solution.

Given the dynamic nature of the problem and the somewhat intractable closed form

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solutions, numerical methods offer the best way to model the seismic response of large masonry structures (Azevedo et al., 2000, Azevedo and Sincraian, 2001, Lourenco et al., 2001, Bicanic et al. 2002, Psycharis et al., 2000 and 2003). In the following an example case for the remaining 6 columns of the Jupiter Temple in Baalbeck is developed using two different numerical methods.

Methods and Models

Numerical Methods

Numerical methods are used when closed form solutions are intractable or when time stepping is required to update system properties and geometry such as in dynamic problems involving time histories of loading and large displacements. Earthquake loading is essentially a time history of ground motion or acceleration such as recorded by seismographs after a ground shaking event. When these time histories are applied to the foundations of structures they result in forcing functions that develop all types of dynamic stresses and forces inside the structural members concerned. The response of the structure depends on its material constituents and the geometric assemblage of its elements. When structural damage or partial/total collapse under earthquake loading takes place in large block masonry structures it could be the result of either or both:

1-stresses building up beyond material resistance thus causing local failure, which in turn could translate into global failure;

2-cumulative relative displacements of blocks with respect to one another which results in the partial or global loss of single or multi-block stability.

Discrete elements (DEM) are traditionally used to investigate the mechanics of rigid blocks and discontinuous media such as jointed rock, granular materials, and masonry structures. The DEM method allows the determination of collapse modes, block displacements, block contacts, and block interactions. The DEM method has limited capabilities in estimating internal block stresses and strains, as well as large internal block deformations. The Universal Distinct Element Code (UDEC) 2D version (www.itascacg.com) was selected to be used in the example problem.

Finite elements (FEM) are traditionally used to investigate the state of stresses/strains inside a material continuum. Structures are modeled as assemblages of different types of FEM elements with different stress resolution capabilities such as bars, beams, 2D and 3D solid elements. The FEM method allows also the determination of the Eigen modes of a structure, i.e. the natural frequencies and modes determined for buckling and resonance problems.
The FEM method has however limitations and difficulties in solving problems with contact surfaces, opening cracks, and discontinuities in general. The Automatic Dynamic Incremental Nonlinear Analysis (ADINA) code (www.adina.com) was selected to be used in the example problem.

The Colonnade at Baalbeck

A UNESCO World Heritage site since 1984, the temple of Jupiter at Baalbeck in the Bekaa valley of Lebanon is the largest temple that the Romans built. The site has been destroyed by devastating earthquakes some focused in the Bekaa or nearby, over the last ten centuries. Six Corinthian columns are left standing. Historical records from travelers to the region report that 9 undamaged columns still remained in the colonnade of the Jupiter temple at Baalbek in 1751. Only 6 damaged columns survived the November 22nd, 1759 Bekaa valley earthquake (Ms ~7) (Ambraseys and Barazangi, 1989, and Ambraseys and Jackson, 1998). These large roman columns, probably the largest in the world, have a 2.2m diameter and more than 20m in height. They are constituted by five distinct blocks: a base block, three cylindrical block, and one capital block. The 6 columns are connected at the top by three layers of lintel blocks. The vertical elements of the colonnade are connected to each other with three short metallic dowel bars used by the Romans to center the blocks and insure perfect verticality. Exact geometric dimensions of the colonnade were used for the numerical models. The colonnade sits on an elevated foundation made of large masonry blocks. Locally quarried strong yellowish limestone was used for all blocks. Fig. 1 shows frontal and side views of the colonnade.

Figure 1. Baalbek Colonnade frontal and side views.

The Aqaba, November 22nd, 1995 Earthquake

Ideally, the foundation of the colonnade should be subjected to the ground acceleration records of a well-documented, major earthquake with epicenter closest to the site. However, since the availability of seismic records in Lebanon is very limited, the closest available earthquake record found was the Aqaba earthquake (Aqaba, 1995). It occurred on November 22nd, 1995, with its epicenter located in the Aqaba gulf waters at 28.76oN, 34.66oE, with a focal depth of 12 km and a Richter Magnitude of 6.2. The peak ground accelerations were: 0.109g, 0.097g and 0.086g for the UP-DOWN, EAST-WEST and NORTH-SOUTH components respectively. The epicenter falls along the Dead Sea Fault System which passes through Lebanon. The acceleration time history records for the Aqaba earthquake of time span = 60 seconds were obtained from the PEER strong motion database (Aqaba, 1995). The records were imported into UDEC and were used as the seismic loading in the analysis (the EAST-WEST record for the ground acceleration in the x-direction and the UP-DOWN record for the ground acceleration in the y-direction). Figure 4 shows the acceleration time history for the three components of the earthquake. Figures 5 and 6 show the response spectrum, or the frequency content, of the earthquake for 0.5% and 5% damping respectively.

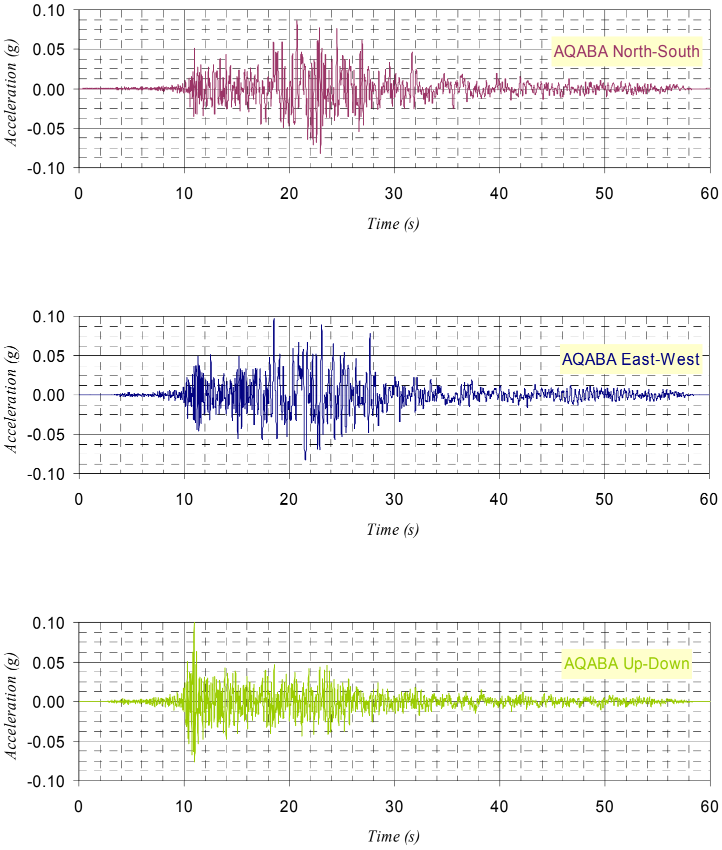

Figure 2. Aqaba acceleration time history for its three components

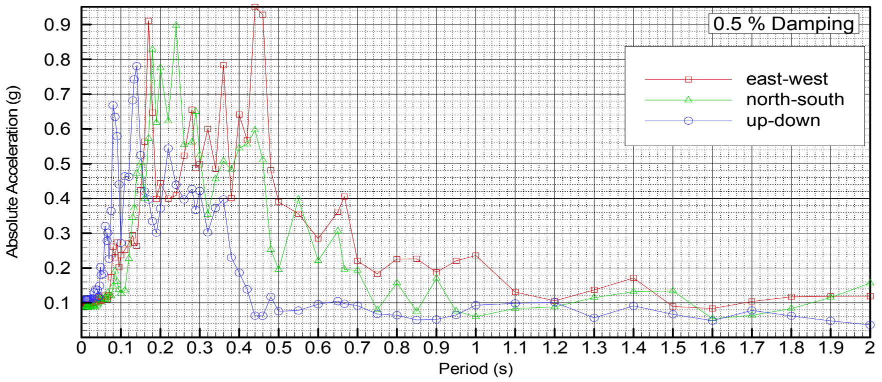

Figure 3. Aqaba 1995 response spectrum for 0.5% damping

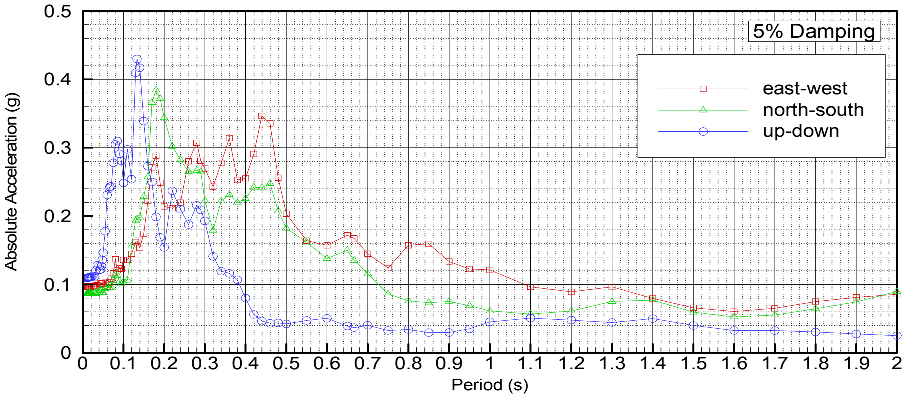

Figure 4. Aqaba 1995 response spectrum for 5% damping

Results and Discussion

UDEC Analysis

In the distinct element method, a rock mass is represented as an assembly of discrete blocks. Joints are viewed as interfaces between distinct bodies. The physical structure was modeled in three parts: (1) the foundation blocks, (2) the six columns and (3) the lintels at the top which are resting on the columns. In the UDEC model each stone is modeled distinctly and is treated as a rigid block. The joints between stones are assigned a friction angle of 20^o, or a coefficient of friction, μ= tan 20 = 0.364, and zero tensile strength.

The UDEC analysis consists of two phases: (1) The static response due to the structure's own weight (this insures that the correct friction forces develop) and (2) The dynamic response (time span = 70 s) due to the Aqaba earthquake. The analysis can be run with rigid non-deformable blocks, or with deformable blocks accounting for the deformations caused by internal stresses. For the rigid blocks approach solving the problem requires about 5min of PC time with 470,000 time steps. For the deformable blocks approach solving the problem requires about 2.5h of PC time with 3.5 million time steps.

The analysis revealed no collapse of the columns. However, there was a permanent shear slip between the bottom of the lintels and the top of the columns of 3.8 mm as shown in Figure 5. The maximum displacements take place at time = 23.5 s of the earthquake showing very low displacements of the foundation blocks and a maximum displacement of about 17 mm at the top of the lintels. In order to explain the sustained stability of the columns under seismic loading the time history for the x-direction shear force or V and the y-direction normal force or P forces acting on the middle stone of the exterior (first from left) column were analyzed. It was evident that at all times $V < \mu P$ which means that the friction force (μP) prevented this stone from moving. Verification at other locations showed that the friction forces were not exceeded.

In order to verify that the model could predict collapse under different seismic excitations, a harmonic sinusoidal loading with a period = 0.75 s and velocity amplitude = 0.40 m/s was applied to a single column showing a sequence of collapse in Fig. 6.

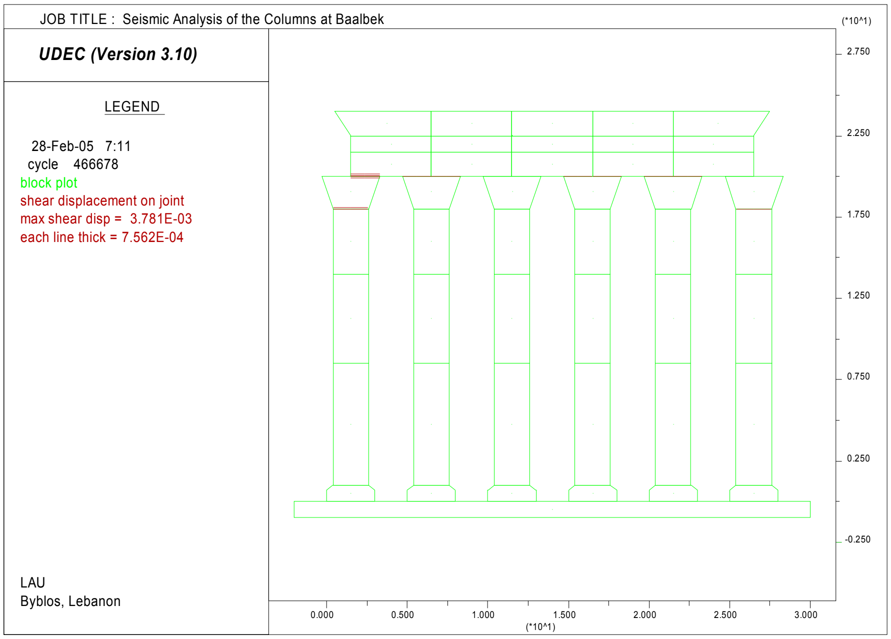

Figure 5. Distribution of permanent shear slip in UDEC (2D).

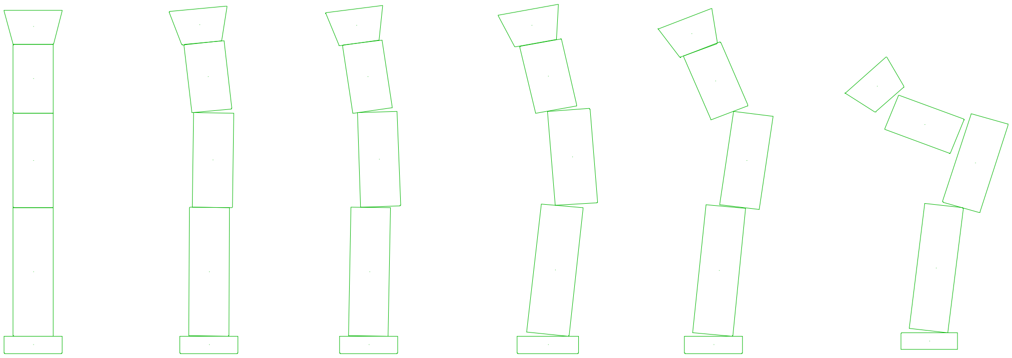

Figure 6. Collapse sequence at the end 0, 5, 10, 19, 20 and 21 cycles of harmonic loading.

ADINA Analysis

In the finite element method the earthquake response of structures typically involves the Eigen mode shapes or natural frequencies. No Eigen modes can be calculated for block structures. It is however possible to calculate natural frequencies and Eigen mode shapes for a tied or connected block colonnade structure. For very low amplitude excitations when full friction has not yet been mobilized on the contact surfaces of the large masonry blocks these frequencies may represent the first response of the structure to a probing forcing function; the

Eigen mode shapes may then represent a first reading of the possible group movement of the individual blocks. The following approaches were used to investigate the problem:

> 1-the colonnade was modeled with 3D solid tied contact blocks for a closer estimate of the natural frequencies and detailed block stresses estimation;
>
> 2-the colonnade was modeled with 3D solid blocks with contact surfaces combining a detailed estimation of the internal block stresses and discrete large block movements.

The Eigen modes found from the first approach are shown in Figure 7 with modal frequencies of 1.346; 2.535; 2.961; 8.565; and 10.11 for the first five modes respectively.

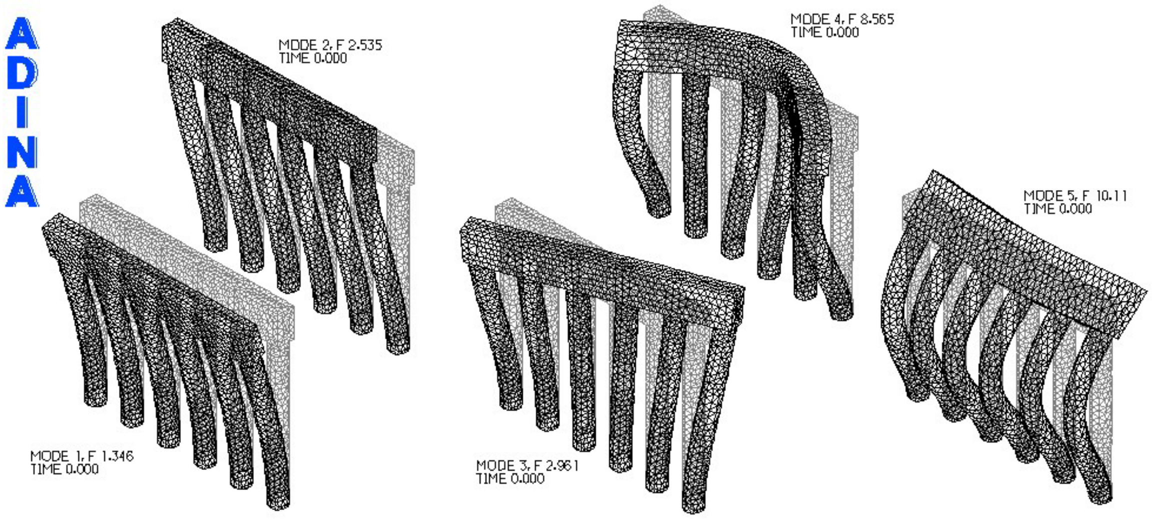

Figure 7. Eigen modes of tied contact 3D solid blocks

It can be seen that modal frequencies can be determined as long as the structure behaves as a connected whole, while the inter-block shear has not yet exceeded the available friction and the resistance provided by the metallic dowel bars used for placing and centering the column drums. From these modal frequencies critical natural periods of the tied colonnade can be obtained, they are: 0.74s, 0.39s, 0.34s, 0.12s, 0.01s for the first five modes respectively. The response spectrum of the earthquake, in this case the Aqaba earthquake, can be queried for peak accelerations corresponding to these periods. From Figs. 3 and 4 it can be seen that peak acceleration values are reached for periods between 0.1s and 0.5s. It can be hypothesized that the 2nd, 3rd, and 4th Eigen modes of the colonnade would have been activated by this earthquake. Once a frequency of excitation in the earthquake is very close to a natural frequency in the colonnade it is thought that the corresponding mode would be activated in the structure leading to large forces. When these forces exceed the available friction the structure starts to behave as a set of independent rigid blocks and the analogy to a tied structure stops there.

The second approach using 3D solid blocks with contact surfaces combining a detailed estimation of the internal block stresses and discrete large block movements is simply a detailed time stepped simulation of the seismic event. Given the numerically intensive methods at work the PC runtime for the ADINA FEM Baalbek colonnade model exceeded three days. The results showed no collapse of the structure, only some minor residual displacements similarly to the 2D UDEC analysis. Most interesting in this third approach is the possibility to track with high detail the internal stresses inside the blocks. When this was done, it showed stress concentrations at the edges of lower columns blocks at locations consistent with the observed chipped edges of some cylindrical drums of the colonnade as can be seen in Fig. 1. Highly magnified frontal and side view snap shots of the structural response of the colonnade to the Aqaba earthquake are shown in Fig. 8.

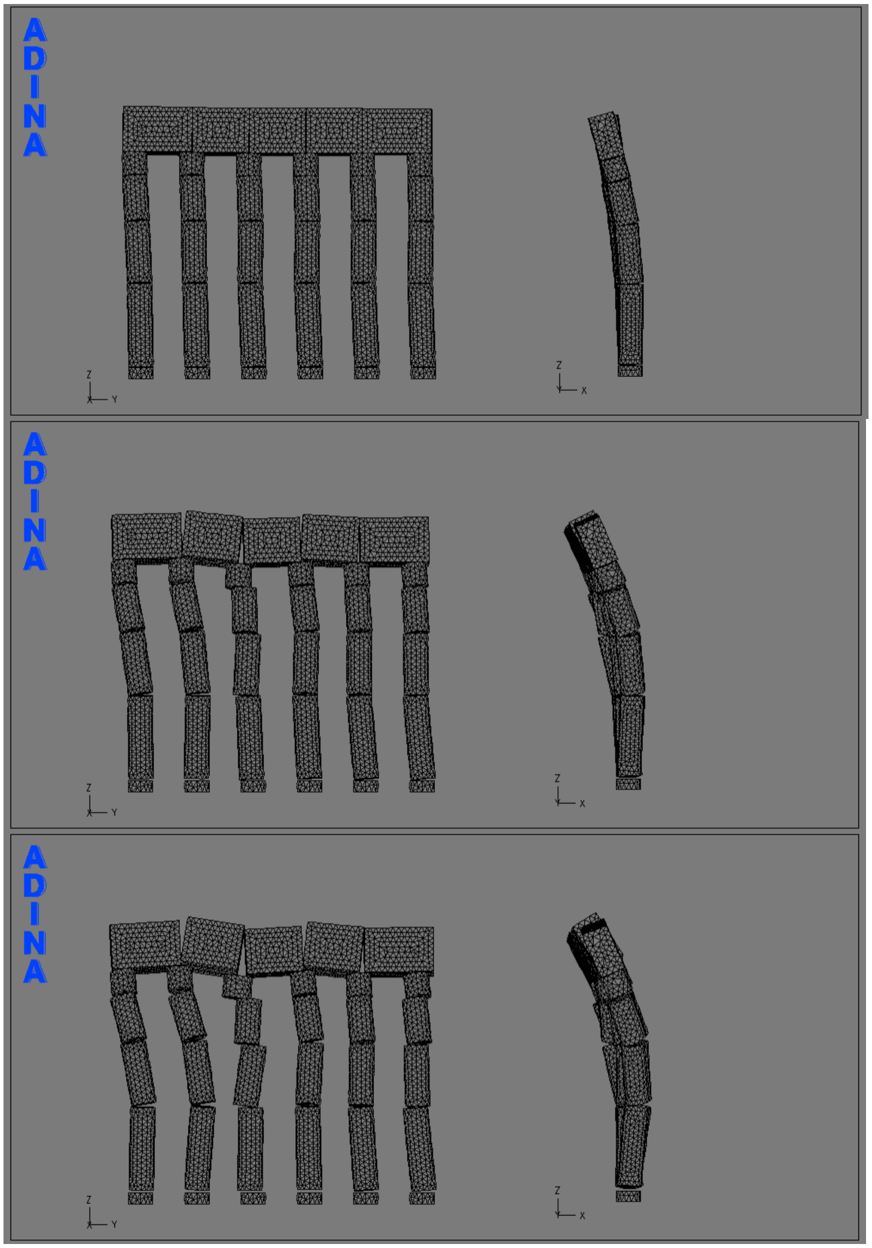

Figure 8. Frontal and side view snapshots of the colonnade magnified response to Aqaba earthquake.

No collapse was observed again, but the impending movement of the colonnade is similar to the first and second Eigen mode shapes lending some credence to the proposal for determining pseudo-natural frequencies from tied block models.

Conclusions

The following conclusions can be drawn:

- Both finite and discrete element numerical techniques could be adapted to model the seismic response of a large block masonry colonnade with each method having its advantages and disadvantages. Displacements or structural disorder can be modeled as well as stress concentrations resulting in localized damage or loss of stability.
- Given the acceleration-time history (real or synthetic) of an earthquake it is possible to predict its impact on a large masonry cultural heritage structures (forward problem). Vice-versa given a structurally disordered or damaged historical masonry structure it would be possible to identify some basic characteristics of the critical seismic event by simulation of the event and comparison of the results (inverse problem).
- An example problem was presented for the Jupiter temple colonnade in Baalbek and subjected to the Aqaba 22nd of November, 1995, earthquake showing survival of the structure with only minor residual displacements. It was also shown that collapse could be modeled given critical combinations of signal amplitudes and frequencies.
- A method to establish pseudo-natural or most critical frequencies for block structures using a tied block model and FEM Eigen mode analysis was proposed. Preliminary results warrant further investigation.
- Additional investigations are necessary to establish the validity of the different methods for multiple types of large masonry structures using a library of acceleration-time histories and synthetic harmonic loading.

Acknowledgments

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