MODELLING THE SEISMIC BEHAVIOUR OF MONUMENTAL MASONRY STRUCTURES

J. AZEVEDO[1], G. SINCRAIAN[2]
[1]Professor, [2]Research Assistant
Civil Engineering and Architecture Department, Instituto Superior Técnico, Lisboa, Portugal

SUMMARY

This paper focuses on a methodology for modelling the seismic behaviour of masonry structures. A special emphasis is given to structures of typical monuments built either with brick or stone blocks. The discrete element method is shown to adequately simulate the behaviour of the blocky structures. The simulation of collapse patterns is analysed for some structural elements. Case studies related to the seismic behaviour of real monumental structures are also presented.

1. INTRODUCTION

Most of the existing historical monumental structures are, at least in Europe, made of masonry, using either stone or brick blocks. These unreinforced blocky masonry structures can not be considered a continuum, but rather an assemblage of compact stone or brick elements linked by means of mortar joints. Seismic events have often caused massive damage or the destruction of such structures with great cultural significance. Examples can be found in past earthquakes, which affected most of this type of constructions of the ancient Middle East, Greek, Roman, pre-Columbian, Indian and Chinese civilisations. In recent events, earthquakes have also caused great damage and destruction of religious temples and other monumental buildings [1, 2, 3].
Unlike today's structures where the seismic vulnerability can be inferred by means of existing codes and analysis methodologies, the assessment of the seismic behaviour of old masonry structures lacks scientific background.
The evaluation of the seismic vulnerability of such structures, as is the case for the other types of structures, depends on reliable numerical simulation of their seismic response. Numerical

modelling of the seismic behaviour of masonry structures represents a very complex problem due to the constitutive characteristics of the structural material and its highly physical and geometrical non-linear behaviour when subjected to strong ground motion. Whatever method is used to analyse this type of structures, it must account for the fundamental importance of the discontinuities, for an unreinforced masonry structure will display a mechanical behaviour essentially different from a continuum. The numerical modelling methods available for the study of historical structures and monuments under seismic action are reviewed in [4].

Masonry structures can not be correctly studied by conventional methods of structural mechanics like the ones that are used to analyse today's structures. Being composed of two very different materials, i.e. the masonry units and a joining material such as mortar, masonry exhibits a heterogeneous structure and it is a discontinuous system. Its blocky nature governs the deformation and failure mechanisms.

This work presents a methodology for the assessment of the seismic behaviour of blocky masonry structures [5]. It allows, on one hand the modelling of the response up to stages of collapse corresponding to large displacements and highly geometrical non-linear behaviour, and on the other hand the modelling of the physically non-linear behaviour of both the structural blocks and their interfaces, the identification of failure patterns and the control of internal stresses and deformations as a function of the seismic input.

For that purpose, the discrete element methods are used, because they allow for large displacements and rotations between blocks, including sliding between blocks, the opening of cracks and even the complete detachment of the blocks, and automatically detect new contacts as the calculations progress.

2. THE USE OF THE DISCRETE ELEMENT METHOD

The discrete (or distinct) element methods fall within the general classification of discontinuum analysis techniques. Originally used to model jointed and fractured rock masses [6], they were developed for the analysis of structures composed of particles or blocks and are especially suitable for problems in which a significant part of the deformation is accounted for by relative motion between blocks. Masonry provides a natural application for these techniques, as the deformation and failure modes of these structures are strongly dependent on the role of the joints. This approach is well suited for collapse analysis, and may thus provide support for studies of safety assessment, namely of historical stone masonry structures under earthquakes.

Two main features of the discrete element method (DEM) led to its use for the analysis of masonry structures by means of *UDEC - Universal Distinct Element Code* [7]. One is the allowance for large displacements and rotations between blocks, including their complete detachment. Other, is the automatic detection of new contacts as the calculation progresses. The block material may be assumed rigid or deformable.

In discrete element models, the representation of the interface between blocks relies on sets of point contacts. Adjacent blocks can touch along a common edge segment or at discrete points where a corner meets an edge or another corner. At each contact, the mechanical interaction between blocks is represented by a force, resolved into a normal (F_n) and a shear (F_s) component. Contact displacements are defined as the relative displacement between two blocks at the contact point. In the elastic range, contact forces and displacements are related through the contact stiffness parameters (normal and shear).

The necessary parameters to define the contacts mechanical behaviour are the normal stiffness (k_n), shear stiffness (k_s), friction angle (?), cohesion (c) and tensile strength ($?_t$). To approximate a displacement-weakening response, the Coulomb slip model with residual strength (Figure 1) is used.

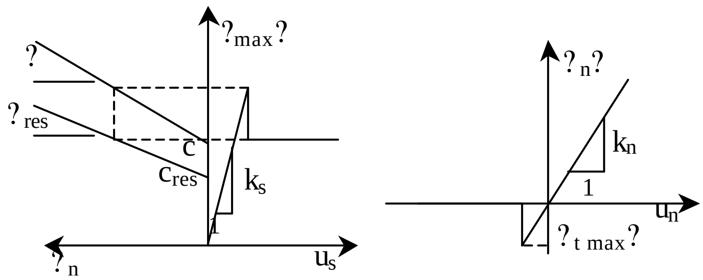

Figure 1 : Coulomb slip model with residual strength (shear and normal behaviour)

The selection of a solution algorithm for the discrete element method must take into account the fact that the geometry of the system, as well as the number and type of contacts between the discrete bodies, may change during the analysis. In the discrete element method the structural analysis, both static and dynamic, is based on explicit algorithms.

Among the most important capabilities of DEM (and *UDEC*) that make it very suitable for masonry structures could be mentioned: the ability to simulate progressive failure associated with crack propagation; the capability of simulating large displacements/rotations between blocks; the fact that contact points are updated automatically as block motion occurs and the fact that the problem of interlocking is overcome by automatically rounding the corners.

3. SEISMIC RESPONSE OF STRUCTURAL ELEMENTS

To illustrate the applicability of the methodology to assess the seismic response of blocky masonry structures, some simple structural elements were selected, such as a single column, a set of two columns supporting a lintel, a roman arch and a gothic arch. As an initial effort, for each one of these structures, the qualitative response to static and seismic loading was examined.

Figure 2 displays some of these results for the single column, a set of two columns with a lintel and a roman arch when subjected respectively to a vertical load and seismic action.

In another situation, displayed in figure 3, is shown the simulation of the collapse of a gothic arch when subjected to an initial differential settlement and a seismic action. It can be seen how the initial settlement influences the collapse due to earthquake, showing that one can also model static actions or a combination of static and dynamic actions with this approach.

In all cases there is a good agreement with what could be expected for the different structural typologies and actions.

Other cases, involving the in plane and out of plane behaviour of masonry walls were also analysed with success [5].

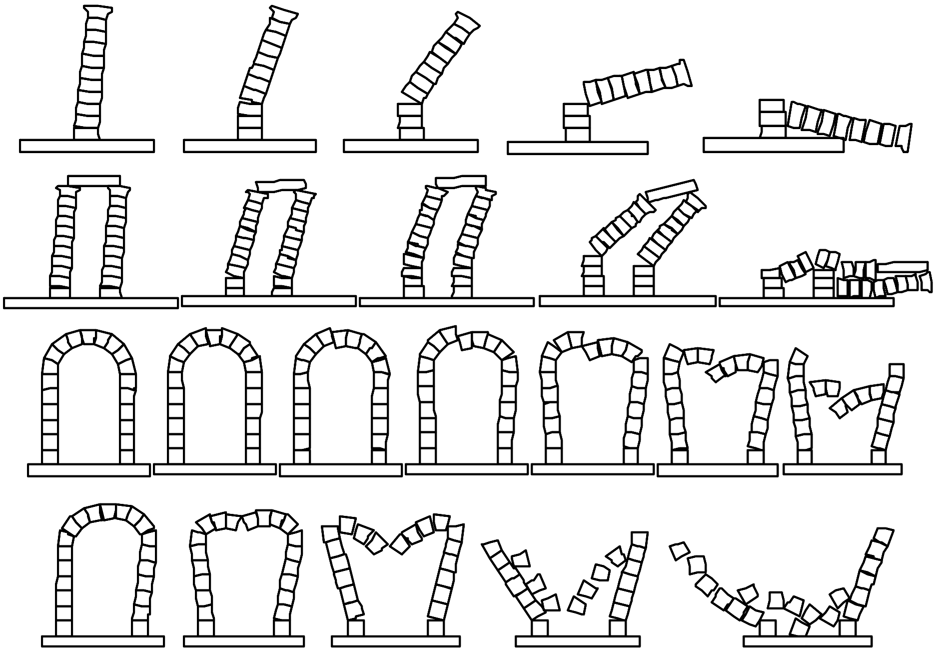

Figure 2 : Seismic behaviour and collapse patterns for different structural elements.

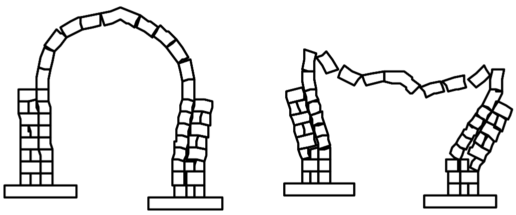

Figure 3 : Collapse sequence for a gothic arch subjected to settlement and seismic action.

4. ANALYSIS OF CASE STUDIES

Some case studies corresponding to real structures were also analysed and their seismic vulnerability assessed. Among the analysed case studies are the Lisbon aqueduct, that survived the 1755 Lisbon earthquake and the S. Giorgio in Trignano bell tower in S. Martino del Rio, Italy, which was seriously damaged during the October 1996 earthquake [8].

Figure 4 displays the possible longitudinal collapse mode for the Lisbon aqueduct, for which a very large acceleration would be necessary.

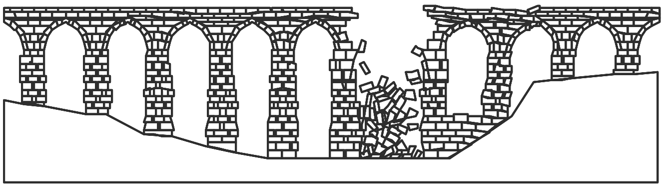

Figure 4 : Longitudinal mode of collapse for the Lisbon aqueduct.

Figure 5 displays the collapse sequence for the bell tower that would occur for a seismic action slightly higher than the observed one. The kind of damage that can be seen in the early stages of the sequence shown in this picture is in agreement with the “in loco” observed damage.

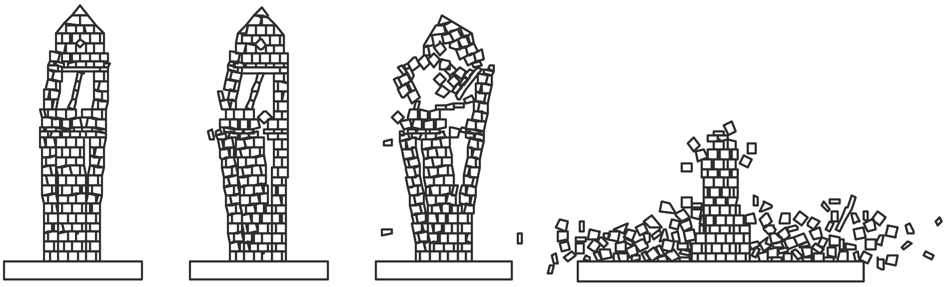

Figure 5 : Collapse sequence for the S. Giorgio in Trignano bell tower.

To analyse reinforcing schemes using cables, an added capability was introduced to the UDEC program, making possible the consideration of cables connecting any two blocks in the structure and with the capability to consider initial pre-stressing.
Possible reinforcement schemes were thus tested in the different structures with the introduction of these reinforcing cables, either made out of steel or other innovative materials [7].

Figure 6 displays the simulation of the bell tower response to the same seismic action when using two different reinforcing schemes (vertical cables or vertical and horizontal cables) as compared to the response of the unreinforced tower (left picture).

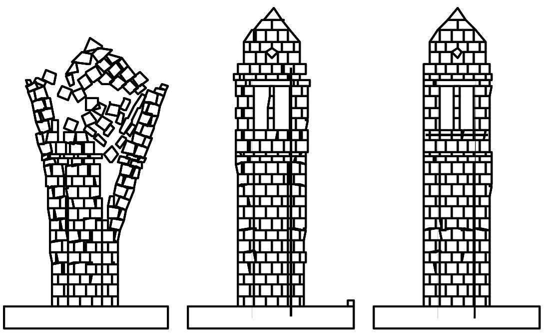

Figure 6 : Bell tower seismic response with alternative reinforcing schemes.

5. CONCLUSIONS

It was shown that the discrete element method can lead to a correct representation of the structural behaviour of blocky masonry structures, including the collapse patterns under seismic loading.

6. ACKNOWLEDGEMENTS

Part of the present work is related to activities developed in the framework of the ISTECH Project, ENV4-CT95-0106, Project nº PL 950852, 1996, financed by DGXII of the European Commission, which support is acknowledged. Financial support of PRAXIS XXI by means of a Ph.D. grant NR. BD/11180/97 awarded to G. Sincraian is also acknowledged.

7. REFERENCES

[1] Croci, G., 1998, The conservation and structural restoration of architectural heritage**,** *Computational Mechanics Publications*, 1998.

[2] Croci, G., 1998, The collapse occurred in the Basilica of St. Francis of Assisi and in the Cathedral of Noto**,** *Structural Analysis of Historical Constructions II*, (Eds. Roca, Gonzalez, Oñate, Lourenço), CIMNE, Barcelona, 1998, pp. 297-317.

[3] Macchi, G., 1998, Seismic risk and dynamic identification in towers – A Keynote Lecture, *Proc. Monument-98, Workshop on Seismic Performance of Monuments*, Lisbon, Portugal, 1998, K3-K17.

[4] Lemos, J.V., 1998a, Numerical models for seismic analysis of monuments - A Keynote Lecture, *Proc. Monument-98, Workshop on Seismic Performance of Monuments*, Lisbon, Portugal, 1998, K19-K36.

[5] Azevedo, J., Sincraian, G., and Lemos, J.V., 2000, Seismic behavior of blocky masonry structures, Earthquake Spectra, **16** (2), 2000, 337-365

[6] Cundall, P.A., 1971, A computer model for simulating progressive large scale movements in blocky rock systems', in *Proc. of the Symposium of the International Society of Rock Mechanics* (Nancy, France, 1971), **1**, Paper No. II-8.

[7] Itasca Consulting Group, Inc., UDEC – Universal Distinct Element Code, version 3.1 – User's manual, Minneapolis USA, 2000.

[8] Forni, M. et al., 1997, Rehabilitation of cultural heritage damaged by the 15th October 1996 Earthquake at San Martino in Rio, Reggio Emilia, Italy, *Proc. International Post-SMiRT Conference on Seismic Isolation, Passive Energy Dissipation and Active Control of seismic Vibrations of Structures*, Taormina, Italy, August 25-27, 1997.