

Exploring Historical Masonry Structural Behavior Using Modern Finite Element Based Method: A Brief Review

Manik Deshmukh*

Assistant Professor, Department of Civil Engineering, SVERI's College of Engineering Pandharpur, Maharashtra, India

Abstract – The study of masonry historical construction, encompassing both classical and advanced ones, is presented. Firstly, the paper offers a discussion on the main challenges posed by historical structures and the desirable conditions that approaches oriented to the modeling and analysis of this type of structures should accomplish. Secondly, the main available methods which are actually used for study masonry historical structures are referred to and discussed. The main available strategies, including limit analysis, simplified methods, FEM macro- or micro-modeling and discrete element methods (DEM) are considered with regard to their realism, computer efficiency, data availability and real applicability to large structures. A set of final considerations are offered on the real possibility of carrying out realistic analysis of complex historic masonry structures.

Keyword: BIM Model, Historical Building, Masonry Structure

-----X-----

1. INTRODUCTION

Masonry structures comprise a majority of the global built environment. These structures exist in the form of typical houses and office buildings, but also include a wealth of invaluable structures which compose the fabric of human history. Masonry refers to “the art and craft of building and fabricating in stone, clay, brick, or concrete block” (“masonry”, 2009)[1]. In this dissertation, masonry is used to refer to traditional masonry, often referred to as unreinforced masonry. The array of structures within this category is vast, ranging from historic stone structures to mortared brick structures still being constructed today.

The vulnerability of masonry structures and the need to reliably assess their seismic capacity, determining an increasing interest towards research subjects aimed at the study of the mechanical behaviour of masonry constructions. The numerical modeling of masonry structures through the FEM is a very computationally demanding task because of two different aspects: on the one hand the typological characteristics of masonry buildings do not allow us to refer to simplified static schemes, on the other hand the mechanical properties of the material lead to a widely non-linear behaviour whose prediction can be very tricky, besides the incomplete characterization of the material, due to the lack of reliable experiment.

The traditional approach to structural analysis relies on the elaboration of a specific disciplinary model, more or less sophisticated. With the advent of BIM (Building Information Modelling) technology, this process is starting to change, at least for which concerns new buildings. In fact, thanks to the increasing level of BIM interoperability, the same model can be used for many purposes by exchanging the information between the different figures involved in a project. In particular, for the structural field, specific BIM packages exist and can perform finite element analysis; however they can deal only with simple and regular geometric objects. On the contrary, for existing buildings, especially historical ones, this procedure results to be not feasible for many reasons, one of which is the complexity of real geometry. The transformation of a 3D architectonic model into a finite element model (FEM) with the meshing procedure may appear to be a trivial operation, but, in reality, a lot of subtle measures, not trivial at all, have to be taken, in order to get a compatible and regular mesh. For this reason, it is important that, since the beginning of the modelling phases, the analyst must take care not only about the perfect shape reproduction but also to the fulfillment of the requirements needed for a structural model. Thus, what is really important is a rationalization of the shapes to be included in the model, being able to distinguish the irregularities and complexities that can influence the mechanical behaviour of an

element, such as vaults or irregular walls, from the small irregularities not relevant from a structural point of view.

2. REVIEW OF LITERATURE

Conservation and restoration of historical structures have recourse to structural analysis as a way to better understand the genuine structural features of the building, to characterize its present condition and actual causes of existing damage, to determine the true structural safety for a variety of actions (such as gravity, soil settlements, wind and earthquake) and to conclude on necessary remedial measures. In short, structural analysis contributes to all the phases and activities (including diagnosis, reliability assessment and design of intervention) oriented to grant an efficient and respectful conservation of monuments and historical buildings. Accurate structural analysis is needed to avoid erroneous or defective conclusions leading to either over-strengthen the structure, causing unnecessary loss in terms of original material and cultural value, or to insufficiently intervene on it, and hence generate inadmissible risks on people and heritage. Unsurprisingly, ancient structures have been studied, since long time ago, using the most advanced tools available for structural assessment. The application of advanced computer methods to the analysis of historical structures was pioneered by the studies of the Brunelleschi Dome by Chiarugi et al. [2], the Pisa Tower by Macchi et al. [3], the Colosseo in Rome by Croci [4], see also Croci and Viscovik [5], Mexico Cathedral by Meli and Sánchez-Ramírez [6] and San Marco's Basilica in Venice by Mola and Vitaliani [7], among others. By then, the development of methods for accurate analysis of steel and concrete structures, including non-linear applications, was already at a very advanced stage thanks to the work of Zienkiewicz and Taylor [8], Ngo and Scordelis [9] and many others. Notwithstanding, analysts attempting to use computer tools for the study historical structures were by then facing overwhelming challenges. Methods then available were not yet prepared to 300 P. Roca et al. tackle the specific problems of ancient constructions concerning materials, structural arrangements and real preservation condition. In fact, the difficulties posed by historical structures are still very challenging, and still reminiscent of those encountered by the pioneers, in spite of significant progress during the last decades. Some of difficulties encountered are related to the description of geometry, materials and actions, all of which acquire remarkable singularity in the case of historical construction. Additional important difficulties are related to the acquisition of data on material properties, internal morphology and damage, as well as to the adequate interpretation of structural arrangements, overall organization and historical facts. Because of all these difficulties, it is generally accepted (Icomos/Iscarsah Committee [10])

3. SEISMIC ASSESSMENT OF MASONRY STRUCTURES

The safety of masonry structures in seismic regions? First, the majority of these structures did not benefit from modern engineering design, but instead resulted from empirical expertise. As a result, masonry assessment methods have naturally lagged far behind assessment methods for modern steel and concrete structures. Second, the long existence of many masonry structures yields several unknowns. In most cases, geometry is difficult to determine because construction drawings do not exist, and environmental factors have resulted in material degradation, support displacements, and damage during extreme events. Third, the basic nature of masonry remains difficult to model. Finite Element Modeling (FEM), the most widespread structural analysis tool, is tailored toward continuous structures which remain relatively connected during elasto-plastic failure under both static and dynamic loading. Masonry, on the other hand, is discontinuous by nature. Failure is brittle and individual units (e.g. stones, bricks) are often free to separate, especially during dynamic loading. While progress has been made towards modeling these behaviors using FEM, alternative methods are attractive but underdeveloped. Engineers remain divided in their emphasis on what is important: strength or stability. Certainly, the answer is a combination of the two, and largely depends on the nature of the specific structure. However, the assessment methods applied to these structures generally emphasize strength, while neglecting stability (Boothby 2001)[11]. There is need for integration of these two concepts, and an understanding for what is critically important. These difficulties have resulted in a misunderstanding of structural behavior of masonry. In turn, this has led to unnecessary interventions, and even destructive interventions, which must be prevented in the future. It has also made it difficult to identify which buildings are at risk of collapse.

4. THE DIFFERENT MODELLING APPROACHES FOR MASONRY

a) Modeling with FEM

The presence of vertical and horizontal mortar joints causes the masonry to be anisotropic. Basically, two different approaches have been adopted to model such anisotropy: the 'micromodel', or 'two-material approach', and the 'macromodel', or 'equivalent-material approach'. In the two-material model, the discretization follows the actual geometry of both the blocks and mortar joints, adopting different constitutive models for the two components. Particular attention must be paid in the modelling of joints, since the sliding at joint level often starts up the crack propagation. Although this approach may appear very

straightforward, its major disadvantage comes from the extremely large number of elements to be generated as the structure increases in size and complexity. This renders unlikely the use of micromodels for the global analysis of entire buildings, also considering the fact that the actual distribution of blocks and joints might be impossible to detect unless invasive investigations are performed. The macromodel assumes that the masonry structure is a homogeneous continuum to be discretized with a finite element mesh which does not copy the wall organism, but obeys the method's own criteria

b) Modeling with interface elements: The FEM

The blocks are modeled using conventional continuum elements, linear or non-linear, while mortar joints are simulated by interface elements, the 'joint elements', made up of two rows of superimposed nodes with friction constitutive law. The introduction of the joint is easy to implement in a software programme, since the nodal unknowns are the same for continuum and joint elements, though for the latter the stress tensor must be expressed in terms of nodal displacements instead of deformation components. Two major concerns balance the apparent simplicity of this approach.

- Block mesh and joint mesh must be connected together, so that they have to be compatible, which is possible only if interface joints are identically located. This compatibility is very difficult to ensure when complex block arrangements are to be handled, like in 3D structures.
- The joint element is intrinsically able to model the contact only in the small displacement field. When large motion are to be dealt, is not possible to provide easy remeshing in order to update existing contacts and/or to create new ones

c) Modeling with DEM

The above-mentioned limitations are overcome by the DEM. In this approach, the structure is considered as an assembly of distinct blocks, rigid or deformable, interacting through unilateral elasto-plastic contact elements which follow a Coulomb slip criterion for simulating contact forces. The method is based on a formulation in large displacement (for the joints) and small deformations (for the blocks), and can correctly simulate collapse mechanisms due to sliding, rotations and impact. The contacts are not fixed, like in the FEMDE, so that during the analyses blocks can lose existing contacts and make new ones. Once every single block has been modeled both geometrically and mechanically, and the volume and surface forces are known, the time history of the

block's displacements is determined by explicitly solving the differential equations of motion.

5. BIM TO 3D FINITE ELEMENT MODEL

The elaboration of a 3D FEM model capable to catch the complex shapes characterizing the load-bearing elements of an historical building (mainly vaults and irregular walls) into a structural analysis. Actually this is not yet possible to be made in a BIM perspective, because BIM software do not deal with 3D solid elements. So, the aim is to find a way to transform the 3D BIM model, already made for architectonic purposes, into a FEM model by exploiting the complex model. The software Midas FEA has been chosen for this work because it allows dealing with 3D elements and it gives the possibility to import advanced 3D geometry to be meshed. A lot of time can be saved in the phase of development of the FEM model, starting from the 3D architectonic BIM model, also taking the advantage of having a much more detailed model with respect to the usual simplified models adopted for these purposes. Previous works [2, 6] have found that, among the different formats that can be imported in Midas FEA, the format STEP is particularly suitable for maintaining the complex shapes during the exchange of information. The FEM model has been generated by using the automatic 3D meshing algorithm provided by Midas FEA. After some preliminary tests involving two different meshing (tetrahedral and hexa-dominant) algorithms, it has been decided to use tetrahedral elements which have been resulted in a better quality mesh. In order to limit the overall number of elements of the model, while maintaining a good quality of the results, a mesh size of 0.2 m has been set. This allows having at least 3–4 elements across the thickness of the load-bearing walls. The meshing process has requested a continuous modification of the BIM model, based on a trial and error procedure, because the most suitable drawings rules in order to achieve a good FEM were not defined a-priori owing to the originality of the work.

6. CONCLUSION

The geometric information together with the historical and diagnostic analysis. This procedure has implied a significant effort for its great interdisciplinary, required to deal with all the aspects of the problem when trying to consider different fields by using the same model for many purposes. This necessity has become evident especially in the modelling phase, where a lot of specific procedures have been checked in order to find the best way to convert the BIM model into a finite element model.

The global behaviour of the tested specimens, thus proving that they can be effectively used in the study of masonry structural elements. As a matter of fact, the actual ultimate strength in monotonic

loading can be predicted with good approximation performing non-linear push-over analysis. This good agreement with the experimental results seems to be encouraging. For the ABAQUS model, nevertheless, major concern derives from the inability to predict cyclic behaviour, so that further investigations are certainly needed, possibly involving the development of a fully masonry-oriented constitutive model.

7. REFERENCES

1. Masonry (2009). In Encyclopædia Britannica. Retrieved March 13, 2009, from Encyclopædia Britannica Online: <http://www.britannica.com/EBchecked/topic/368060/masonry>.
2. Chiarugi A., Fanelli A., Giuseppetti G. (1993). Diagnosis and strengthening of the Brunelleschi Dome. In: IABSE Symposium, IABSE, Zürich.
3. Croci G. (1995). The Colosseum: safety evaluation and preliminary criteria of intervention. Structural Analysis of Historical Constructions, Barcelona
4. Croci G. & Viscovik A. (1993). Causes of failures of Colosseum over the centuries and evaluation of the safety levels. In: Public assembly structures. From antiquity to the present. IASS-Mimar Sinan University, Istanbul, Turkey, pp. 29–52
5. ICOMOS/ISCARSAH Committee (2005) Recommendations for the analysis, conservation and structural restoration of architectural heritage.
6. Macchi G., Ruggeri M., Eusebio M., Moncecchi M. (1993). Structural assessment of the leaning tower of Pisa. In: Structural preservation of the architectural heritage, IABSE, Zürich, Switzerland, pp. 401–408
7. Meli R. & Sánchez-Ramírez A.R. (1995) Structural aspects of the rehabilitation of the Mexico City Cathedral. In: Structural analysis of historical constructions I, CIMNE, Barcelona, Spain, pp. 123–140
8. Mola F. & Vitaliani R. (1995). Analysis, diagnosis and preservation of ancient monuments: the St. Mark's Basilica in Venice. In: Structural analysis of historical constructions I. CIMNE, Barcelona, Spain, pp. 166–188.
9. Ngo D. & Scordelis A.C. (1964). Finite element analysis of reinforced concrete beam. J Am Concr Inst 64: pp. 152
10. Zienkiewicz O.C., Taylor R.L. (1991). The finite element method. McGraw Hill, New York
11. Boothby, T.E. (2001). Analysis of masonry arches and vaults, Progress in Structural Engineering and Materials, 3, pp. 246-256.

Corresponding Author

Manik Deshmukh*

Assistant Professor, Department of Civil Engineering, SVERI's College of Engineering Pandharpur, Maharashtra, India

kmda53@gmail.com