Construction and Building Materials 101 (2015) 287–297

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Application of a new methodology based on Eurocodes and finite element simulation to the assessment of a romanesque church

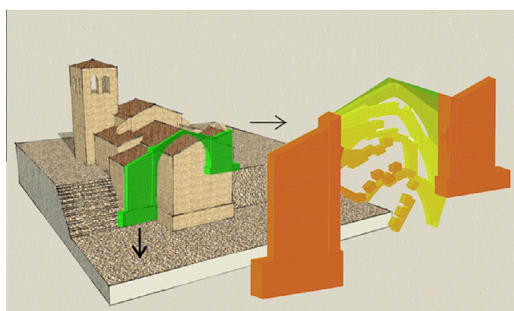
A. Ayensa [a], B. Beltrán [b], E. Ibarz [b], L. Gracia [b,*]

[a] Architecture School, San Jorge University, 50830 Villanueva de Gállego, Zaragoza, Spain
[b] Department of Mechanical Engineering, Engineering and Architecture School, University of Zaragoza, María de Luna 3, 50018 Zaragoza, Spain

HIGHLIGHTS

- Methodology based on Eurocodes and analysis of discontinuous MEF model is presented.
- Eurocodes reliability criterion and classical limit analysis approach are combined.
- Methodology allows checking all the ultimate limit states in any design situation.
- Ultimate limit states of SEQ, with sliding between blocks, STR and SBC are analyzed.
- Collapse progress can be predicted in case that the structure loses the stability.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 25 June 2015
Received in revised form 15 September 2015
Accepted 17 October 2015

Keywords:
Historical structures
Finite element models
Masonry
Stone
Arch
Vault
Church

ABSTRACT

This work proposes a methodology, based on finite element simulation, for analyzing masonry historical structures, according to Eurocodes, that has been applied for the assessment of the Saint Sebastian church, located in Piedratajada (Zaragoza, Spain). Settlement pathologies were detected and the aim of the work is to verify the current safety level and to propose reinforcement solutions if necessary. Results confirm the effect of soil settlement and allow establish the maximum admissible value. If that value is reached, a couple of reinforcement solutions, installing sheets of steel or carbon fiber composite, are proposed and analyzed.

1. Introduction

The most common methodology applied currently to check the ultimate limit state of static equilibrium (SEQ) of masonry historical structures is based on the application of the limit analysis criterion developed by Heyman [1] after the numerical or graphical resolution of the structural equilibrium equations system. It is based on a comparative study between the equilibrium situation of the structure and its limit situation considering the stability. The result of that study is the geometrical factor of safety [1] as an indicator of the safety of the structure considering its stability when any combination of loads is applied and fixed supports are considered at its foundation. The equilibrium situation of the

* Corresponding author.
E-mail address: lugravi@unizar.es (L. Gracia).

http://dx.doi.org/10.1016/j.conbuildmat.2015.10.115
0950-0618/

structure, applying this methodology, is determined considering the equilibrium equations, but not the compatibility and the material constitutive equations and therefore, the calculated result only depends on the geometry of the structure, the applied loads and the reactions considered at its supports. This methodology assumes the following hypothesis [1]:

- The masonry blocks are rigid elements and it is assumed that the material failure is not possible in compression.
- The masonry tensile strength is null. The cohesion due to the mortar located between blocks is not considered.
- The sliding between blocks is not possible.

The graphical representation of the equilibrium equations system solution is the funicular polygon that equilibrates the applied loads on the structure. From this polygon can be deduced the thrust line that allows knowing the minimum dimensions of the structure that are necessary to be in situation of static equilibrium and comparing them with the actual dimensions of the structure, the geometrical factor of safety can be determined. It is considered by Heyman [2] that a masonry historical structure is safe, in terms of stability, when its geometrical factor of safety is equal or higher than 2.

An essential aspect in the numerical simulation of historical structures concerns the constitutive laws that define the material behavior. On this respect, different papers can be found in the specialized literature. So, different authors focus their research on the development of constitutive laws for masonry and the interfaces (Benedetti [3], Lourenco [4]). Other authors use specific constitutive laws in the finite element simulations (Dhanasekar [5], Giordano [6], Kishi [7]).

In the experimental field, some authors have applied different techniques for the strength assessment of de masonry walls (Binda [8], Corradi [9]). Other authors apply experimental techniques for the structural integrity assessment (Ercan [10]).

Most of the published works are focused on the structural integrity after seismic effects (Betti [11], Castellazi [12], Corradi [13], de Luca [14], Kishi [7], Mallardo [15]) in order to evaluate firstly the damage induced by the earthquake, and then to study reinforcement solutions that allow recovering the stability and functionality if possible. Most of these works (Betti [11], Castellazi [12], Mallardo [15], Modena [16], Valluzzi [17]) deal with the study of huge monumental buildings like churches, cathedrals, aqueducts, etc., by using experimental techniques (Valluzzi [17]), computational models based on the finite element method (Betti [11], Castellazi [12], Modena [16], Valluzzi [17]), or a combination of both (Ercan [10]).

Concerning structural analysis, in the situations where the hypotheses that are assumed by the limit analysis criterion are not satisfied, the ultimate limit state of structural resistance (STR) should be checked. The most common methodology applied currently to check this ultimate limit state of masonry historical structures is based on the application of the FEM based approaches described by Roca [18] which take into account the equilibrium, compatibility and material constitutive equations and therefore, they also allow checking the ultimate limit state of SEQ in these particular situations although not to know the geometrical safety factor of the structure. E.g. a macro-model was used by Roca [19] in the analysis of the Küçük Ayasofya Mosque in Istambul and a micro-model was used by Lourenço [20] in the analysis of masonry shear walls. A widespread review concerning the different techniques used for analyzing and repairing historical structures can be found in Roca [18].

The majority of works applying FEM to historical structures are devoted to evaluate the damage induced by earthquakes, and then to study reinforcement solutions that allow recovering the stability and functionality. Besides that, other authors analyze the structural behavior of historical structures under different conditions. So, in Del Coz [21] a study of the structure of the chapel of San Salvador de Valdediós (Spain) and proposals for its restoration are presented, considering the severe damage detected in the chapel vault. The Romanesque Farneta abbey (Italy) is analyzed in Betti [22] in order to assess the effectiveness of the usual structural reinforcement in terms of increased the seismic capacity. In Romera [23,24] the Basilica of Pilar (Spain) is analyzed by means of a set of structural models of the entire temple and local models of the Regina Martirum dome identifying the actual structural state of the church, its safety level and the relationship between the structural behavior and the damages observed. A study on the bell tower of the Church of Santas Justa and Rufina (Spain) is carried out in Ivorra [25] to predict the evolution of its dynamic behavior in relation to subsidence caused by variations in the level of the water table during periods of drought. Finally, the static behavior and the seismic vulnerability of the Basilica of Santa Maria all'Impruneta (Italy) are analyzed in Betti [26], evaluating the capacity of the church to withstand lateral loads together with the expected demands resulting from seismic actions.

In this context, the aim of this work is the assessment of the Saint Sebastian church, located in Piedratajada (Zaragoza, Spain), in which were currently detected several cracks, which could be due the soil settlement. In a first step, the structure is analyzed in normal conditions; in the second step, the influence of soil settlement effects are analyzed, determining its maximum admissible value; finally, in the third step, a couple of reinforcement solutions are studied in order to guarantee the requested structural safety in the long term. The Eurocode criteria have been considered for the structural assessment.

2. Materials and methods

2.1. Description of the assessed church and current pathologies

The Saint Sebastian church, located in Piedratajada (Zaragoza, Spain), was built based on the romanesque architecture style in the 14th century and it suffered a refurbishment in the 16th century, when its roof was removed and it was built again based on the gothic architecture style. The church was restored in 1990 in order to improve its appearance but new cracks have been detected currently. The origin of these pathologies appears to be the soil settlement shown in Fig. 1, which was detected at the west area of the church. Consequently, a portal frame of the structure has been assessed in order to check the current safety level of the structure in the affected area according to the Eurocodes and to propose the optimal reinforcement of the structure if it will be necessary to increase its reliability.

2.2. Methodology basis

The proposed methodology in this work for the assessment of masonry historical structures as the Saint Sebastian church, is based on the analysis of a discontinuous FEM model created under a particular criterion which allows checking both the ultimate limit state of SEQ through the geometrical factor of safety and the ultimate limit states of STR and soil bearing capacity (SBC), according to the Eurocodes, under the consideration of the following hypotheses:

- There is no tensile strength at the joints between blocks.
- The shear strength of the masonry is limited by the tensile strength of the blocks (masonry units) and the static frictional coefficient in the contact surfaces between blocks.
- The brittle facture of the blocks occurs in tension as the elastic limit in tension is reached.
- Plastic deformation and crushing appear as the elastic limit in compression of the masonry is reached.

2.3. Geometric model

The dimensions of the assessed portal frame are shown in Fig. 2. They have been used to create the geometric model of the church which represents the "design" shape of the historical construction, not the current shape that is affected by the execution tolerances and the action of loads or settlements. This geometric model