Cracks modelling in presence of notch and seizure effects in historical buildings damaged by an earthquake in Piedmont

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Abstract

A moderate earthquake shock (VII MCS) struck the central-southern part of Piedmont in August 2000. The area hit most severely included several towns in the provinces of Asti and Alessandria. A plan of urgent interventions on damaged historical and monumental buildings was produced through the joint efforts of the Superintendency, the Structural Engineering Department of Turin Polytechnic and the Administrative Offices of Technical Services of Prevention. In Asti and Alessandria 166 churches were damaged to a significant extent. The CNR – GNDT data sheet was compiled for each church. By processing the data it proved possible to have a global vision of the upkeep and vulnerability of the churches; 57% of them suffered minor damages (0 < id < 0.1). In most cases (65%) the index of damage was lower than the index of vulnerability.

A damaged church was analysed with the aid of a FEM based computer code in order to determine the static behaviour and the dynamic response of the buildings in the case of future seismic events. The model was produced by taking into account the vulnerability elements of the church, such as the formation of cracks due to seismic shocks, building discontinuities, historical static damages,. The computer code used was DOLMEN WIN by CDM of Turin. In order to obtain simulations of the behaviour of the building during an earthquake shock, the church was subjected to Equivalent Static Analysis. Cracks were modelled with and without seizure between bricks.
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1 Introduction

The analysis of a building damaged by a seismic event begins by identifying its vulnerability elements and studying damage, as this, in addition to revealing needed repairs, provides an understanding of the resistant mechanisms activated in the structure and the failure modes to be counteracted in view of future seismic events. If the building analysed is made of masonry, as in our case, representing its behaviour by means of a numerical model will often be difficult, since its constituent material is anisotropic, non homogeneous, and is characterised by differences in terms of tensile and compressive strength and well as uncertainties as to the connections between the individual structural elements. If the brickwork of the building is historical, in addition to the complex non linear mechanical behaviour of the building in the field of major transformations, the model should also take into account the heterogeneity of the masonry elements brought about over time by corrosion phenomena or by works performed on the building during its lifetime.

At present, the modelling of a masonry building for the study of its static and dynamic behaviour can be achieved in two ways: one consists of representing the building by means of a local model that breaks the building into individual masonry diaphragms subject to specific failure mechanisms; the other consists of representing the building by means of a global model, based on the finite element method, which makes it possible to capture implicitly the interactions between the different constituent elements of a structure.

Following the earthquake that hit Piedmont in August 2000, a plan of urgent interventions on damaged historical and monumental buildings was produced. With a view to using the modelling approach based on the finite element method, it was decided to model one of the damaged churches. The chosen church is an isolated building, geometrically and dimensionally simple. The vulnerability elements introduced into the global model included: lesions ascribed to the seismic shock of August 2000, the discontinuities in the masonry due to historical transformations (openings filled with brickwork), historical damage of a static nature (damage due to settlements of the foundations). In the realisation of the global model the attention was focused on the representation of lesions, whether pre-existing or caused by the earthquake itself.

2 Modelling the church

The church was modelled with the finite element computation code, DOLMEN WIN, an integrated system of dedicated procedures for civil and structural engineering applications developed by CDM DOLMEN of Turin; this computation code yielded good results for the modelling of the building in question, the main limitation lying in the fact that the masonry was considered as elastic and isotropic. Whenever this simplification entailed results that did not match actual conditions, especially as concerned the location and values of tensile stresses, this was remedied by reducing the linear elasticity modulus of
the masonry, from 20000 daN/cm² to 200 daN/cm², thereby depriving it of the tensile strength ascribed to it by the code.

The masonry walls and vaults of the church are represented by means of "shell elements": two-dimensional elements subject to axial and bending stresses.

In addition to the cracks, the model also takes into account the discontinuities associated with openings in the masonry filled at some later stage: these were considered without the added brickwork, as if they were still open, because the added brickwork is often poorly bonded to the rest of the masonry so that, in an earthquake, the wall and the brickwork filling will oscillate in different ways and come apart.

Figure 1: Local reference system of the shell element and its stress components.

Six stress components, \(\sigma_x\), \(\sigma_y\), \(\sigma_{xy}\), \(M_x\), \(M_y\), \(M_{xy}\), are transferred to the shell element; these stress components are associated with five movements blocked in space: movements along the x, y, z axes, rotations around the x and y axes; no stress is produced by the rotation of the shell around its axis z, in other words, the shell has no stiffness associated with its movement around this axis and responds to a global rotation with local rotations around the nodes. It proved necessary to take into account this internal relief mechanism specific to "shell" type elements when modelling the cracks in order to determine the value of seizure between the masonry elements.

Figure 2: Overall dimensions of the solid portions of the vault system.
3 Modelling the cracks

Cracks were modelled by means of "rod" elements, each rod element being delimited by an initial and a final node. Each node can move along the x, y, z axes and rotate around the x, y, z axes, to a total of six movements each of which is associated with a specific state of stress, N, Ty, Tz, Mx, My, Mz, being associated with each of these movements.

Figure 3: Overall dimensions of the solid portions of the walls and stiffening arches of the vault system of the church.
Each rod element was defined in relation to its geometry and inertia, i.e. as a function of its stiffness in the direction of the three local reference axes, $x$, $y$, $z$. Rod geometry was defined with reference to the dimensions of three courses of bricks; dimension $y$ of the rod element turned out to be 20 cm, $z$, the dimension representing the thickness of the wall, turned out to be 64 cm, while dimension, $x$, representing the opening of the crack, was taken to be 2 cm.
The shell element has no stiffness around its axis z and translates the global elements to which it is subject into local rotations. A rod element placed between coplanar shells is hinged at the ends and therefore is not subject to bending stresses in the y direction.

By modelling the crack by means of hinged rods it becomes possible to represent the behaviour of an open crack, i.e. with no contact between the masonry elements and hence no seizure. If these hinged rods are assumed to have nil area and nil inertia in the x direction, the faces of the cracks (at the nodes of the rods) can move apart without generating axial stresses.

3.1 Cracks in the absence of seizure

The absence of seizure can be assumed when the masonry faces of a crack are not in contact with one another, or are made of weak elements, which break easily and hence do not generate sufficient friction. In these circumstances, the damaged wall behaves as if it were made of independent masonry diaphragms, in which the distribution of stresses is a function of the loads applied to each portion of the masonry.

From the colour maps showing the principal stresses caused solely by the dead loads of the structure, we can clearly see that the evolution of the principal compressive stresses in each masonry portion is a function of the loads applied directly to it; compressive stresses increase in value proportionally with the loads as we move towards the bottom. From an analysis of the principal tensile stresses due solely to the dead loads of the structure, instead, we find that in the absence of seizure, the highest stresses concentrate at the roots of the cracks, where a notching effect fostering the propagation of the crack can also be observed.

Figure 7: Compressive stresses (daN/cm²) in two cracked walls, in the assumption of absence of seizure between the opposite faces of the cracks.
Figure 8: Principal tensile stresses (daN/cm²). The highest values of the tensile stresses concentrate at the roots of the cracks where a notching effect fostering crack propagation is also present.

3.2 Cracks in the presence of seizure

In the presence of seizure, the two masonry faces on the opposite sides of the crack are assumed to collaborate with one another. In order to model this assumption with DOLMEN WIN was necessary to change the horizontal rods simulating the crack from hinged at the ends to restrained at the ends, so as translate the concentrated moments transferred by the shells into couples of forces transferred into the rod element. To create the restraint conditions along the boundaries of the crack, new rod elements adjacent to the shells were added and assigned the same geometry and same inertia values as the horizontal rod elements.

From an analysis of the principal tensile and compressive stresses it has been determined that in the presence of seizure the notching effect is less pronounced than in the absence of seizure; between the two masonry faces divided by the crack there is collaboration and therefore the stresses are distributed over a larger resistant area.
Conditions of dead load: seizure.

Figure 9: Colour maps showing the principal compressive stresses [daN/cm²] in the assumption of the presence of seizure between the masonry elements; stresses are distributed over a larger area.

4 Conclusions

In order to simulate its behaviour under seismic shocks, the church was subjected to an Equivalent Static Analysis through the application of horizontal forces perpendicular to one another (x and y) not acting simultaneously. From a comparison between the stresses and strains imposed by the earthquake on the church in question, in the x and y directions respectively, it was ascertained that the church is especially vulnerable in the y direction, due to low stiffness and the presence of cracks in the walls arranged parallel to the seismic action, i.e., the walls responsible for counteracting this action. In actual fact, as can be seen from the colour maps illustrating the stresses, even in the assumption of seizure, stresses are lower in cracked walls, on account of their having lower stiffness, to the detriment of cracked parallel walls, and in particular to the detriment of the corner elements. The numerical analyses of bending stresses at the crack have shown that the value of seizure is non negligible; the highest value, recorded in the most adverse seismic condition in the y direction, ranges from 1 to 1.5 daN/cm².
A model of the church without the cracks generated by the earthquake of August 2000 was used to work out the direction of the seismic action under which the building demonstrated its vulnerability through the opening of cracks. By comparing the direction of tensile stresses with the pattern of real cracks, it was determined that the seismic shock that generated the cracks was the one acting in the $-$ $y$ direction; the values of the tensile stresses that produced the cracks, as determined with the finite element method, ranged from 1 to 2 daN/cm$^2$; it was also possible to obtain a confirmation of the configuration of the cracks, which was found to depend primarily on the geometry of the wall, and, in particular, on the positions of the openings.
Figure 11: Left: representation of the principal stresses as vectors. Right: principal tensile stresses, as revealed by colour maps, in the uncracked facade under the seismic action in the -y direction.

References


