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# Annex and rigid diaphragm effects on the failure analysis and earthquake damages of historic churches

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ABSTRACT

Historical churches, in the most of cases, are characterised by the presence of annexes and rigid diaphragm that influence their seismic response. Therefore, this research aims to investigate the disadvantages and the benefits which emerge during the horizontal dynamic actions between these structures. This study presents some analyses carried out on the Gesù Church in Mirandola, which was damaged by the 2012 Northern Italy earthquake.
The first fundamental steps have been the geometrical, material and in particular the seismic damage survey. An undamaged finite element model of the actual configuration of the Gesù church with a perfectly connected annex was created and was also considered the same model as an isolated structure. Through these FE models preliminary modal dynamic analyses were conducted in the linear elastic field. Subsequently non-linear static analyses were carried out to investigate the ultimate capacity of the building.
The churches are characterised by large halls without internal thorn walls, slender walls, pushing elements and lack of intermediate horizontal connection. All these factors lead each macroelement to have an independent dynamics, showing the absence of box-like behaviour. Since the roof trusses are one of the few structural elements that can determine a better global behaviour, it has been decided to perform the same numerical analyses even in the FE models without the roof, then considering the extreme case of a not effective simply supported roof.



## 1. Introduction

Mediterranean countries are particularly rich in historical heritage monuments and unfortunately are located in geographical areas with high seismic activity. In particular, historic masonry churches present the most vulnerable structural configuration to dynamic actions, especially on the seismic one. The accelerated ageing process due to environmental factors [1], the historic buildings are vulnerable to dynamic loads, as seismic and wind action [2] which may induce a local collapse or a rapid global failure.

Churches usually are characterised by a high seismic vulnerability due to their structural and geometric configurations, heterogeneous and deteriorated materials. These structures have very large and high walls without internal orthogonal walls and the presence of some thin vaults or thrusting arches. Furthermore, the macroelements present an autonomous dynamic behaviour mainly caused by the lack of rigid intermediate horizontal diaphragm. For this reason, historic churches often show the absence of box-like behaviour.

The systematic damage survey observed in the historic churches hit by the Friuli earthquake [3] has led researchers to define the concept of the macroelements (such as facades, nave, transept and apse), for which the collapse mechanisms are determined on the observation of their independent failure. The research done on the damage survey after the Umbria–Marche earthquake [4] confirms

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that the problem of the local failure is generalised and fairly recurring. As a matter of fact, this problem is mostly due to the absence of adequate masonry connections between the different macroelements. The lack of connection, between these orthogonal walls, is often due to a bad execution of the work and materials with poor mechanical properties.

In this particular scientific field, there are some approaches used to analyse the seismic behaviour and capacity of masonry structures. The most appropriate methods to verify the seismic vulnerability are the limit analysis and non-linear FE analysis. These approaches have the purpose to evaluate the activation load of the failure mechanisms of the macroelements.

Italian Guidelines for the Cultural Heritage [5] presents a schedule of twenty-eight potential collapse mechanisms, based on experience of failures observed in the historic churches during past earthquakes, as already mentioned above. It is necessary, however, considering that this approach presents the risk to exceed the estimation of the horizontal acceleration at collapse. For this reason, it is indispensable to consider additional methods of analysis, for example the FE limit analysis procedure that has been recently applied on many churches in seismic areas [6]. An alternative to limit analysis is represented by the static non-linear analysis considered in this paper. In more detail, for this analysis, it is necessary to consider both a horizontal load uniformly distributed to the church that one associated with the main vibration mode of the structure. A more accurate analysis is the non-linear dynamic analysis which seems to get more precise results as the collapse acceleration and the behaviour factor [7]. However, the static non-linear simplified analysis is accepted by the scientific community to evaluate the seismic capacity of the structure.

In the last decades the sequence of earthquakes stroked seriously the historic heritage, primarily the churches showing their intrinsic factor of weakness [8–13], mainly due to the absence of stiff intermediate diaphragm with the exception of the roofing. This is an issue that concerns all historic structures without box-like behaviour under seismic loading as showed by Lourenço et al. [14].

Concerning this theme it becomes necessary to investigate the weakness of these monuments through the analysis of the possible local collapse of the macroelement, the material and damage survey, the structural identification procedures and the subsoil–structure interaction [15,16].

The old towns often appear as the result of an uncontrolled structural development that leads the interaction between these ancient buildings when exposed to horizontal actions [17]. An extremely high number of churches are located in these complex structural configurations, as a matter of fact they have often annexed buildings such as convents, sacristy, tower or minor constructions.

The first operation is the historical analysis to determine the construction phases of the church and of the annexes. Very important is also the study of the documentations of the structural interventions. There could be, for example, interventions that made a more stiffened one of the structure to the other.

In addition to the churches that belong to the aggregates in the historic centres, the cases of incorporated churches, present in all over the world, are the different types of monasteries. As a matter of fact, this amazing complex structures are the most clear and spread example of churches affected by the presence of the annexes. These other buildings can affect partially the church (in width and height) or fully incorporate it.

The paper presents the case study of Gesù Church in Mirandola and its annex, the Jesuit College, hit by the earthquake that occurred in May 2012. Through this case study the collapse behaviour of a historic church constrained by a building of significant dimensions was analysed; how the annexed College affected the seismic behaviour of the church was discussed. This church and this topic have already been partly discussed in the previous article [18] of the authors, however, only in the linear elastic field. It was also decided to understand how the presence of a rigid diaphragm given by an effective roof may affect this particular structural context. The study was carried out through a preliminary dynamic analysis and subsequent non-linear static analysis through a global FE model.

## 2. The Gesù Church and the damage

The Church of Gesù has a considerable annex to the south: the Jesuit College (Fig. 1). This annex was inaugurated a 'year later of the conclusion of the construction of the church in 1689'.

This typical basilica plan (Fig. 2) was characterised by a large single nave which presents on both sides of the two chapels. The transept and the apse have significant geometrical size both in plan and in height and are linked on both sides to the sacristy.

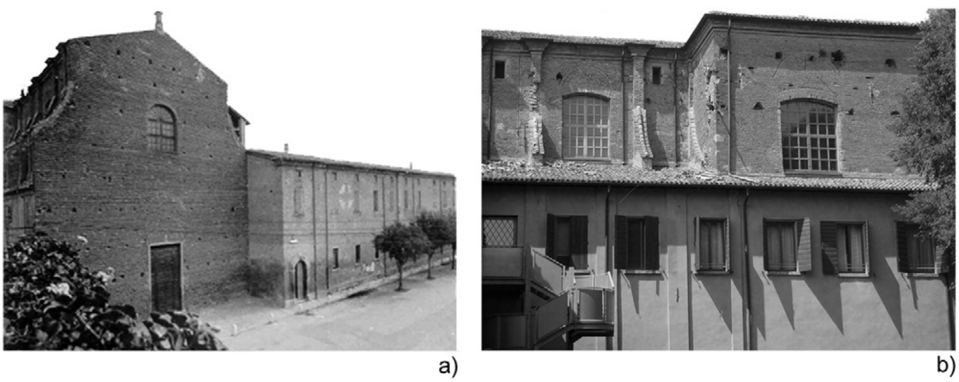


**Fig. 1.** Church of Gesù, view of the façade and annex (a) and of the south side with the lower annex (b).