Analysis of the Influence of Atriums in Seismic Performance of RC Primary School Buildings

Beatriz Zapico-Blanco, Maria-Victoria Requena-Garcia-Cruz, Emilio Romero-Sánchez, Jaime de-Miguel-Rodríguez, and Antonio Morales-Esteban

1 Introduction

Most of the Spanish primary school buildings were built prior to the enforcement of the PGS-1 [1], the seismic code that first introduced a seismic action value for Huelva. The code provided basic considerations, only applicable to the design of new buildings. It was not until 1994 that a more demanding and enforcing code was released: the NCSE-94 [2]. This code was more rigorous, including a probabilistic seismic hazard analysis and more advanced guidance for new buildings seismic design. Consequently, buildings constructed prior to that date were designed with very little or no seismic considerations.

Moreover, primary schools present a high child-to-adult ratio, which compromises the effectiveness of the evacuation plans [3]. In addition to this, it has been observed that children can be severely traumatized by catastrophic events [4] and have a comparatively difficult recovery process.

B. Zapico-Blanco (✉) · M.-V. Requena-Garcia-Cruz · E. Romero-Sánchez ·
J. de-Miguel-Rodríguez · A. Morales-Esteban
Department of Building Structures and Geotechnical Engineering, University of Seville, Av. Reina Mercedes, 2, 41012 Seville, Spain
e-mail: bzapico@us.es

M.-V. Requena-Garcia-Cruz
e-mail: mrequena1@us.es

E. Romero-Sánchez
e-mail: eromero13@us.es

J. de-Miguel-Rodríguez
e-mail: jdemiguel@us.es

A. Morales-Esteban
e-mail: ame@us.es

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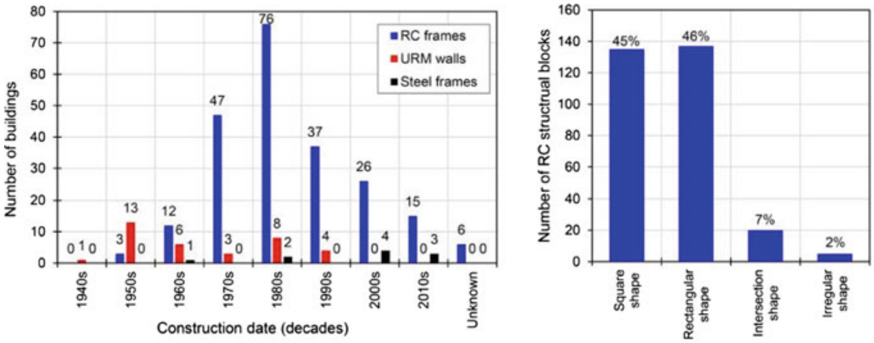
In brief, the school community is characterized by a low seismic resilience [5]. In this context, the European project named PERSISTAH (*Projetos de Escolas Resilientes aos SISmos no Território do Algarve e de Huelva*, in Portuguese) aims to increase the seismic resilience of the schools located in the Algarve (Portugal) and Huelva (Spain) regions [6]. The south-western Iberian Peninsula is affected by far away earthquakes of long return period and of large magnitude [7], due to its proximity to the Eurasia-Africa plate boundary. Buildings in this area have been severely damaged in the past by relevant seisms such as the 1344, 1531, 1722, 1755, 1859 and 1909 earthquakes [8]. In order to achieve the goal of the project, two parallel paths are undertaken: to increase the awareness of the school community and to analyse the seismic performance of the buildings. This paper concentrates on the latter.

When assessing the seismic vulnerability of the existing building stock, several paths can be followed. In this case, the assessment was performed at a regional level, which requires data of a large number of buildings. Resorting to detailed inspections in this scenario is not realistic, and the use of simplified methods, such as the Index Building Approach, for gathering enough data and information is required [9]. The first step to assess the vulnerability of the school buildings is to properly classify the population under study. Several groups which could potentially share a similar seismic behaviour have been identified. Within each group, a representative building has been selected as index of the typology, which has been assessed in detail. The conclusions of the analysis, as well as the retrofitting schemes prescribed, can thus be conceived at typology level, and then be slightly adapted to each individual building.

With the aim of determining the characteristics that define each typology, several sensitivity analyses have been done, quantifying the relative relevance of each feature studied. This paper is focused on the existence of an atrium and its position. This is the most recurrent irregularity of the population studied and a potential weak point of these building, together with the existence of short columns in the basement, which is the object of separated study [10]. To assess the influence of this parameter, different versions of the index building model, varying the position of the atrium, have been analysed. Nonlinear static analyses have been used to study the respective seismic performance of these models, with special attention to the effect of the addition of the atrium on the torsional behaviour and hence the modal participation mass, which could invalid the method (see Sect. 3.3).

2 Characterization of the Schools

First, the schools of the Spanish province of Huelva (139 in total) have been characterized. The school complexes are composed of one to six individual buildings, adding up to 267 buildings. Data about the buildings have been gathered employing the available information sources in each case: original and rehabilitation projects, aerial images, visits, *ad-hoc* surveys sent to the schools, etc. Then, the information has been processed. First, a general classification, based on the structural type (Fig. 1a), has been carried out. The buildings present three main structural types:



a

b

Fig. 1 **a** Number of buildings per construction date and structural system, **b** Number and percentage of RC structural blocks based on their general geometry

reinforced concrete frames (RC), unreinforced masonry, and steel structures. The most represented type is the RC structure which is a 83% of the total (Fig. 1a).

The work described in this paper is focused on the study of the aforementioned group and the paper will refer exclusively to it from now onwards. The RC structures studied present structural joints, which divide the buildings in different structural blocks that need to be analysed separately. 297 blocks have been identified.

The RC blocks have been divided into groups depending on their geometrical shapes: *square*, *rectangular*, *intersection* and *irregular* (Fig. 1b). *Square* blocks are the most regular, with similar dimensions in both directions. *Rectangular* blocks are characterised by a predominant dimension, which is at least twice as big as the orthogonal one. *Square* and *rectangular* are the predominant types, with a 45% and a 46% of the total population, respectively. The other two groups are not representative (<10% of the population). The present paper focuses on the *rectangular* RC blocks, since they are potentially more vulnerable than the *square* ones, given their comparatively larger asymmetry.

Rectangular RC blocks can be divided in four subgroups: *small*, *medium*, *large* and *L shape*. Again, the first two groups are the most representative ones, being 42% and 40% of the population, respectively. *Small rectangular* blocks are very regular in both plan and elevation, and present one single storey. *Medium rectangular* blocks are similar to them, but bigger in plan and with two storeys, which makes them potentially more vulnerable to the seismic action. The index building selected for the present work belongs to this sub-group.

In these buildings, the RC structure is completed with perimeter infill walls. Infill walls can influence the seismic behaviour of the buildings, especially when irregularly distributed [11]. A recurrent characteristic of the population studied is the presence of atriums. Where an atrium is present, some infill walls are removed and others are added, creating an irregularity and potentially changing the seismic performance of the building. In the present work, the sensitivity of this typology to the existence and the position of the atriums is studied.

In the case of *rectangular blocks*, one or more atriums are present in 39% of the buildings, while it has not been possible to verify their presence in 33% of them. Atriums can be found in the corner or in the middle bays of the block and on one or two floors. They can be distributed either symmetrically or asymmetrically.

3 Method

3.1 Building Configurations

The analysis has been carried out considering a case study/index building (Fig. 2). The index building has been selected on the basis of its representativeness of the typology under study (*Medium regular RC blocks*) and because of the completeness of the available information about it (blueprints and specifications). The building is a two-storey RC structure constructed during the 70s, like most of the buildings of this typology. It presents nine RC frames in the Y direction and four irregular bays in the X direction. The building has a slab on the ground floor, which generates short columns. This is another important irregularity of the building with a strong effect on its seismic behaviour, as can be seen in [10]. All floors are composed of ribbed slabs spanning in the Y direction. The building's initial situation (IS) can be observed in Fig. 2.

The geometrical characteristics of the RC frames are listed in Table 1. The RC compressive strength (f_{ck}) is 17.5 MPa and the steel minimum yield stress (F) is

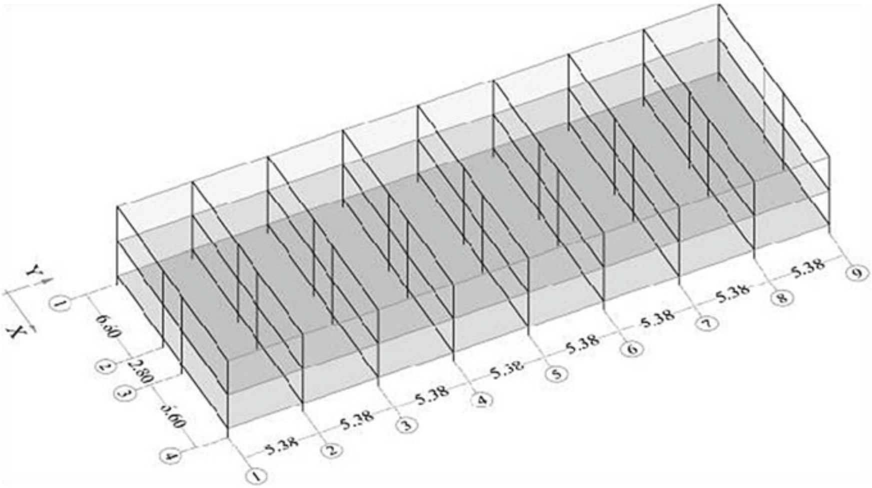


Fig. 2 3D model of the case study building, Initial Situation (IS)

Table 1 Geometrical characteristics of the RC frames

Structural element	Columns	Load beams	Tied beams
Dimensions	40 × 30 cm	40 × 30 cm	30 × 30 cm
Longitudinal Rebar	4Ø12 mm	Top: 2Ø12 mm	Top: 2Ø12 mm
		Lower: 4Ø16 mm	Lower: 2Ø12 mm
Transversal rebar	Ø6 mm/20 cm	Ø6 mm/20 cm	Ø6 mm/20 cm

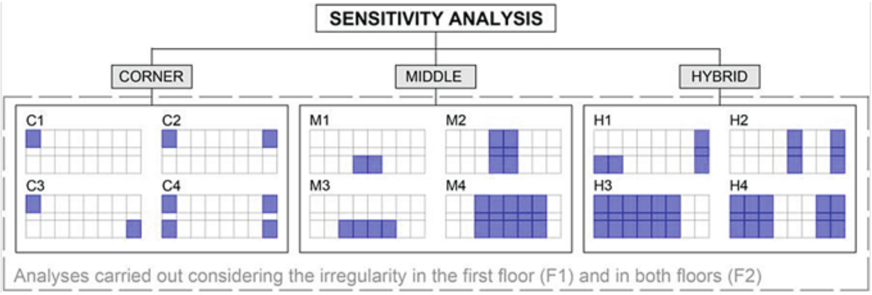


Fig. 3 Different positions of the atrium considered in the sensitivity analysis

420 MPa. The modulus of elasticity (E_c) are 25 000 MPa and 200 000 MPa for the concrete and the steel, respectively.

3.2 Sensitivity Analysis Set-Up

In the typology studied, atriums are located in either the corners (C), the middle bay (M) or both (i.e. hybrid, H). Based on this, the configurations presented in Fig. 3 have been used to study the influence of the position of the atrium on the seismic performance of the blocks. Combinations of the possible locations which were not observed in the population or which were not logical have not been considered.

3.3 Nonlinear Static Analysis

The capacity of the models has been determined by means of nonlinear static analyses performed with OpenSEEs [12] in both orthogonal directions of the models (X and Y). It is important to notice that the existence of an atrium might lead to torsional effects, which can in turn invalid the results from nonlinear static analyses. Hence, for this specific case, a validation of the procedure is carried out considering the results of modal analyses, as will be described. Two load patterns have been taken into account as established in the EC8-1 [13]: uniform and modal. However, reference will be made only to the modal load pattern since it is the most restrictive one [10]. From these modal analyses, the eigen vectors in each direction (X and Y) for all of the master nodes (located in the middle of each slab) have been obtained according to the corresponding mode of vibration. The solver *fullGenLapack* (available in OpenSEEs) has been used, since the models analysed present few interactions. This solver performs a displacement normalization of the eigenvectors. It has been checked that the principal mode of vibration of each model according to each direction is lower than mode 1 and 2. If the principal modes of vibration are higher than those, then, it would mean that not enough mass is moving and the torsional effects are heavily affecting the analyses. Therefore, it proves that the procedure is valid in this specific case. Then, these vectors have been mass-normalised, resulting in the effective modal pattern.

The frames have been modelled using fibres and OpenSEEs nonlinear elements. The concrete and the steel have been simulated using ‘Concrete04’ and ‘Steel02’ materials. The concrete slabs present significant stiffness. Therefore, their effects have been simulated by connecting the RC beams by a rigid diaphragm at each floor level. Infills have been modelled following the two diagonal truss approach as in [14]. Only perimeter infills, which present a minimum thickness of 200 mm, have been included in the model. Internal partitions have not been considered due to their slenderness (thickness < 100 mm), which makes their contribution to the global behaviour negligible. Special attention has been paid to the modelling of the short columns, taking into account the geometrical characteristics of the building.

4 Analysis of the Results

The results obtained from the analyses are shown and discussed in this section. In Fig. 4, the pushover curves obtained for each of the models are plotted. Although both uniform and modal load patterns have been taken into account, only the curves corresponding to the modal pattern are shown, since they are the most restrictive.

It can be observed that the changes produced in the behaviour of the building by the addition of an atrium are different when considering the X and the Y direction. The curves have been normalized by considering the total weight (W) and the total height (H_t) of the structure.

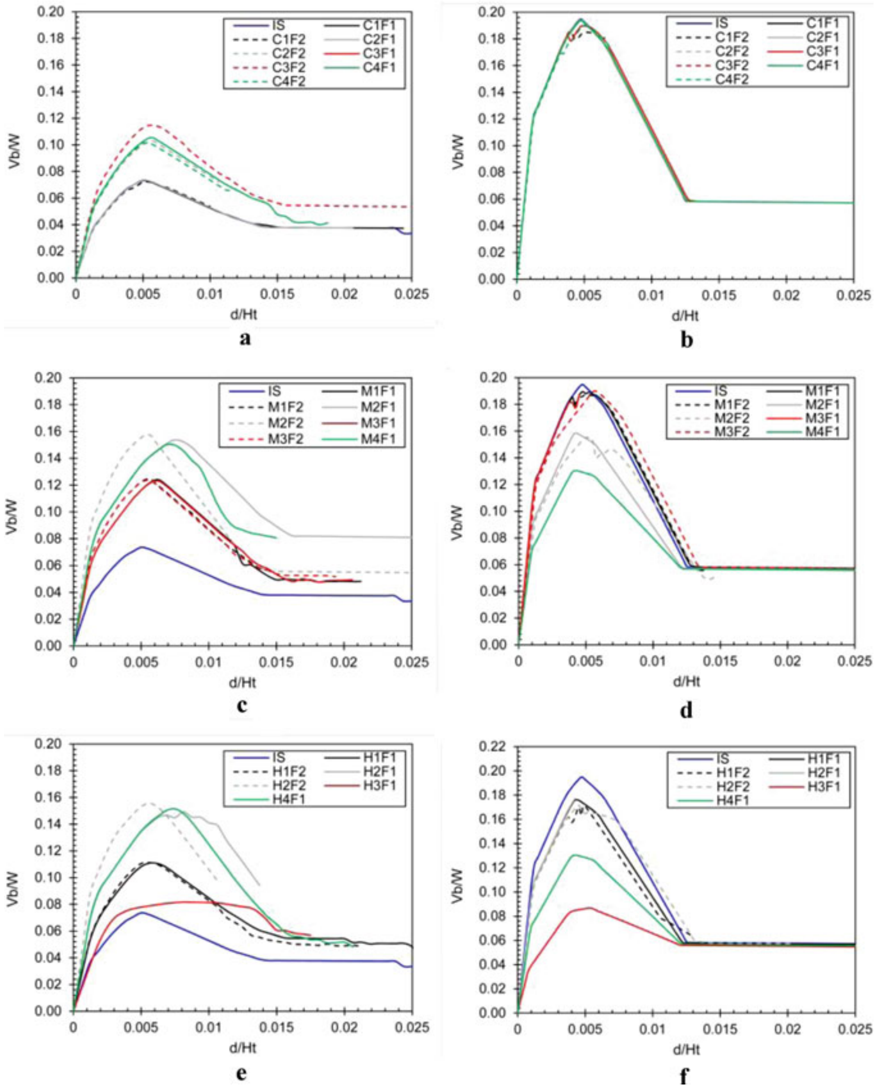


Fig. 4 Pushover curves for models with (**a, b**) corner, (**c, d**) middle and (**e, f**) hybrid atriums. X and Y direction curves are on the left and right, respectively. Irregularity is present only in the first floor for the F1 models and in both floors for the F2 models

4.1 Pushover in the X Direction

The maximum capacity of the building (IS) in the X direction is of about 7500 kN, for a displacement of the control node of 0.04 m. The residual capacity is of about 4000 kN, after a displacement of 0.1 m, when the infills fail.

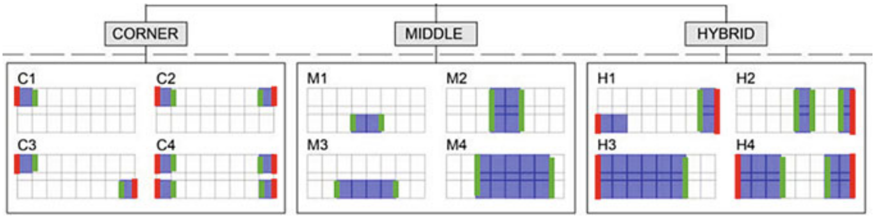


Fig. 5 Added (green) and removed (red) infill walls related to each atrium configuration, affecting the X direction

The addition of one or more atriums has, in most of the cases selected, a positive effect on the global strength, the initial stiffness, the residual capacity, the displacement for maximum shear and the point of the infills failure of the models. The figure below shows the added (green) and removed (red) infill walls related to each atrium configuration, contributing to the capacity in X.

In particular, when the atrium added is located at the building corners (see Figs. 4a and 5), the total capacity is increased up to a 46% and the peak takes place for a displacement of the control node slightly larger than in the IS. The initial stiffness in these models is also slightly bigger.

When the atrium is located in a middle bay (see Figs. 4c and 5), the total capacity of the model can even double the IS, as does the initial stiffness and residual capacity. The maximum shear peak takes place at a larger displacement, up to 0.06 m. This effect is more important when the atrium is pass-through (M2 and M4). The same applies to the models when the atriums are located in hybrid positions (see Figs. 4e and 5), especially in H1 and H2. In model H3, the increase in capacity is not so significant and a torsional effect is observed (see Fig. 7).

4.2 Pushover in the Y Direction

The maximum capacity of the building (IS) in the Y direction is of about 20000 kN, for a displacement of the control node of 0.04 m. The residual capacity is of about 6000 kN, after a displacement of 0.1 m, when the infills fail.

The addition of one or more atriums in the Y direction diminishes the global strength of the building, while the initial stiffness, residual capacity and displacement for maximum shear and point of infills failure remain similar. This is due to the fact that the addition of an atrium entails the removal of contributing perimeter infill walls and the addition of new ones, in different locations depending on the atrium configuration. In the case of the Y direction, as can be seen in Fig. 6, the number of walls added (in green) are equal or less than the number of walls removed (in red).

In particular, when the atrium is located at the building corners (models C1 to C4, see Figs. 4b and 6), the reduction in capacity is negligible.

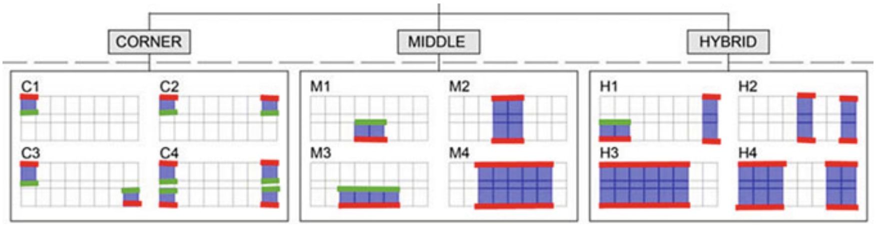
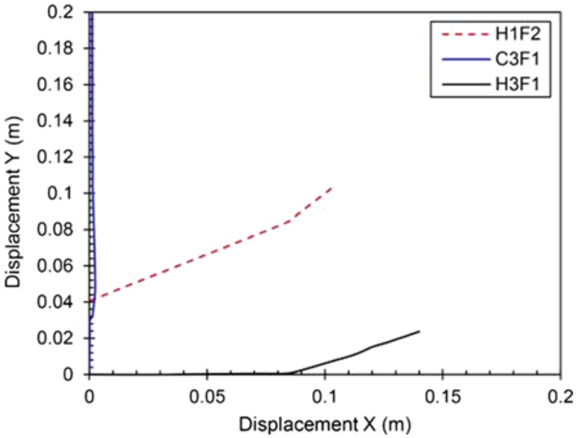


Fig. 6 Added (green) and removed (red) infill walls related to each atrium configuration, affecting the Y direction

Fig. 7 Displacement of the control node. Solid lines: pushover in the X direction. Dashed lines: pushover in the Y direction



When the atrium is located in a middle bay (see Figs. 4d and 6), two situations are possible: (a) if the atrium is only in one side of the building (models M1 and M3), its influence is not noticeable; (b) if the atrium is pass-through (M2 and M4), the total capacity of the building is reduced up to a 35%, depending on the total area of the atrium.

When the atriums are located in hybrid positions (see Figs. 4f and 6), a reduction of the total resistance has been observed in all the models, in this case, up to a 58% compared with the IS model.

In both directions, whether the atrium is present both in the ground floor and in the first floor or only on the ground floor, no effect in the results have been observed.

4.3 Torsional Effects

Torsional effects, which are not present in the behaviour of the original building, arise when the atrium is in a non-central location and/or the atrium to building surface ratio is high (see Fig. 7). This effect is especially noticeable in models H1F2 (see Fig. 4e), and H3F1 (see Fig. 4f).

5 Conclusions

In this work, the schools of the Spanish region of Huelva, mainly RC framed buildings from the 70s, have been studied. It has been observed that the existence of atriums is a recurrent irregularity and a seismic vulnerability. This paper has focused on quantifying the relative relevance of this irregularity by means of a sensitivity analysis. To do so, different versions of an index building model (rectangular in plan), varying the position of the atrium, have been analysed. Nonlinear static analyses have been used to study the seismic performance of these models.

The results show that the existence of an atrium produces quite different effects in the X and Y directions.

When a pushover is performed in the X direction (see Fig. 2), six infill panels, located at each side of the long dimension of the building, per floor contribute to the resistance of the building if no atrium is present. The addition of an atrium entails the introduction of additional contributing infill walls, separating the interior of the building from the new open space (which was not present in the original configuration). Those extra walls will contribute to the global capacity of the building. However, given the configuration of the building under study, a new atrium will introduce additional walls only in the X (short) direction. Figure 5 shows the added (green) and removed (red) infill walls related to each atrium configuration, contributing to the capacity in X. The infills added are located closer to the centre of the building than the perimeter ones, which could also increase the total stiffness of the system. These positive effects have been observed in all the models studied; although they could be impaired by the torsional effects caused by a big non-central atrium (see case H3F1 in Fig. 4e).

By contrast, when a pushover is performed in the Y direction (see Fig. 2), 16 infill panels per floor contribute to the resistance of the building in the initial situation. Adding an atrium can cause the reduction in number of contributing infill panels in this direction, especially, when the atrium is pass-through and panels are eliminated in both facades (see Fig. 6). This negative effect can be observed only at a total capacity level (shear strength at the peak), but not in the shape of the capacity curve, which indicates that the stiffness of the system remains basically unchanged. The existence of torsion enhances this effect, as can be seen in H3F1 (see Fig. 4f). In this model, then total number of infills is not reduced, and yet, the peak shear reaches a lower value when compared with the IS.

In the light of the results observed it can be concluded that not taking into account the effects of an atrium, when analysing a block similar to the index building, could lead to unrealistic results. However, the presence of the atrium has an effect on the response of the building only when located at the ground floor.

Further studies are required to determine to what extent the effects described depend on the number of bays, on the total length of the façades and/or on the length to width ratio of the building.

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