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Review of experimental cyclic tests on unreinforced and strengthened masonry spandrels and numerical modelling of their cyclic behaviour

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ABSTRACT

A reliable numerical modelling for the cyclic behaviour of unreinforced and strengthened masonry spandrels is herein presented. The proposed numerical model is adapted from Tomazevic-Lutman's model for masonry piers in shear and it has been validated upon an experimental campaign conducted at Department of Engineering and Architecture of University of Trieste. The tests were conducted on H-shaped full-scale specimens imposing vertical displacements of increasing amplitude on one leg. Four unreinforced masonry specimens arranged with different masonry material (bricks and stones) and lintel supports (wooden lintel, masonry arch) were considered. Each specimen was then reinforced with a different strengthening technique (tensioned bars, steel profiles, CFRP laminates) and re-tested. Analytical relationships were proposed, based on those available in some Codes of Practice, to estimate the maximum shear resistance of URM and RM spandrels. These relationships provide resistance values in good agreement with the experimental results and can be correctly employed to define the cyclic model of the spandrel to be used in the numerical simulation. The cyclic shear-displacement curves obtained through the numerical model are in good agreement with those of the experimental tests and very good assessment of the dissipated energy was obtained.

1. Introduction

Unreinforced masonry (URM) buildings represent a large portion of existing structures in most earthquake prone regions. The evaluation of the seismic vulnerability of these buildings is of actual importance. In fact, these buildings have shown poor performance in past earthquakes causing heavy damage, structural collapse and casualties [1,2]. Due to both the frequent location of these types of structures in areas characterized by medium to high seismic hazard and their low shear capacity to seismic excitation, it is required to perform the structural assessment and to provide the most useful intervention in order to adequately improve the structural performances of these buildings when subjected to earthquakes.

A good knowledge of the building is needed to develop a reliable assessment of the capacity and to detect their structural shortcomings. The built heritage, in fact, is characterised by a wide range of construction techniques used for both walls and floors. Many different materials are normally used for masonry walls (e.g. solid bricks, stone blocks, rubble stones, cobblestones, etc.) and arranged with various textures (single leaf or multiple leaves with or without diatones, coursed blocks or uncoursed stones, etc.). The floors are mostly wooden made, but also masonry vaults and precast beams with ceiling bricks can be found.

In the case of perforated walls, the behaviour is strongly influenced by the coupling between piers and spandrels. In fact, in case of horizontal loads applied to a perforated wall, the spandrel element affects both strength degradation and lateral resistance of the wall. If there are weak piers and strong spandrels, the damage is mostly concentrated in the piers, but in case of strong piers and weak spandrels the wall performance is strongly dependent of the spandrel response. Some recent experimental studies proved that in many cases the spandrel provides a very important resistance contribute to the masonry wall shear capacity (e.g. [3–9]).

A rough knowledge of the structural system in conjunction with an inadequate analysis may lead to either overestimate or underestimate the safety of these structures. In the first case serious risks for human lives can be met, while a large increment of costs may be due to the excessive strengthening measures related to the latter case. Furthermore, an underestimation of the building capacity may request strengthening interventions with important changes in the original structures.

In the professional practice, due to the high costs connected to a rigorous evaluation, the analyst usually choose the most suitable

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schematization for the masonry wall between the "weak spandrel-strong pier" type and the "strong spandrel-weak pier" type, as suggested by the "Prestandard for the Seismic Rehabilitation of Existing Structures" [10]. Both approaches are formulated on the bases of simplified assumptions concerning the capacity of spandrels. In the first case, the strength of spandrels is neglected and the horizontal forces are supported only by the piers, which span from the foundation to the roof of the building. In the latter case, the spandrels are assumed to be infinitely stiff and resistant, thus a shear type behaviour is assumed for the piers and the building collapse is associated to a storey mechanism. Because of these strong assumptions on the masonry spandrel behaviour, both approaches provide a rough estimation of the actual deformability and capacity of perforated masonry shear walls.

The definition of reliable analytical and numerical models for the seismic evaluation of URM buildings has been the object of several studies in the last two decades. Depending on the field of use, various models concerning different theoretical approaches have been developed. Many of such models are used for research and, being based on complex finite element formulations (e.g. [11]), they are high computation demanding, so that they cannot be employed for realistic analyses of whole buildings.

Many other different models have been developed for the analysis of URM structures; most of them use one-dimensional macro-elements to model the masonry wall so the seismic performance of whole buildings can be assessed with an acceptable computational effort. In particular, in last nineties, improved numerical models based on the equivalent frame approach have been defined. In these models, suggested by the current design codes of practice (e.g. [12,10]), different failure mechanisms (i.e. shear with diagonal cracking, shear with sliding and rocking) are provided for each macro-element (as in [13–15]). Chen et al. [16] proposed an interesting practical approach that allows analysing the in-plane behaviour of unreinforced masonry perforated walls, within an equivalent frame model taking into account different types of failure modes. A particular macro-element allows modelling piers and spandrels; the formulation of this macro-element includes three nonlinear shear springs in series with two rotational springs and an axial spring in order to simulate axial failure, bed joint sliding, diagonal tension, rocking collapse and toe crushing. The validation of the model was given only for piers because of the lack of experimental test on spandrels.

Such numerical models have been developed on the basis of both theoretical and experimental results. But, while many experimental outcomes (shear-compression test, diagonal compression test, etc.) on numerous types of masonry, even under cyclic loads are available for piers, to date very little tests have been carried out on the behaviour of spandrels. These experimental achievements are of paramount importance because the spandrel structural response is considerably different from that of the piers. In fact, under seismic loads, the masonry beams are subjected to shear and bending with negligible axial force.

It is necessary to analyse the available strengthening techniques so to evidence their effectiveness to increase the bending and shear resistance of spandrels. The most frequently utilized strengthening techniques are the application of pre-tensioned tie-rods, the gluing of CFRP strips on both faces of the masonry or the coupling of RC tie-beams.

To study the above mentioned problems, in recent years several studies has been carried out. Based on the earthquake damage observations, Cattari and Lagomarsino [17] reduced the possible failure mechanisms for spandrels without coupled reinforced concrete beams or tie-rods, to the most frequent: diagonal cracking or rocking. Through a preliminary theoretical study on brick walls, they underlined that the interlocking phenomena at the interface between spandrel ends and contiguous masonry provide significant flexural resistance to the spandrel, even in absence of tension-resistant elements. On this concern, some predictions are reported also in FEMA 306 [18].

A first reliable experimental study for the cyclic behaviour of spandrel was presented by Gattesco et al. [3]. The test set up was made by a full-scale specimen composed by two piers connected by a spandrel, so the sample have an H shape. Then, one of the piers was forced to move vertically with a cyclic load history so to simulate the stress condition in the spandrel occurring in a perforated wall subjected to in-plane horizontal cyclic forces, as for earthquake excitation.

Each specimen was tested, in a first time, as unreinforced and then the sample was strengthened with the application of a reinforcing technique. Thus, the strengthened sample was subjected to the cyclic test again and the results evidenced the effectiveness of the intervention.

A similar test set up was recently adopted also at the University of Pavia by Graziotti et al. [19] to perform two experimental tests on stone spandrel specimens: the first sample was tested without any reinforcement, while in the second test an axial force was applied to the spandrel so to simulate the effects of a tie-rod. A slightly different test methodology was proposed by Beyer and Dazio [5]: instead to move vertically one pier with respect to the other, both piers are rotated at their base. The effects of a varying axial force on the spandrel force-deformation characteristics were also investigated by means of rods that were pre-tensioned and locked-in. Four brick masonry spandrels were studied: two were made with a wooden lintel and two with a shallow masonry arch.

In the paper, the results of an experimental campaign developed after a first investigation carried out at the University of Trieste [3,20] are presented and discussed. In particular, four H shape specimens, three made of brick masonry and one of rubble stone were analysed before and after the application of different reinforcement techniques on the spandrel. Interesting results, both in terms of resistance and deformability of the spandrel, were obtained.

Besides, in order to modelling the hysteretic behaviour of spandrels, a cyclic model is proposed and implemented in the FE code ABAQUS. The proposed model can be used in the ambit of the equivalent frame method; every single spandrel is composed by an assemblage of rigid links and zero-length springs. The nonlinear spandrel model, implementing stiffness and strength degradations, can be easily used in static and dynamic non-linear analyses.

2. Experimental tests

Eight experimental tests were carried out on full scale masonry specimens, representing a portion of a perforated wall. The test apparatus was studied in order to subject the spandrel to a loading condition that simulates the actual state of stresses occurring in the perforated walls in case of in-plane horizontal forces.

In particular, three unreinforced samples made of clay brick masonry and one made of rubble stone were built. After the cyclic test on the plain sample, stopped just before the collapse so as to allow applying the strengthening technique, each specimen was tested again in order to evaluate the effects of the reinforcement on the spandrel performance. The effectiveness of three intervention techniques were investigated on the brick masonry samples: the application of a couple of horizontal steel ties, the application of one L-shaped steel profile to the internal face of the wall at the floor level and the gluing of CFRP (carbon fibre-reinforced polymer) horizontal laminates on both surfaces. The sample made of stone was strengthened with the coupling of an L-shape steel profile on the internal surface of the wall. In this way, it was possible