PERFORMANCE OF RC WALLS WITH OPENINGS STRENGTHENED BY FIBER REINFORCED POLYMERS. AN EXPERIMENTAL AND THEORETICAL INVESTIGATION

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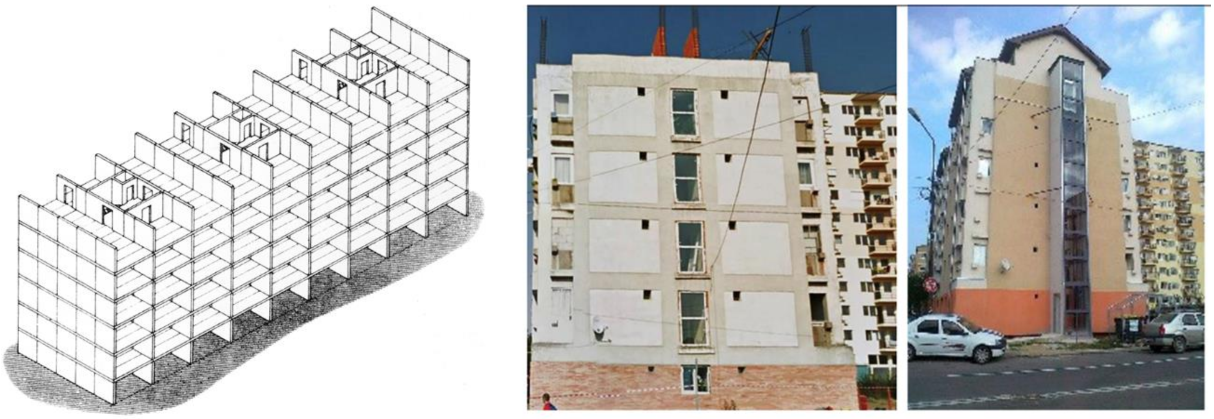
Abstract

Redesigning buildings to improve their space efficiency and allow changes in use is often essential during their service lives to comply with shifts in living standards and functional demands. This may require the introduction of new openings in elements e.g. walls, which inevitably reduces their structural performance, and hence necessitates repair or strengthening. Here the authors report an experimental investigation of the effectiveness of fibre-reinforced polymer (FRP)-based strengthening for restoring the axial capacity of a solid reinforced concrete wall after cutting openings. Nine half-scale specimens, designed to represent typical wall panels in residential buildings with and without door-type openings, were tested to failure. FRP-confinement and mechanical anchorages increased the axial capacity of walls with small and large openings (which had 25% and 50% reductions in cross-sectional area, respectively) by 34-50% and 13-27%, to 85-94.8% and 56.5-63.4% of their pre-cutting capacity, respectively. Current design models are assessed against experimentally obtained capacities.

1. INTRODUCTION

At present, one of the most significant discussion points relating to sustainable development of our society is that such development must always be supported by a safe, functional and durable built environment. It is widely acknowledged that our building stock requirements (e.g. maintenance) are enormous, due to the ever-increasing demands of society, with continual wear and degradation on structures potentially leading to large monetary and social losses. For example, the need for repair and refurbishment in the housebuilding sector increases annually (FIEC 2014); figures indicate an estimated 270 billion Euros were spent in 2014 in the E.U.

The majority of structures around the world are made of reinforced concrete (RC), most of which were built between 1946 and 1980 [1]. A high proportion of these buildings are multi-dwelling buildings made of prefabricated sandwich panels. The system (see Figure 1a), called large panel building, was developed in the West and used for the first time in Denmark, England and France [2], later expanding across the whole of Europe. This type of structure consists of an integral wall system in which load-bearing walls run along both longitudinal and transversal directions of the building. This makes the floor layout rather rigid in terms of space utilisation. In recent years, there has been a growing interest in enlarging spaces by connecting adjacent rooms using openings created in existing solid walls. Thus, greater flexibility and better use of spaces can be achieved. However, such modifications may involve cutting openings into structural walls to allow for new windows, doors or ventilation systems (Figure 1b). The effects of such openings are stiffness and load-bearing capacity reduction.



(a) (b)

Figure 1: (a) Typical large panel building [3] and (b) example of structural modifications in buildings

Two methods have, traditionally, been employed to strengthen RC walls with openings. One is to create a frame using RC/steel members around the opening, the other is to increase the cross-sectional thickness. An alternative is to use externally bonded fiber-reinforced polymers (FRPs), a technique successfully tested by a number of authors in seismic retrofitting scenarios [4-7]. However, the contexts of these tests were seismic retrofits, and thus, they may not be applicable for repairing gravitationally-loaded walls. Literature on the behaviour of axially loaded walls has been recently reviewed by Popescu et al. [8]. It was concluded that research studies investigating walls with cut-out openings strengthened by FRP is scarce. For non-seismically designed walls with openings, Mohammed et al. [9] was the first who investigated performances of one-way walls (supported only on top and bottom edges of the wall) when FRP-strengthened. Hence, in the current study the effectiveness of FRP-repaired two-way walls (restrained along all four edges) for increasing the axial strength weakened by cut-out openings was investigated.

2. EXPERIMENTAL PROGRAMME

2.1 Design of experiments and test matrix

The specimens were designed to represent typical wall panels in residential buildings. In total, nine half-scale specimens were tested to failure. The walls were 1800 mm long, 1350 mm high and 60 mm thick. The size of opening and structural condition of the wall were selected as the two most influential parameters.

For the first parameter, namely size opening, small (450 × 1050 mm) and large openings (900 × 1050 mm) were set as the minimum and maximum levels. The minimum level represents the width of a typical door opening in a residential building whereas the maximum level corresponds to a double-door opening. Note that the terms small and large carry no meaning other than being a useful way of labelling the opening sizes.

For the second parameter, pre-cracked and uncracked conditions were established as the minimum and maximum levels. The minimum level represents the wall in a pre-cracked state (loaded until 75% of the peak load) whereas the maximum level corresponds to the uncracked condition. The 75% level was obtained based on nonlinear FE analyses [10] and observations of when the reference specimens developed a significant crack width.

The designed test matrix is shown in Figure 2 and divided into stages I, II and III, relating to reference specimens, pre-cracked and uncracked specimens strengthened with CFRP, respectively. For convenience, the naming system adopted consists of the test stage described above (I, II or III) and the type of wall C, S, L (where C refers to a solid wall, S and L refers to a wall with a small and large opening, respectively). In addition, the tests from the third stage were repeated and thus, the specimen's name contains a serial number. For example, II-S refers to a pre-cracked wall with a small opening, strengthened with CFRP.

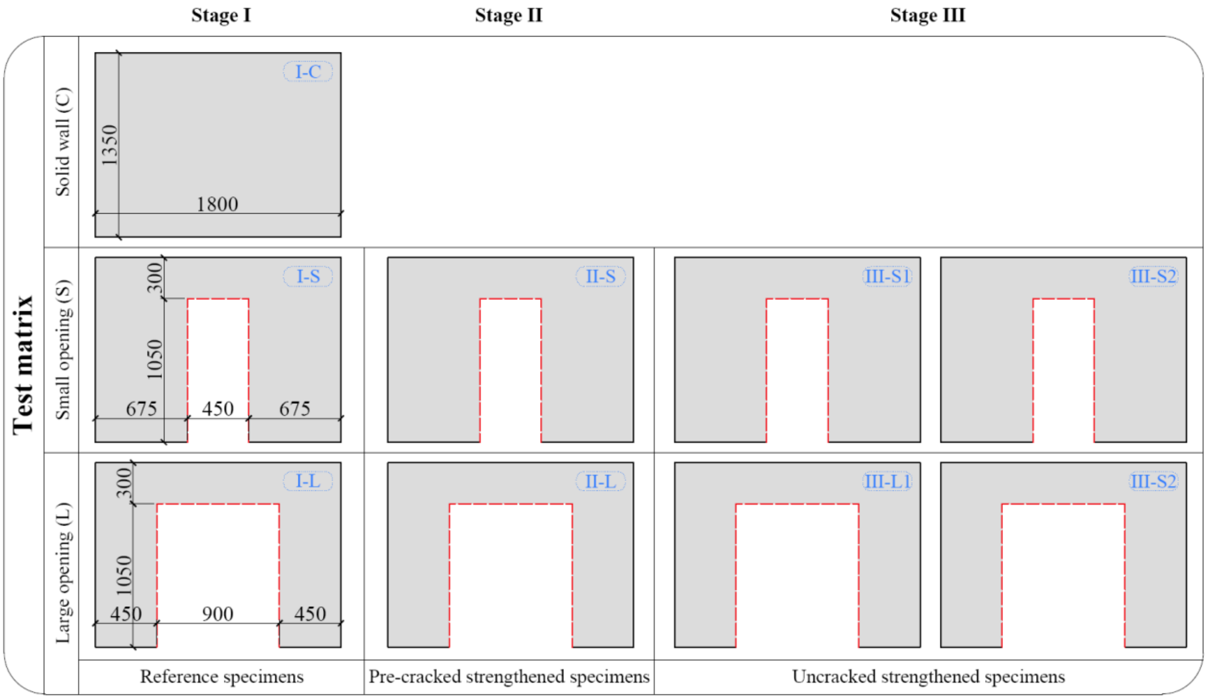


Figure 2: Test matrix

2.2 Specimen preparation

The specimens were solid panels (i.e. constant thickness) with no voids or insulating layers. They were reinforced with a single, centrally placed, welded wire mesh. The welded fabric consisted of 5 mm diameter deformed bars, spaced at 100 mm in both orthogonal directions (see Figure 3). Before casting, electrical resistance strain gauges with pre-attached wires were bonded to the reinforcement. The walls were long-line cast, laid down on a steel platform. A batch line can accommodate up to five specimens.

Two methods were available to restore the capacity to that of a solid wall. One was to increase the specimen's thickness (e.g. RC jacketing, textile-reinforced mortars), the other was to increase the concrete compressive strength through confinement. The latter was the focus of interest for the work presented here. Confinement has proved to be a viable solution where ductility and/or axial strength are concerned. The method is highly dependent on the cross-section geometry: a uniform confinement effect is obtained for circular cross-sections whereas only part of the cross-section is effectively confined for rectangular cross-sections [11, 12]. The transverse fibre sheets were fixed using steel bolts so as to create virtual cross-sections with an aspect ratio limited to 2 (60 × 120 mm starting from the opening edge.

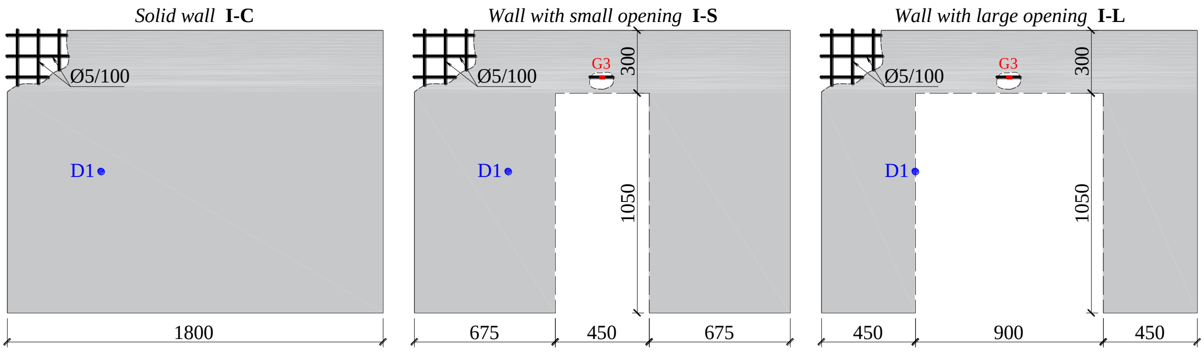


Figure 3: Configuration and details of the tested wall

Prior to the application of the CFRP strengthening, 8 mm holes were drilled through the wall at positions marked on the concrete surface to help the installation of the mechanical anchorages. The concrete surfaces were then prepared by grinding – to remove the irregularities and cement paste layer, and thus, exposing the aggregates – and cleaning with compressed air. The CFRP sheets were applied using the wet lay-up procedure. First, a two-component epoxy primer (StoPox 452 EP) was applied to the specimens, followed by the application of the impregnated fibres on the concrete surface after approximately 6 hours. They were wrapped around the piers in a U-shape; full wrapping was not possible due to the existing boundary conditions. High-strength CFRP sheets (two and three 0.17 mm thick layers for the specimens with small and large openings, respectively) were used to strengthen the walls. When the epoxy had cured, the anchorage bolts were inserted into predrilled holes and prestressed with a torque estimated from the clamp load (i.e. 8.7 kN).

2.3 Material properties

The average cubic compressive strength of the concrete was 62.8 MPa and 64.4 MPa for the first and second concrete batch. Coupons were taken from the reinforcing steel meshes and tested to determine their stress-strain properties. Their mean yield strength was 632 MPa at mean strain of 0.28%. No material tests were carried out on the CFRP system (fibres + epoxy) and their nominal properties are given here according to the tests undertaken by the supplier. The fibres of the CFRP sheets were unidirectional with tensile strength of 5500 MPa and elastic modulus of 290 GPa. The epoxy resin had an elastic modulus of about 2 GPa.

2.4 Test set-up and instrumentation

The walls were tested in two-way action and subjected to axial loading with low eccentricity along the weak axis (1/6th of the wall's thickness) to represent imperfections due to thickness variation and misalignment of the panels during the construction process. The specimens were tested in a test-rig specifically designed to simulate as-built conditions: side restraints permitted rotation and prevented translation while top/bottom restraints allowed full free rotation.

Four hydraulic jacks were networked together to apply a uniformly distributed load along the wall length. The load was incrementally increased at 30 kN/min with breaks every 250 kN to allow stress distribution and to monitor the cracks in the specimens. All reactions were transmitted to a reaction frame fixed in a strong floor. A general view of the test setup is shown in Figure 4.

An extensive instrumentation scheme was devised in order to monitor the behaviour of the walls during the loading cycles. Linear displacement sensors were used to measure out-of-plane and in-plane displacements, with strain gauges placed on steel reinforcement and on the compression side of the concrete surface. These measurements were supplemented by measuring full-field strain distributions using the three-dimensional digital image correlation (3D-DIC) technique. Due to space limitations, however, only selected measurements are presented herein. The location of the sensors is shown in Figure 3.

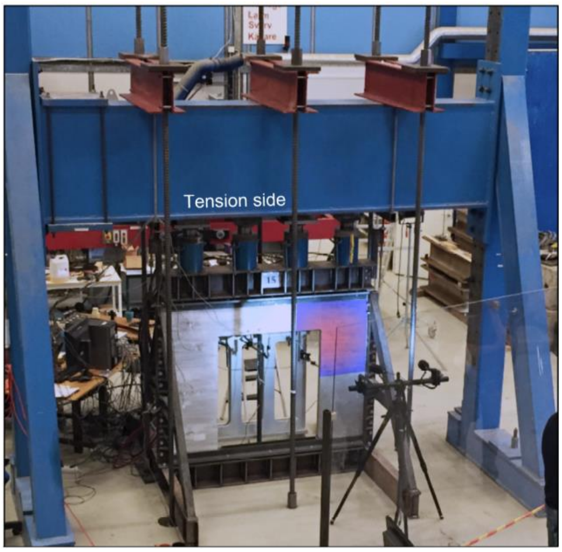


Figure 4: General overview of the test set-up. Reprinted from Popescu et al. [13] with permission from ASCE

3. EXPERIMENTAL RESULTS

In order to investigate the effect of the cut-out on the axial strength, three specimens were loaded to failure in stage I: one was a solid panel, one had a symmetric half-scaled single door-type opening and the third had a symmetric half-scaled double door-type opening. The small and large openings represented a 25% and 50%, respectively, reduction in the cross-sectional area of the solid wall. The damage level was evaluated in terms of ultimate load, crack pattern, displacement profiles, strains in concrete and steel reinforcement and ductility and energy release at failure. Only selected results are given here and the reader is referred to Popescu et al. [13].

The effectiveness of the selected strengthening method was investigated in two scenarios: Stages II and III. The performance of the strengthening method was evaluated in terms of axial strength increase, ductility and energy release at failure, and steel reinforcement and CFRP strain utilisation. Only selected results are given here and the reader is referred to Popescu et al. [14] for more detailed results and analysis.

3.1 Reference specimens

The first stage comprises the reference specimens (i.e. a solid wall, a wall with small and large opening, respectively) that were loaded until failure. In this way a first analysis would be possible to evaluate the effect of introducing new openings in a solid wall. The walls behaved as predicted by the numerical analysis, showing a TW behaviour by deflecting in both vertical and horizontal directions. This aspect was also captured by the ARAMIS system in addition to strain development and distribution around the openings during loading cycles, as shown in the images in Figure 5.

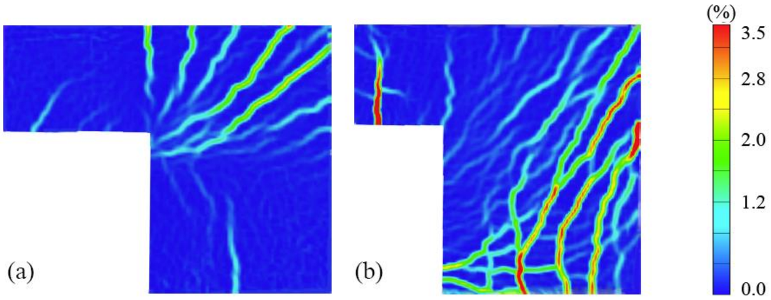


Figure 5: Principal strain development on the tension side of the specimens at peak load: (a) specimen I-S; (b) specimen I-L. Reprinted from Popescu et al. [13] with permission from ASCE

Cracks opened late in the loading of the solid wall (at 85% of the peak load), and earlier in the loading of specimens with both small and large openings (at 50% and 20% of peak load, respectively). The tensile and compressive strains that developed in the reinforcement were significant at higher loads, with yielding of some bars occurring at failure. All specimens failed by concrete crushing with spalling and reinforcement buckling showing no forewarning prior to failure. Effects of opening size are shown in Figure 6, in which load-displacement curves of all three specimens (recorded at the same position on both piers – D1 as indicated in Figure 3) are plotted on the same graph. The crack pattern captured at failure is shown in Figure 7.

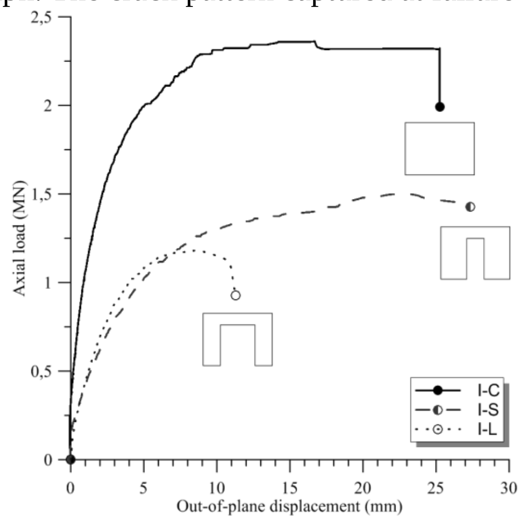


Figure 6: Load-displacement responses for reference specimens

Figure 7: Crack pattern captured at failure of the unstrengthened specimens

3.2 Strengthened specimens

The strengthened walls failed due to crushing of concrete followed by debonding of the CFRP. The failure was concentrated in smaller regions compared to reference specimens i.e. at the bottom of one of the piers as seen in Figure 88. The strengthened specimens had lower deformations (thus increasing the stiffness) and higher capacity when compared with the unstrengthened ones, as can be seen in Figure 99. The increase in capacity was in the range of 34 – 50% and 13 – 27% for specimens with small and large openings, respectively.

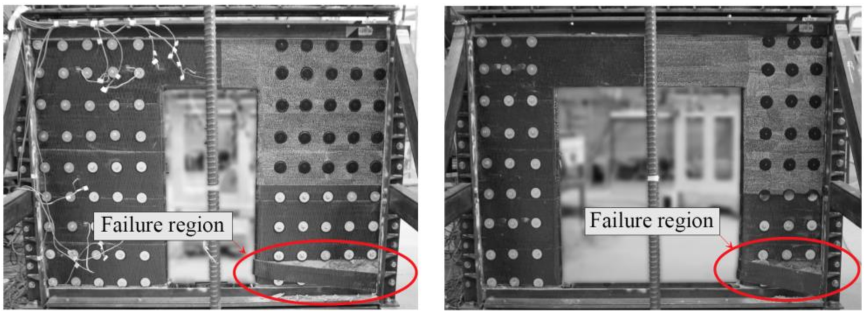


Figure 8: Typical failure mode of strengthened walls

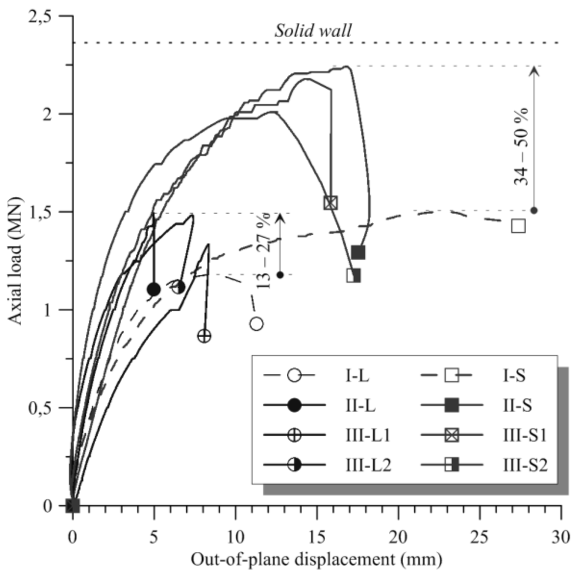


Figure 9: Strengthening effect on the walls with small and large openings

4. ANALYSIS OF RESULTS AND DISCUSSION

Practical design of axially-loaded concrete walls is generally based on column theory that accounts for the equilibrium of forces over their cross-sections, and stress-strain compatibilities. A simplified procedure is described in design codes such as [15-18] and research literature [19-21], just to mention a few. A complete description of the performance of current design models for axially-loaded walls with and without openings was published by the authors in [8]. Here, only the results obtained using the European [18] design model are presented. The equation used to predict the axial capacity of a solid wall was:

$$N_u = f_c \cdot L \cdot t \cdot \Phi \tag{1}$$

$$\Phi = 1.14\left(1-2\frac{e+e_a}{t}\right) - 0.02 \cdot \frac{H_{eff}}{t} \le \left(1-2\frac{e+e_a}{t}\right) \tag{2}$$

Here, f_c is the concrete compressive strength, L is the length of the wall, t is the wall thickness, e is initial eccentricity, equal to $t/6$ and e_a is the additional eccentricity due to lateral deflection of the wall; $e_a = H_{eff}/400$. The effective height $H_{eff,}$ is obtained by amending the wall height with the effective height factor, β. For walls with L<H and restrained along all their sides, $\beta = L/2H$.

Currently there are no design philosophies or reliable theoretical guidelines for calculating the capacity of strengthened walls in the literature. The only design model [9] found in the literature only considered top and bottom restrained walls, and so the associated design model is only valid for such walls. For the current research, the authors used the European design model [20] in combination with Lam and Teng [22] design model to predict the increase in axial capacity.

The predictions using the European design model [18] for the unstrengthened walls were in good agreement with the test results; an average ratio between theoretically and experimentally determined capacity of 1.02 was obtained. The same cannot be said for the strengthened walls; the inability of the design model to capture the loading eccentricity seem to have produced inaccurate predictions. The average ratio between theoretically and experimentally determined capacities of 1.37 was obtained.

6. CONCLUSIONS

In this study, the authors report on an experimental investigation of the effectiveness of CFRP–based strengthening for restoring the axial capacity of a solid reinforced concrete wall after cutting openings. The following conclusions can be drawn from this investigation:

- Reducing the cross-sectional area with 25% (small opening) and 50% (large opening) of a solid wall the capacity decreases with nearly 36% and 50%, respectively.
- The failure progression can successfully be monitored during specimen loading using 3D-DIC measurements.
- Confining the walls with CFRP increases the capacity up to 95% of that of a solid wall.
- Design methods for predicting the axial capacity increase due to CFRP strengthening should be revisited. A design model capable of capturing complex effects such as load eccentricity and large aspect ratios of elements' cross-sections is currently developed by the authors and will be published upon completion of the study.

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