AUTOMATED DESIGN OF FRP-STRENGTHENED MASONRY

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ABSTRACT

Advanced composites have been used as strengthening materials of masonry structures for more than a decade, in the form of strips, grids and fabrics. Such reinforcing elements may increase the in-plane flexural and shear capacity as well as the out-of-plane flexural capacity of masonry walls subjected to seismic loads. One of the main difficulties associated with the retrofitting of planar masonry elements is the selection of the FRP reinforcement configuration as well as the dimensioning of the FRP elements (cross section areas) for given strength requirements. This problem is addressed in this study through the development of a computer program, which, based on strut-and-tie methodology, enables the definition of the locations where FRP strips should be placed in masonry walls subjected to in-plane loading. The procedure is illustrated through application examples.

1. INTRODUCTION AND BACKGROUND

Masonry structures in need of intervention through strengthening constitute a significant portion of the building stock throughout the world, as either they have suffered from the accumulated effects of inadequate construction techniques and materials, seismic and wind loads, foundation settlements and environmental deterioration, or they need to be upgraded in order to meet more stringent seismic design requirements, often combined with change in use. Standard methods to upgrade masonry structures include: filling of cracks and voids by grouting; stitching of large cracks and other weak areas with metallic or brick elements or concrete zones; application of reinforced grouted perforations; external or internal post-tensioning with steel ties; and single- or double-sided jacketing by shotcrete or by cast in-situ concrete, in combination with steel reinforcement (e.g. two-directional mesh).

Certain disadvantages associated with some of the above techniques (e.g. increased thickness and mass produced by jacketing, high labour intensity) as well as developments in modern materials technology have led researchers [e.g. 1, 2] to the idea of strengthening masonry with fibre-reinforced polymers, commonly known as FRP. These materials are typically made of carbon (CFRP), glass (GFRP) or aramid (AFRP) fibers bonded together with a polymeric matrix (e.g. epoxy), offering the designer an outstanding combination of properties, such as high strength and stiffness in the direction of the fibers, low weight, immunity to corrosion and availability in the form of strips, fabrics and tendons of practically unlimited lengths.

Studies on the use of FRP as strengthening materials of masonry have been numerous. Detailed concepts and analytical results on the applicability and effectiveness of FRP tendons used to apply circumferential prestressing to historic masonry structures are given in [1, 3]. A detailed study on the use of epoxy bonded CFRP strips as seismic strengthening elements of masonry was performed by [2], who demonstrated the effectiveness of this technique through full-scale in-plane and out-of-plane cyclic testing of one-storey masonry walls and developed an analytical model for the in-plane behaviour of CFRP-strengthened walls within the framework of stress fields theory. The work reported in [4, 5] focused on in-plane shear (monotonic static) testing of unreinforced masonry specimens strengthened with epoxy-bonded glass fabrics. A similar concept involving epoxy-bonded carbon overlays was studied by [6, 7], who performed cyclic tests on approximately half-scale masonry wall panels and on a full-scale masonry building, and proved that such overlays are highly effective in increasing the strength, reducing the shear deformations and improving the overall structural ductility. Detailed design equations and interaction diagrams for FRP-strengthened masonry under out-of-plane bending, in-plane shear and in-plane bending, all combined with axial load, were developed in [8]. Experimental studies performed on masonry walls subjected to monotonic

[9, 10] and cyclic [11-13] out-of-plane loading demonstrated the effectiveness of vertically placed GFRP strips. The effectiveness of this system was also confirmed by [14], through shake table testing. Similar studies were conducted by [15] on walls strengthened with overlays covering the full tensile zone as well as with vertical and horizontal strips and confirmed the effectiveness of the FRP systems as out-of-plane flexural strengthening elements. The use of GFRP rods embedded into epoxy-based paste near the surface of masonry walls at the locations of bed joints has been investigated for the case of in-plane shear by [16]. Recently, the in-plane response of FRP-strengthened masonry has received a bit more attention than in the past years: failure modes associated with in-plane response of masonry buildings and global response were analyzed in [17] through pushover analysis; shake table testing of single masonry walls strengthened on one side with GFRP fabrics or vertical CFRP strips was performed in [18]; and cyclic loading of a single wall strengthened with vertical and horizontal GFRP strips reported the effectiveness of this system in [19]. In another field of application, epoxy bonded CFRP strips have been bonded to the extrados of vaults and arches, thus providing increased capacity against lateral loads [e.g. 20, 21]. Last, the range of applicability of FRP has been extended to blast loaded masonry, where it was proved that flexible, easy to apply hybrid glass/aramid fabrics offer interesting solutions [22].
One of the main conclusions from the above studies is that, for the sake of both economy and effective mechanical response, unidirectional FRP reinforcement in the form of strips (that is 100 – 300 mm wide bands) is preferable than two-dimensional fabrics that cover the whole surface. However, the selection of the reinforcing pattern and the calculation of cross section areas associated with that reinforcement still remains an unsolved problem. Most FRP strengthening systems involving epoxy-bonded strips are designed today based on limited, if any, structural analysis, on the basis of the engineer's experience and expertise. While the positioning of strips in some simple masonry structure configurations subjected to in-plane loading may be a straightforward task (e.g. shear-critical rectangular walls without openings), this may not be the case in walls with complex geometry (e.g. a wall with many openings). It is this gap that the present study aims to fill: (a) to propose a methodology, based on strut-and-tie modelling, for the definition of the positions – the ties in the "strut-and-tie" model - where FRP strips should be attached, given the configuration of a masonry wall subjected to in-plane loading and the loads, and (b) to apply this methodology for the dimensioning (calculation of number and cross sectional area) of the strips.

2. STRUT-AND-TIE MODELLING

Strut-and-tie models have been originally proposed and developed as a hand calculation procedure for the rational and consistent design of structural concrete plates and of two-dimensional regions of static or geometric discontinuity, often called D-regions [e.g. 23-24]. According to this procedure, the engineer, based on experience and intuition, draws load paths through the structure in the form of a truss, which is analyzed for the design loads and proportioned according to the applicable code and/or to other rules of practice. In this exercise, the engineer may be aided by the knowledge of the magnitude and of the directions of principal stresses, obtained by a linear elastic plane stress finite element analysis of the structural element under the design loads. The struts and ties of the model may then be drawn collinear to the principal stress resultants. However, even when such finite element results are available, the development of an appropriate strut-and-tie model requires experience, expertise and time. This consideration has led to the development of various computational tools for the construction of strut-and-tie models, which allow for reductions in total design time and cost. Typical examples are tools which allow for the automatic verification of the nodes of a strut-and-tie model [25], for the selection of a model so that the total weight of steel in the ties is minimized [26] and for the automatic generation of the topology of struts and ties based on finite element analysis results [27]. The procedure employed in this study is described next.

3. SOLUTION ALGORITHM

The first stage of the procedure involved the development of a FORTRAN programme for the linear elastic finite element analysis of the two-dimensional masonry wall, subjected to the in-plane force and displacement boundary conditions of the problem, using isoparametric eight-node elements. The mesh is defined with user-selected constant spacing in two orthogonal directions (x and y). The analysis yields nodal stresses by averaging over the neighbouring elements and from them computes and plots the magnitude and the direction of the principal stresses σ_1 and σ_2. Two datasets are then formed, one for the positive principal stresses and one for the negative. Each record in these datasets includes also the coordinates of the point where σ_1 and σ_2 are calculated and the respective angle θ_1 and θ_2 between principal stresses and axis x.

Next, the computer programme identifies the points of relatively high nodal stresses, separately for the positive and the negative stresses. This is achieved by identifying the nodal points where the magnitude of principal stresses of interest lies within a user-specified range with respect to the mean value of this stress over the entire masonry wall. This range is defined by subtracting and adding a certain multiple of standard deviations of the stress in question to its mean value and may be changed by the user after each calculation.

In the following step, that is when the points of relatively high nodal stresses have been identified and the associated stresses have been plotted, the user introduces graphically provisional struts and ties by using the mouse, hence defining a statically determinate truss consisting of triangles. The programme stores the coordinates of the joints while the user draws the truss. At the end of this step the user may modify graphically the joint coordinates and define a final set. Subsequently, the user introduces the support conditions, the joint loads and (optionally) material properties for the truss elements. The final step involves the analysis of the truss for the user-specified loads.

Truss elements in tension (ties) indicate regions where FRP strips should be placed; masonry itself constitutes the struts. The dimensioning of the strips is achieved based on the calculated tensile force in each tie, N_{tie}, and the design value of the force in a strip of a given type, N_{strip}:

$$n = \frac{N_{tie}}{N_{strip}} \tag{1}$$

where n = number of FRP strips to be placed collinear to the tie under consideration.

The design value of the force in a strip, N_{strip}, is the minimum of two values, each one of them associated with a specific failure mechanism, which could be either of the FRP fracture type or of the FRP debonding type. In the former case N_{strip} is obtained by multiplying the strip's cross sectional area (A_{strip}) by its design tensile strength, f_{fd} (equal to the FRP characteristic strength f_{fk} divided by the material safety factor γ_f), whereas in the latter case N_{strip} is obtained by multiplying the cross sectional area by the design stress associated with debonding, f_{fb}, provided by an appropriate bond model. It should be noted that if the strips are anchored properly at their ends through the use of mechanical devices so that their full tensile capacity may be mobilised (highly recommended), then $f_{fb} > f_{fd}$ and $N_{strip} = f_{fd}A_{strip}$.

4. NUMERICAL APPLICATIONS

The computational procedure described above is applied to two examples: (a) a simple masonry wall with one opening subjected to uniformly distributed vertical and concentrated horizontal loading (Fig. 1a) and (b) a more complicated wall with several openings subjected to uniformly distributed vertical and horizontal loading (Fig. 1b). These two structures were discretized with eight-node finite elements as shown in Fig. 2. The stress fields corresponding to these examples are given in Fig. 3, and the associated struts (dotted lines) and ties (continuous lines) are shown in Fig. 4.

The results of the analysis for the truss in each case are given in Table 1. Based on these results and assuming that strengthening is provided in both cases with 50 mm wide and 0.5 mm thick FRP strips, with f_{fd} = 1500 MPa, so that N_{strip} = 37.5 kN, the resulting FRP configuration is shown schematically in Fig. 5.

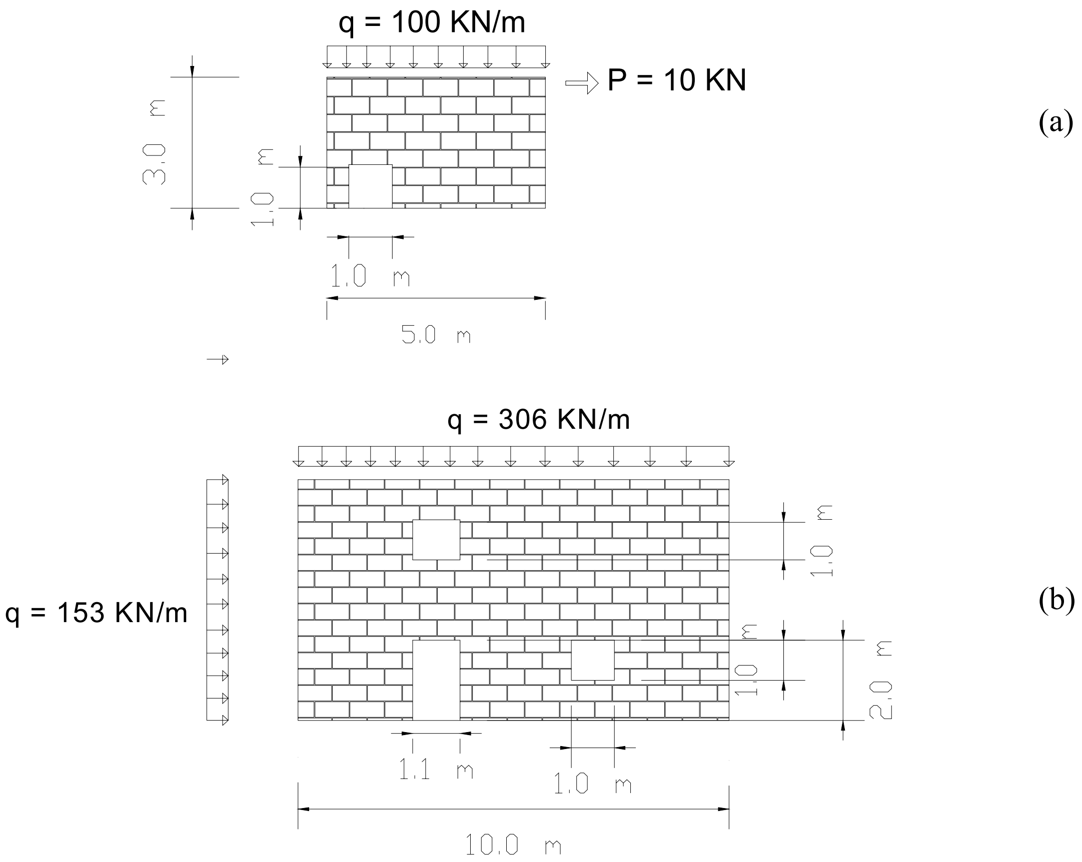
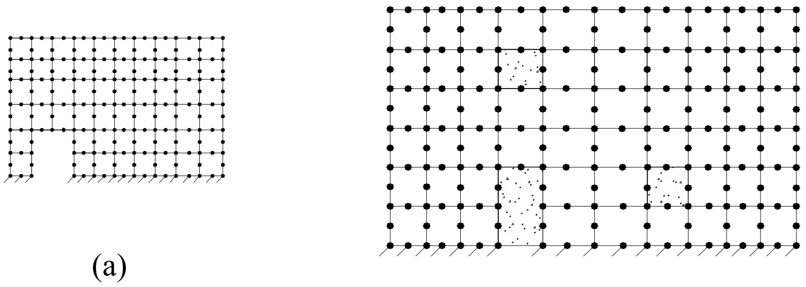


Fig. 1. Case studies of masonry walls.


(a)

(b)

Fig. 2. Finite element discretization.

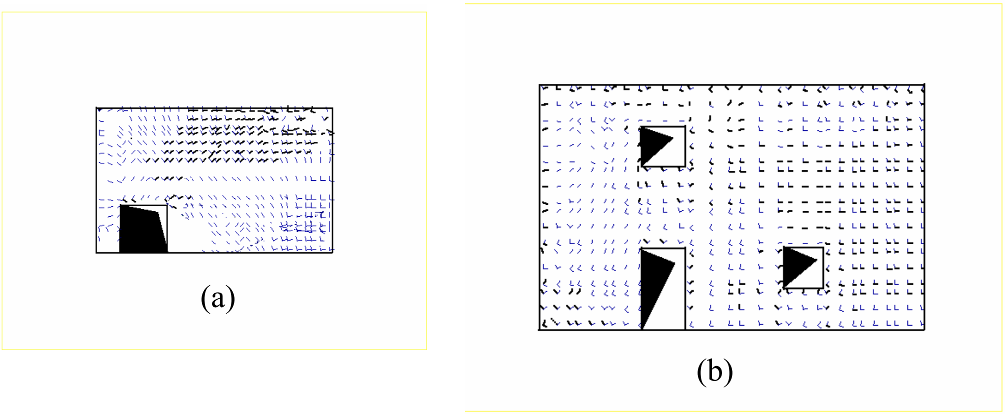
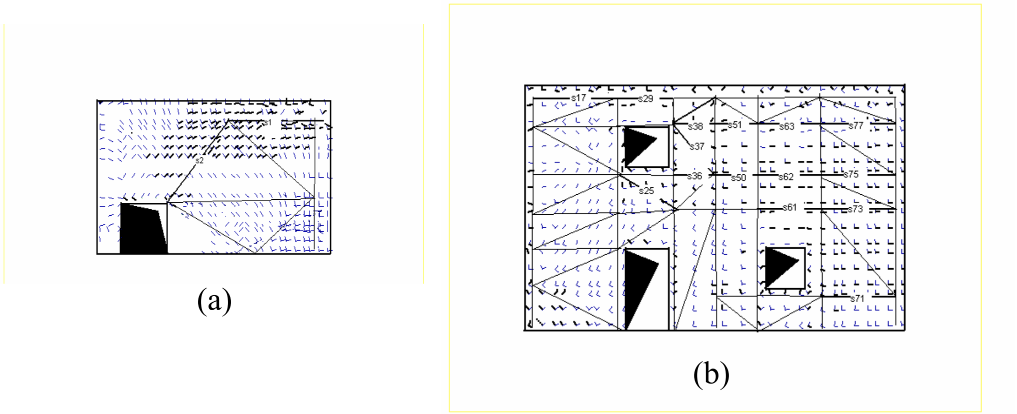

(a)
(b)

Fig. 3. Principal stress fields (thick lines represent tension, thin lines compression).



(a)
(b)

Fig. 4. Strut-and-tie models.

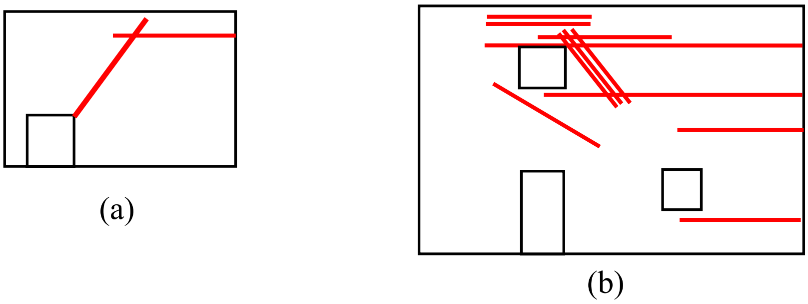
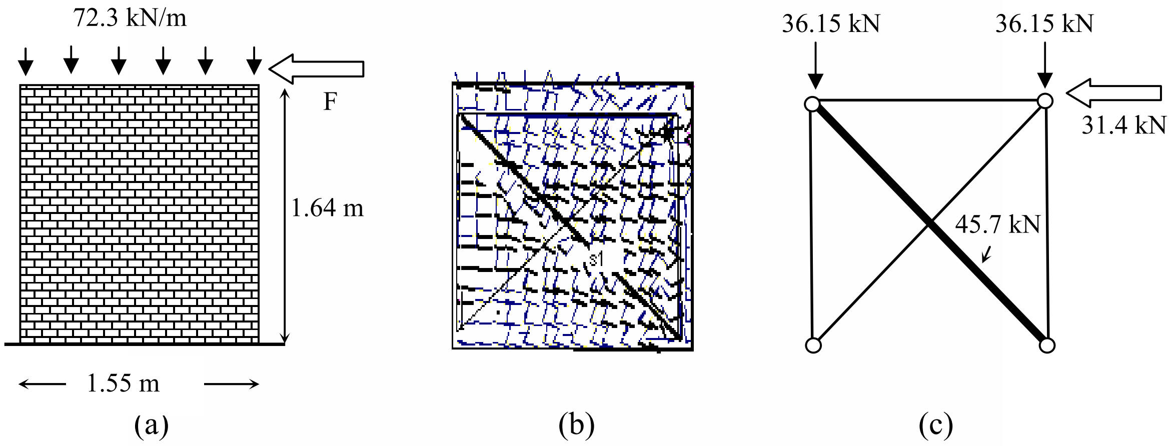

(a)
(b)

Fig. 5. Schematic view of strengthening scheme.



(a)
(b)
(c)

Fig. 6. (a) Test specimen subjected to in-plane shear. (b) Principal stress fields. (c) Strut-and-tie model, force in the FRP tie at failure.

Table 1. Tensile forces in ties, required FRP cross section and number of strips per tie.

Tie	Force, N_{tie} (kN)	Required FRP area (mm^2)	Number of strips, n
Wall (a)			
S1	10.00	6.67	1
S2	35.55	23.70	1
Wall (b)			
S17	0.00	0.00	0
S25	33.82	22.55	1
S29	54.94	36.62	2
S36	11.90	7.93	1
S37	79.75	53.17	3
S38	46.31	30.87	2
S50	13.44	8.96	1
S51	46.31	30.87	2
S61	0.00	0.00	0
S62	13.44	8.96	1
S63	9.15	6.10	1
S71	27.74	18.49	1
S73	16.12	10.75	1
S75	1.00	0.67	1
S77	1.00	0.67	1

5. COMPARISON WITH EXPERIMENTAL RESULTS

The authors made an effort to compare the results provided by the numerical model described above with test data. This would require the availability of experimental results from masonry walls subjected to in-plane loading and strengthened with FRP strips, provided that the following two conditions apply: (a) the strengthening scheme is identical to that provided by the strut-and-tie model and (b) the forces in the FRP strips (ties) are known when the load capacity of the wall is reached. From the experimental database found in the international literature, only one test was identified that met these two requirements. The test is reported in [28] as L1-WRAP-G-X and refers to a planar masonry wall panel with dimensions 1.55 m (length) by 1.64 m (height), subjected to a concentrated horizontal force at the top in combination with vertical loading (Fig. 6a). This wall was strengthened with a single glass FRP strip in each diagonal, with nominal thickness 0.06 mm, width 300 mm and tensile strength 2400 MPa. Fracture of the FRP strip initiated when the horizontal force reached 31.4 kN. From this value and the strut-and-tie model for this specimen (Fig. 6b-c), the tensile force in the diagonal tie is found equal to 45.7 kN. On the other hand, the “experimental” tensile capacity of this diagonally applied tension strip may be estimated from the FRP cross section properties and strength as 0.06x300x2400 = 43.2 kN, a value which is only 5% different from that provided by the strut-and-tie model.

6. CONCLUSIONS

The methodology described in this study, based on strut-and-tie modelling, has been implemented in a computer programme that enables the definition of the locations where FRP strips should be placed in masonry walls subjected to in-plane loading. Moreover, the tensile forces in the ties can be used to calculate the required FRP cross section areas, and from these the number of strips in each location. The available experimental database allowed for limited validation of the proposed approach. Although additional test data are required for a thorough validation of the method, the authors believe that this tool is valuable for the dimensioning (at least, the preliminary) of interventions in masonry walls using FRP materials in the form of strips.

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