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Failure characteristics of FRP-strengthened masonry walls under out-of-plane loads

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ABSTRACT

The failure behavior of masonry walls strengthened with composite materials and subjected to out-of-plane loading up to failure is analytically and experimentally investigated. Emphasis is placed on realistically supported strengthened walls under conditions that restrict the elongation and allow the development of the arching action. A combined experimental–theoretical characterization of the behavior of the strengthened wall throughout the entire loading process and a quantification of their failure criteria are presented. The experimental phase includes loading to failure of a full-scale masonry wall strengthened with composite strips and a full-scale control specimen. A series of tests for the characterization of the mechanical properties of the materials and interfaces involved is also reported. In the theoretical phase, an enhanced analytical model that accounts for the behavior of the various materials, interfaces, and components under the entire spectrum of load levels is presented. The results and the theoretical–experimental comparison provide insight into the failure behavior of the strengthened wall and throw light on some of its unique failure mechanisms.

1. Introduction

Unreinforced masonry walls (URM), subjected to out-of-plane loading such as wind, seismic, blast, and other loads, are characterized by brittle modes of failure due to cracking of the mortar joints or shear and crushing failure of the masonry units. The failure of URM walls is usually involved with a total collapse of the wall with fragments falling into the building. In many cases, these effects may cause severe damage or even injury to the occupants [1–3]. The use of composite materials for the strengthening of URM walls aims to avoid such brittle failure mechanism, to maintain the integrity of the wall, and to increase its strength, stiffness, and ductility.

The application of externally bonded composite materials to strengthening of existing masonry walls subjected to out-of-plane loading was studied by Gilstrap and Dolan [4], Velazquez-Dimas et al. [5], Albert et al. [6], Hamilton and Dolan [7], Kiss et al. [8], Hamoush et al. [2,9], and Kuzik et al. [10]. Most of the experimental and theoretical studies focused on the failure mechanisms of strengthened walls under simply supported end conditions that allow the free elongation of the wall. These studies revealed modes of failure that include rupture of the FRP strip, crushing of the masonry unit, shear failure of the masonry unit and debonding of the composite, debonding of the FRP at the edges, shear sliding along the mortar joints, and buckling/wrinkling of the FRP strip (see Fig. 1). An increase in the failure load of the wall by a factor of 10–50 was reported. In practice, however, the masonry wall is surrounded by a supporting frame that restricts its longitudinal deformation and leads to the formation of the "arching action" (see [11,12]). This action allows the development of a secondary bending resistance mechanism and modifies the behavior of the wall.

The scope of the research on the failure mechanisms of strengthened walls under realistic supporting conditions is more limited. The experimental works of Galati et al. [13], Tumialan et al. [14], and Davidson et al. [15] indicated that the use of the composite materials increased the ultimate load of the wall by a factor of 1.4 only. This is partially due to the improved ability of the unstrengthened wall to carry out-of-plane loads by means of the "arching action". They also revealed that the wall may fail by crushing of the masonry units at the edges, a mode of failure that was not observed in simply supported walls with free elongation. The differences between the effectiveness of the strengthening system and the modes of failure in simply supported walls and those of the longitudinally constrained walls raise questions regarding the ultimate load resisting mechanism of the wall. Consequently, these differences require further investigations (see [11]).

Most of the theoretical approaches to the characterization of the failure mechanisms of strengthened walls used approximate

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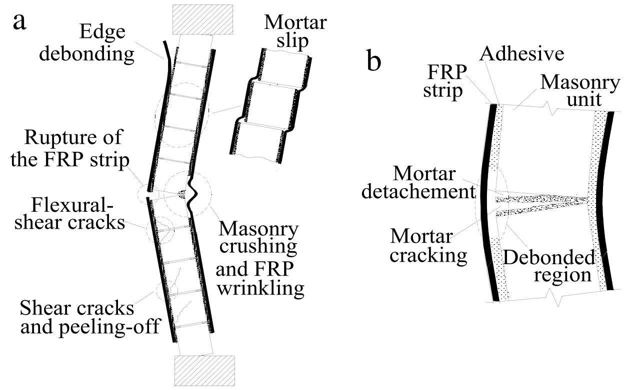

Fig. 1. Structural behavior of the strengthened masonry wall under out-of-plane loading: (a) characteristic phenomena and (b) cracking/detachment in the mortar joint and development of debonded regions.

theoretical models that are limited to specific modes of failure under specific conditions. Among these, the modeling of the strengthened wall as an equivalent bending member with external reinforcement was mostly used [2,7,9]. The flexural failure loads (crushing of the masonry unit or rupture of the composite material) were determined by the strain compatibility method based on the analysis of the critical section. However, under realistic supporting conditions, the distribution of the bending moment depends on the level of damage along the wall (cracking, local crushing, debonding, etc.), and the evaluation of the bending moment at the critical section requires the use of a more detailed analysis.

A shear failure criterion that is based on the shear capacity of the masonry units but without the consideration of the interaction between the existing wall and the strengthening system (which becomes critical near the cracked joints) was developed in [2,9]. Velazquez-Dimas and Ehsani [16] and Tan and Patoary [17] developed a criterion for the debonding failure of the strengthening system based on limit strains in the FRP composite and on a stress criterion in the adhesive layer. Yet, the application of criteria that are based on the level of stresses or strains to the quantification of cracking in brittle materials or interfaces may be problematic and may yield results that strongly depend on the ability to assess these stresses or strains [18,19].

A survey of the existing codes for structures strengthened with composite materials [20–23] reveals that only the CNR-DT 200/2004 [23] provides some instructions and design guidelines for the strengthening of masonry walls. However, while a quantitative characterization is made for the flexural and debonding failure mechanisms in terms of ultimate strains in the FRP layer, guidelines or an analytical approach for the evaluation of the internal forces and moments are not presented.

The literature survey reveals that further efforts are required in order to better understand and characterize the failure behavior and failure mechanisms of the wall, especially under its *realistic* supporting conditions. The objective of the paper is to describe the response of the strengthened wall through the entire loading process, including failure levels of load, and to quantify some of its failure characteristics. Emphasis is placed on realistically supported walls with restricted elongation. The paper aims to take into account the interaction between the wall and the strengthening system, the cracking of the joints, the debonding of the strengthening system, and the development of the arching effect. In particular, the following failure mechanisms are examined: crushing of the masonry unit or the mortar joints, shearing of the masonry unit, sliding at the joints, rupture of the composite material, and debonding of the strengthening system (Fig. 1). The study includes a combined experimental and theoretical characterization of the behavior of strengthened walls throughout the entire loading process, including failure levels of loads, and a quantification of a set of failure criteria. The experimental phase includes loading to failure of a full-scale masonry wall strengthened with CFRP strips and a control wall. It also includes a series of tests for the characterization of the mechanical properties of the materials, components, and interfaces involved. The theoretical study is based on the model developed in [24], which is further enhanced here to account for the behavior of the strengthened wall under failure load levels and for the development of the failure mechanisms. A comparison between the theoretical and the experimental results is then discussed. Summary and conclusions close the paper.

2. Analytical model

In this section, the theoretical model developed in Hamed and Rabinovitch [24] is enhanced in order to account for the nonlinear behavior of the materials under failure levels of load. The analytical model assumes a one-way flexural response of the strengthened wall. Each masonry unit and each mortar joint is modeled as a first-order shear deformable Timoshenko's beam considering the cracking and the material nonlinearity of the joints. The adhesive layers are modeled as two-dimensional linear elastic continua with shear and out-of-plane normal rigidities only and the FRP strips are modeled using the lamination theory. The sign conventions for the coordinates, deformations, loads, stresses, and stress resultants appear in Fig. 2.

The governing equations of the strengthened wall follow [24] and read

$$A_{11}^{frp1} u_{ofrp1,xx} - B_{11}^{frp1} \phi_{b,xx} - \alpha_1^{frp} \alpha_1^c b_{frp1} \tau_{a1} = 0 \tag{1}$$

$$A_{11}^{c} u_{oc,xx} - B_{11}^{c} \phi_{c,xx} - \alpha_2^{frp} \alpha_2^c b_{frp2} \tau_{a2} + \alpha_1^{frp} \alpha_1^c b_{frp1} \tau_{a1} = -n_x \tag{2}$$

$$A_{11}^{frp2} u_{ofrp2,xx} - B_{11}^{frp2} \phi_{frp2,xx} + \alpha_2^{frp} \alpha_2^c b_{frp1} \tau_{a2} = 0 \tag{3}$$

$$A_{55}^{frp1} (w_{frp1,xx} - \phi_{frp1,x}) + \frac{\alpha_1^{frp} \alpha_1^c b_{frp1} c_{a1}}{2} \tau_{a1,x} - \beta_1^c \beta_1^{frp} \frac{b_{frp1} E_{a1}}{c_{a1}} (w_{frp1} - w_c) = 0 \tag{4}$$

$$A_{55}^{c} (w_{c,xx} - \phi_{c,x}) + \frac{\alpha_2^{frp} \alpha_2^c b_{frp2} c_{a2}}{2} \tau_{a2,x} + \frac{\alpha_1^{frp} \alpha_1^c b_{frp1} c_{a1}}{2} \tau_{a1,x} + \beta_2^c \beta_2^{frp} \frac{b_{frp2} E_{a2}}{c_{a2}} (w_{frp2} - w_c) + \beta_1^c \beta_1^{frp} \frac{b_{frp1} E_{a1}}{c_{a1}} (w_{frp1} - w_c) = -q_z \tag{5}$$

$$A_{55}^{frp2} (w_{frp2,xx} - \phi_{frp2,x}) + \frac{\alpha_2^{frp} \alpha_2^c b_{frp2} c_{a2}}{2} \tau_{a2,x} - \beta_2^c \beta_2^{frp} \frac{b_{frp2} E_{a2}}{c_{a2}} (w_{frp2} - w_c) = 0 \tag{6}$$

$$D_{11}^{frp1} \phi_{frp1,xx} - B_{11}^{frp1} u_{ofrp1,xx} + A_{55}^{frp1} (w_{frp1,x} - \phi_{frp1}) - \alpha_1^{frp} \alpha_1^c b_{frp1} \frac{d_{frp1}}{2} \tau_{a1} = 0 \tag{7}$$

$$D_{11}^{c} \phi_{c,xx} - B_{11}^{c} u_{oc,xx} + A_{55}^{c} (w_{c,x} - \phi_c) - \alpha_2^{frp} \alpha_2^c b_{frp2} \frac{d_c}{2} \tau_{a2} - \alpha_1^{frp} \alpha_1^c b_{frp1} \frac{d_c}{2} \tau_{a1} = -m_y \tag{8}$$

$$D_{11}^{frp2} \phi_{frp2,xx} - B_{11}^{frp2} u_{ofrp2,xx} + A_{55}^{frp2} (w_{frp2,x} - \phi_{frp2}) - \alpha_2^{frp} \alpha_2^c b_{frp2} \frac{d_{frp2}}{2} \tau_{a2} = 0 \tag{9}$$

$$\alpha_1^{frp} \alpha_1^c \left(u_{oc} - u_{ofrp1} - \frac{c_{a1}}{2} (w_{frp1,x} + w_{c,x}) + \frac{\tau_{a1} c_{a1}}{G_{a1}} - \frac{\tau_{a1,xx} c_{a1}^3}{12 E_{a1}} - \frac{d_{frp1}}{2} \phi_{frp1} - \frac{d_c}{2} \phi_c \right) = 0 \tag{10}$$