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Shear strength of URM walls retrofitted using FRP

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Abstract

This paper compares different models currently used to calculate the shear strength of unreinforced masonry (URM) walls retrofitted using fiber reinforced polymers (URM-FRP). The shear strengths of six recently tested URM-FRP walls were compared to shear strengths predicted by the models herein. Four of these specimens were tested under constant gravity load and incrementally increasing in-plane loading cycles. The other two specimens were tested on a uniaxial earthquake simulator. The specimens were subjected to synthetic earthquake motions with increasing intensity. Each specimen was retrofitted on the entire surface of a single side using FRP with different axial rigidities. One of the shear strength models compared in this study has been recently developed by the authors. The model was explicitly developed to predict the shear strength of unreinforced masonry walls retrofitted using FRP. The model idealized masonry, epoxy, and FRP in a URM-FRP as different layers of isotropic homogeneous elastic materials. Then, using principles of the theory of elasticity, the governing differential equation of the system is formulated and linearly solved. Then, the material nonlinearity was implemented via a step-by-step degradation in the layer stiffness; after each step the equations were resolved linearly. In most cases, failure occurred in either the masonry or the epoxy and in no case did FRP reach its ultimate load. Comparisons between the different shear models showed that the authors' model is more conservative than the other existing models. In addition, for a small FRP axial rigidity, the difference between the models was insignificant. However, with increasing FRP axial rigidity the differences between the models became more significant. This paper highlighted the advantages and disadvantages of each model. It was found that the authors' model offered several advantages over the other available models. However, the authors' model also has its own disadvantages and limitations. One of these limitations is that it does not explicitly take into consideration the out-of-plane normal stresses. Finally, additional experimental verification of the authors' model is recommended.

Keywords: Masonry; Walls; Shear; Retrofitting; Composite materials

1. Introduction

Existing unreinforced masonry (URM) buildings, many of which have historical and cultural importance, constitute a significant portion of the world's building inventory. Recent earthquakes have repeatedly shown the vulnerability of URM buildings. This brought to light the urgent need to improve and develop better methods of retrofitting for existing seismically inadequate URM buildings. Conventional retrofitting techniques (e.g. ferrocement, grout injection, shotcrete etc.) have several disadvantages such as available space reduction, architectural impact, heavy mass addition, corrosion potential etc. [1]. During the last decade or so on, fiber reinforced polymers (FRPs) offered a promising alternative solution for retrofitting of masonry structures. FRPs present several well-known advantages such as high strength to weight ratio, ease of application, and high resistance to corrosion over existing conventional techniques.

Studies on shear retrofitting of URM using FRP have been limited [2]. Moreover, the priority of the early experimental studies on retrofitting of URM using FRP (URM-FRP) (e.g. [3]) focused on the effectiveness of the technique rather than attempting to quantify effects of different parameters. Understanding of the shear resistance mechanism based on these limited experimental data has not been possible. In addition, the shear behavior of an URM wall is influenced by several parameters such as aspect ratio of the wall, the applied normal force, cohesion, coefficient of friction, and unit tensile

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Notation

The following symbols are used in this paper

E_{FRP}	modulus of elasticity of FRP;
F	shear strength of URM-FRP wall;
F_{FRP}	contribution of FRP to the shear strength of URM wall;
F_m	shear strength of URM wall;
f_c	concrete characteristic compressive strength;
$f_{\mathrm{FRP},u}$	ultimate tensile strength of FRP;
f_j	axial force in FRP;
G^e	epoxy shear modulus;
L	length of masonry wall;
N_{xy}	external applied shear force/unit length of the wall
t	thickness of masonry wall;
t^e	epoxy thickness;
u^m	masonry element's displacement in X direction;
u^f	FRP element's displacement in X direction;
v^m	masonry element's displacement in Y direction;
v^f	FRP element's displacement in Y direction;
$\varepsilon_{\mathrm{eff}}$	effective strain of FRP at failure;
ρ_h	reinforcement ratio (area fraction) of FRP in the horizontal direction;
τ_{xy}^m	in-plane shear stresses acting on masonry;
τ_{xy}^f	in-plane shear stresses acting on FRP;
τ_{zx}^e	shear stresses acting on epoxy layer parallel to X axis;
τ_{zy}^e	shear stresses acting on epoxy layer parallel to Y axis.

strength. Hence, the challenge of calculating the shear strength of URM walls has not been completely resolved [4]. In the case of URM-FRP, the challenge is more complex since other failure modes have been observed and new aspects related to the FRP are introduced.

Using finite element programs, researchers have modeled masonry either as a one-phase homogeneous material with mechanical properties different from its constituents [5] or as a two-phase material where its constituents are considered separately [6]. The use of a one-phase modeling approach is relatively simple and a simple form of the failure criterion has been normally used. However, this approach neglects the planes of weakness, due to the influence of mortar joints, thus making this modeling approach suitable for studying the global behavior of masonry structures. The two-phase modeling approach is relatively costly to use as well as it requires more input data and extensive computational facilities. Also, the failure criteria are more complicated. This approach is generally suitable for studying the local behavior of masonry elements.

2. A linear model for shear strength of masonry walls retrofitted using FRP (URM-FRP)

This section presents an analytical shear model for URM-FRP. The model idealizes masonry, epoxy, and FRP in a single sided retrofitted URM using FRP as different layers (Fig. 1) of isotropic homogeneous elastic materials. Then, using principles from the theory of elasticity the governing differential equation of the system is formulated. A double Fourier sine series was used as a solution for the differential equation. The solution can be used to model the linear shear behavior of URM walls retrofitted using FRP.

2.1. Derivation of governing equations

The differential element in Fig. 2 shows the in-plane shear stresses acting on masonry (τ_{xy}^m) and FRP (τ_{xy}^f) as well as the two components of the epoxy shear stress (τ_{zx}^e, τ_{zy}^e). The model assumptions are: (1) forces are transferred from masonry wall to FRP through shear only; (2) epoxy carries out only surface stresses; both masonry and FRP layer carry only in-plane shear stresses; (3) no dowel action; (4) the applied lateral forces are applied uniformly over the wall cross section; (5) the effect of asymmetry (due to applying FRP on a single side) is neglected. By using force equilibrium on the differential element of the FRP layer (Fig. 2), assuming uniform shear strain through epoxy thickness, the following relationships between the epoxy stress components and the masonry layer can be shown:

$$\frac{\partial \tau_{yx}^f}{\partial y} t^f = \frac{G^e}{t^e}\left(u^f - u^m\right) \tag{1a}$$

$$\frac{\partial \tau_{xy}^f}{\partial x} t^f = \frac{G^e}{t^e}\left(v^f - v^m\right) \tag{1b}$$

where G^e = epoxy shear modulus; t^e = epoxy thickness; u^m = masonry element displacement in X direction; u^f = FRP element displacement in X direction; v^m = masonry element displacement in Y direction; and v^f = FRP element displacement in Y direction. Note that, from hereon superscripts m, e, and f represent quantities belonging to masonry, epoxy, and FRP respectively.

Differentiate Eqs. (1a) and (1b) with respect to y, x respectively and combine them considering $\tau_{xy} = \tau_{yx}$, then

$$t^f \nabla^2 \tau_{xy}^f = \frac{G^e}{t^e}\gamma_{xy}^f - \frac{G^e}{t^e}\gamma_{xy}^m \tag{2}$$

or

$$t^f \nabla^2 \tau_{xy}^f - \frac{G^e}{t^e}\frac{\tau_{xy}^f}{G^f} + \frac{G^e}{t^e}\frac{\tau_{xy}^m}{G^m} = 0 \tag{3}$$

where γ is the shear strain. But

$$\tau_{xy}^m = \frac{N_{xy} - \tau_{xy}^f t^f}{t^m} \tag{4}$$

where N_{xy} is the external applied shear force/unit length of the wall; substitute for τ_{xy}^m from Eq. (4) into Eq. (3) and divide by