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Analytical Model and Design Guidelines for Using FRP System in Strengthening In-filled Frames

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Abstract*: This paper demonstrates an analytical model to simulate a single story brick masonry in-filled frame strengthened by carbon–fiber reinforcement polymer (CFRP) to resist lateral loads. The paper is a part of a comprehensive research related to characterize the behavior of CFRP in retrofitting In-filled Frames. The pervious phase was an experimental program carried out on half scale specimens to study the effectiveness of different strengthening techniques for in-filled frame. The results of the pervious phase showed that the used strengthening methods were effective, with high increase in strength and ductility. In the current phase, an analytical model was presented and investigated. Based on this model, two design formulas were proposed to determine the required amount of FRP needed to resist lateral loads. The first formula represents the accurate solution while the second formula is a simplified empirical design equation. They showed good agreement with the experimental results of the first research phase.*
KEYWORDS: *Masonry, In-filled frame, FRP, Design, Analytical model.*

I. Introduction

The up-to-date design requirements of the recent codes were not followed in constructing many existing structures in seismic areas of the world. As a result, structural members of those structures may experience extensive damage during earthquakes. In order to overcome these deficiencies, researches on the utilization of infill wall as a strengthening technique have studied the development of appropriate and economical systems to resist lateral loads. Infill walls are important resources of strength, stiffness and damping under lateral loads [1]. The utilization of fiber reinforced polymer (FRP) is one of the most effective techniques in strengthening, repair and retrofitting masonry walls. Wherever the use of FRP overlays can considerably increase strength, fairly enhances ductility but slightly affects the initial stiffness. This can be achieved by changing the structural system such that the energy is transferred along alternative load paths, or after natively, increasing the ductility in the individual elements that make up the structural system.

In addition, using FRP for seismic retrofitting applications has some more advantages like aesthetic, rapid application, durability, low cost of installation, no loss of valuable space, and no additional weight for structures. The existing studies in the literature [2 -12] mainly indicate gained advantages of FRP-retrofitted infilled RC frames in terms of increased overall structural strength, stiffness and energy dissipation capacity. many parameters as the dimensions of the walls, the orientation of holes of bricks, the type of mortar, the amount of CFRP sheets and the details of strengthening application were studied in the literature [13]. Also, the seismic behaviors of cross-braced and cross diamond-braced retorting schemes applied on infilled RC frames have been investigated experimentally by H. Ozkaynak et al [14].

For existing structures to benefit from the contribution of infill walls during earthquakes, the walls must be kept in their place and the out-of-plane failure should be prevented. For preventing out-of-plane failures and enhancing the tensile characteristics of hollow brick walls, retrofitting the infill walls with fiber reinforced polymer (FRP) composites and connecting infill walls to the reinforced concrete frame using FRP anchorages is an efficient retrofitting technique [15]. Based on the principles of capacity design, undesirable modes of failure in the structural masonry walls should be avoided. The application of FRP reinforcement can modify the failure mode from brittle shear to flexural failure. Typically, flexural failure in masonry walls strengthened at high reinforcement ratio is due to compressive crushing. The analysis of simple cases of FRP strengthened walls led to the following conclusions; (1) The in-plane shear capacity of masonry walls strengthened with FRP may be quite high especially in the case of low axial loads, (2) The in-plane bending capacity depends on the amount and distribution of FRP reinforcement: reinforcement placed near the highly stressed zones gives a significant strength increase, (3) The achievement of full in-plane strength depends on the proper anchorage of the FRP reinforcement: improper anchorage may result in premature failures [16].

It is well known that bonded FRP requires extensive surface preparation of the masonry prior to installation, and uses large quantities of organic bonding, and saturating adhesives. Also, bonded FRP strengthening has a poor fire performance. In addition, the long-term reliability of the bonded systems is largely unproven [17]. Thus, the experimental phase of this research [18] compared between the effectiveness of using four types of FRP strengthening techniques; bonded sheet, bonded strip, un-bonded sheet and un-bonded strip by testing six half-scale masonry in-filled frames subjected to lateral load and constant vertical load. Load–displacement behaviors, crack patterns, modes of failure, steel strain, FRP strain and enhancement of lateral capacity and ductility were investigated in the first phase (experimental phase).

The aim of seismic retrofitting of any building is to upgrade the ultimate strength of the building by improving the structure's ability to absorb inelastic deformation. The infill panel acts as a diagonal strut with high biaxial compression at the contact corners and dominating shear in the middle while separation takes place at other corners. Depends on this concept, the present paper investigates an analytical model that represents FRP strengthening technique of infilled frame. Based on this model, two formulae were solved to determine the required amount of FRP needed to resist lateral loads. A simplified empirical design equation was proposed. The presented equation showed a good agreement with the experimental results.

II. Brief Review of Phase I

2.1 Experimental Program

In the first phase of this research [18], six half scale specimens were tested to evaluate the performance of two types of FRP used in retrofitting single storey frames. The frames are in-filled with brick masonry strengthened by both bonded and un-bonded techniques under the influence of in-plane lateral load. All specimens have a length, thickness, and width of 1.75, 1.95 and 0.12 m as shown in Fig. 1. Also, all specimens have the same details of reinforcement. The first specimen was a bare frame (BF) and the second was a masonry in-filled frame without any strengthening (CIF) as shown in Fig. 2. The other in-filled frames with masonry wall were strengthened diagonally in tension direction by FRP with four different strengthening schemes; bonded FRP strip with FRP anchors in wall and joints of RC frame (Spec. IF-BST), unbounded FRP strip with FRP anchors in joints of RC frame only (Spec. IF-UST), Bonded FRP sheet with FRP anchors in wall and joints of RC frame (Spec. IF-BSH), and unbounded FRP sheet with FRP anchors in joints of RC frame only (Spec. IF-USH). Table 1 describes the details of the tested frames. Further details of the tested specimens are given in [18].

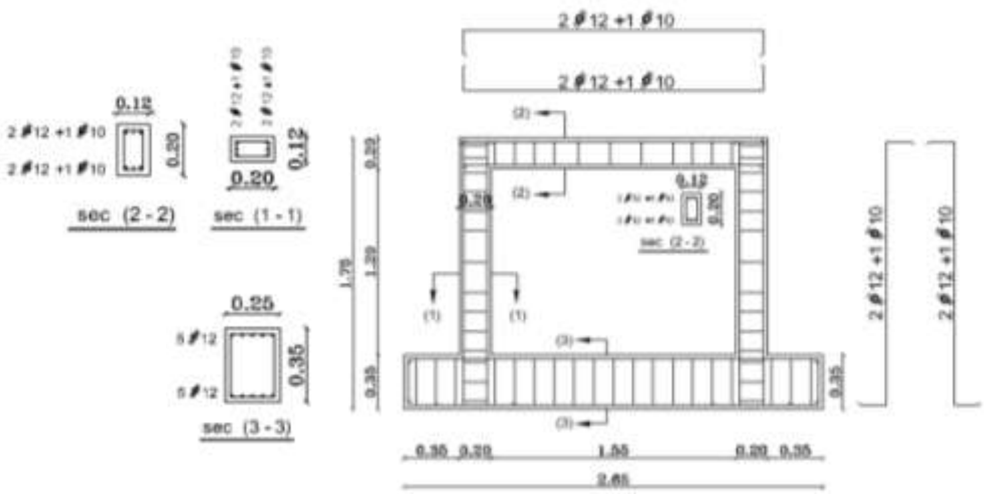


Fig. 1 Details of reinforcement and dimensions of all tested frames (Dimension in m) [18].

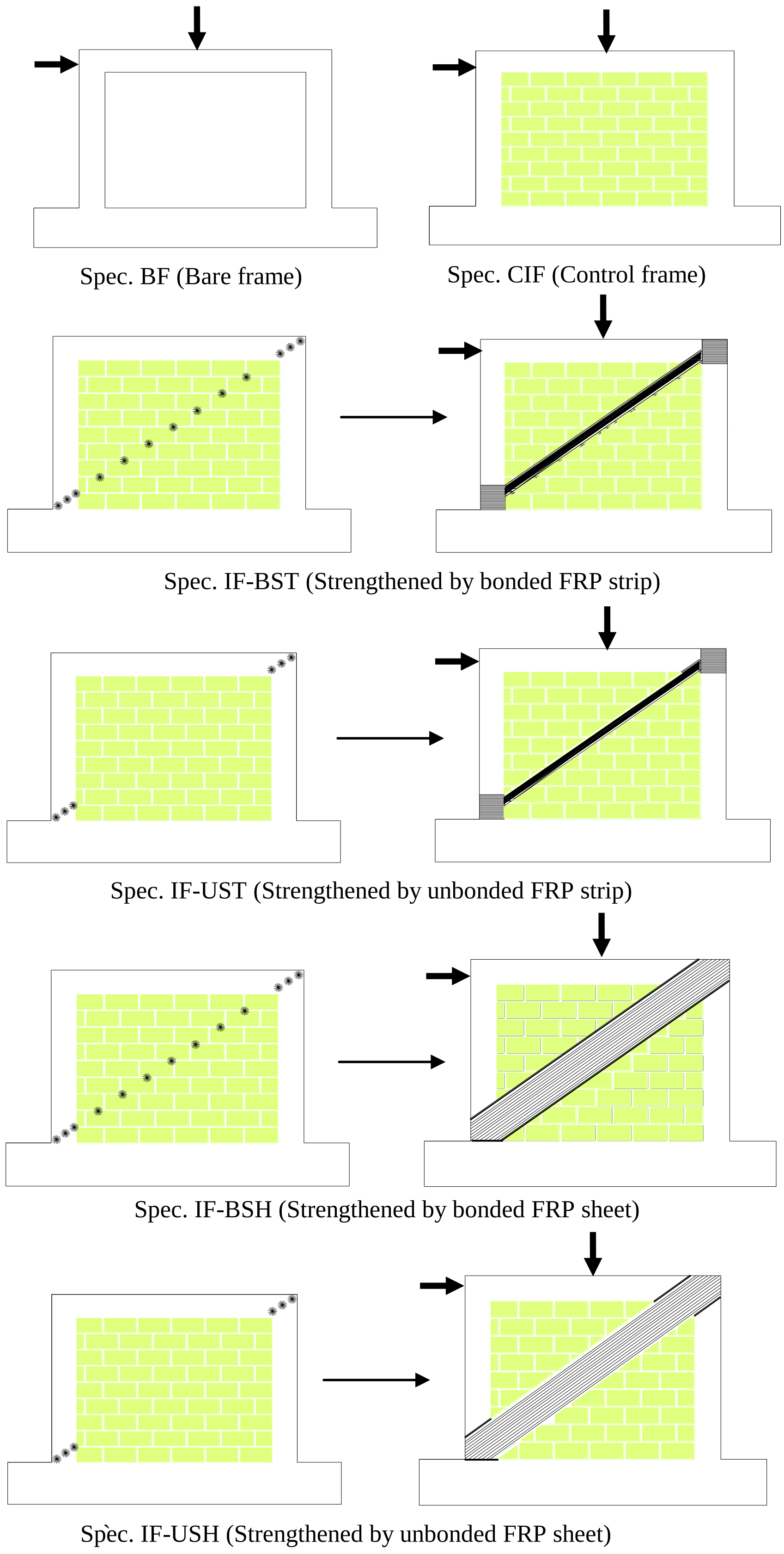


Fig. 2 Details of the experimental program of phase I [18].

2.2 Effect of strengthening schemes

Figure 3 shows a comparison between the ultimate loads of different tested specimen of the first phase. It can be noticed that the increase in strength of control in-filled frame CIF over bare frame BF was 120%. The strengthened schemes achieved a bigger increase in strength than control infield frame CIF can be evaluated in ascending order by 34% for infield frame strengthened by un-bonded FRP sheet (IF- USH), 49% for infield frame strengthened by unbounded FRP strip (IF- UST), 85% for bonded technique with FRP Strip (IF-BST), then 95% for using bonded sheet technique (IF-BSH). The good effectiveness of the used strengthening schemes is due to the FRP strengthening material which strained the opening cracks that developed through the mortar joints and brick units. In addition, the FRP acts as a tie which keep the structural system stable after the formation of plastic hinges at RC frame joints. In terms of strength increase, frames strengthened by bonded FRP performed better than the un-bonded schemes. It was found that all the used strengthened techniques are more ductile than the control in-filled frame by a ratio ranged from 64% to 104%. Also, the un-bonding techniques have ductility bigger than the bonding techniques by ratio ranged from 13% to 24% respectively [20].

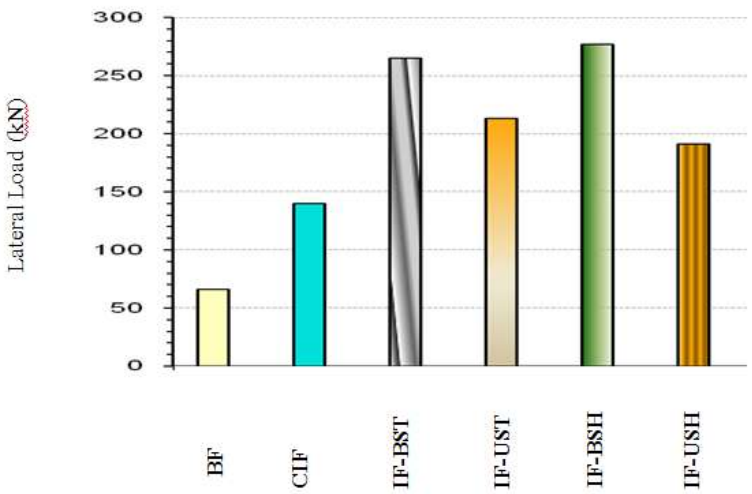


Fig. 3 Ultimate loads for the tested specimens of the experimental program of phase I [18].

III. Analytical Model and Design Guidelines

In-filled frames are complex structures which exhibit a highly nonlinear inelastic behavior. The most important factors contributing to this behavior arise from the material nonlinearity, namely, (i) cracking and crushing of the masonry panel, (ii) cracking of the concrete, yielding of the reinforcing bars and local bond slip in the surrounding frame, and (iii) degradation of the bond-friction mechanism and variation of the contact length along the panel-frame interfaces. Geometric nonlinear effects can also occur in in-filled frames, especially when the structure is able to resist large horizontal displacements. However, these effects did not represent any particularity and can be considered in the analysis using the same methodologies applied to reinforced concrete or steel structures.

The present study was conducted to investigate the effect of using additional FRP tie on the structural response of the in-filled frame. The suitable analytical model for analysis the masonry in-filled frame subjected to lateral load and strengthened with FRP is replace the masonry by a diagonal strut and represent FRP by a diagonal tie. The model is shown schematically in Figure 4. Figures 5-a and 5- b show the straining actions of joints 1 and 2.

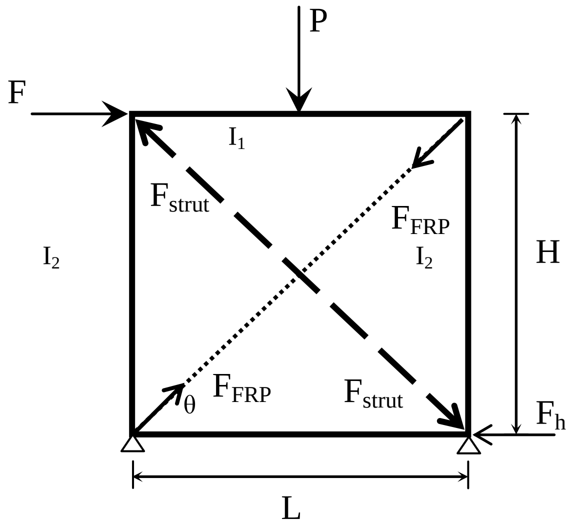


Fig. 4 Analytical model of masonry in-filled frame subjected to lateral load and strengthened by FRP.

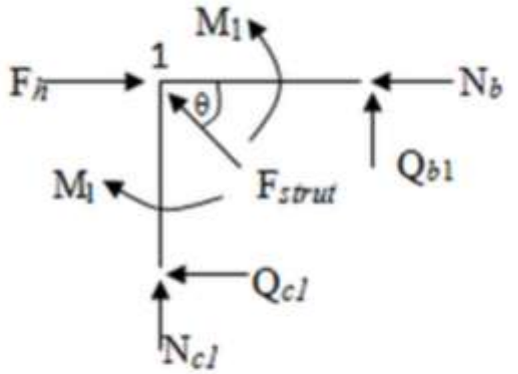


Fig. (5-a) straining actions of joint 1.

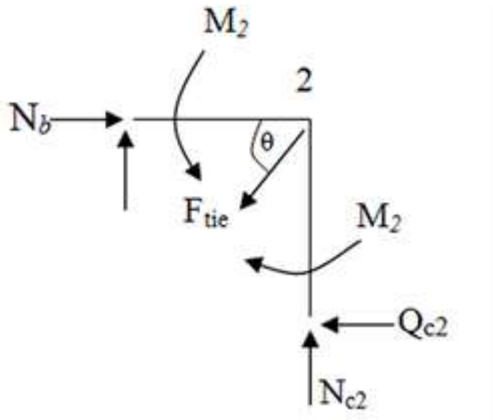


Fig. (5-b) straining actions of joint 2.

From the equilibrium of the forces acting at joint 1 and joint 2 in x- direction, the following equations can be driven:

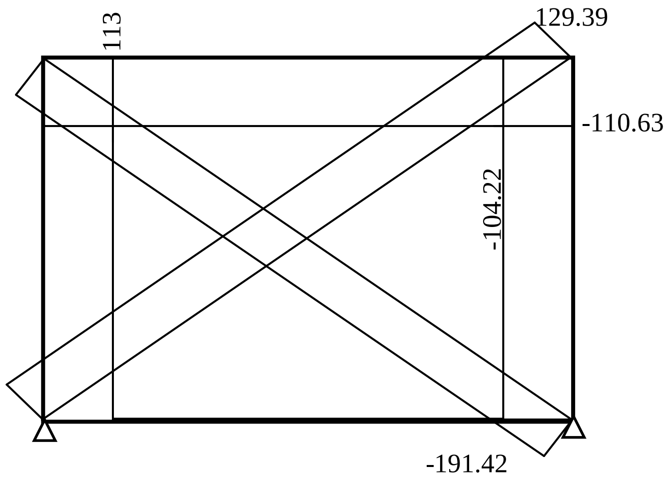
$F_h = F_{strut} \cos\theta + Q_{c1} + N_b$ (1)

$N_b = F_{tie} \cos\theta + Q_{c2}$ (2)

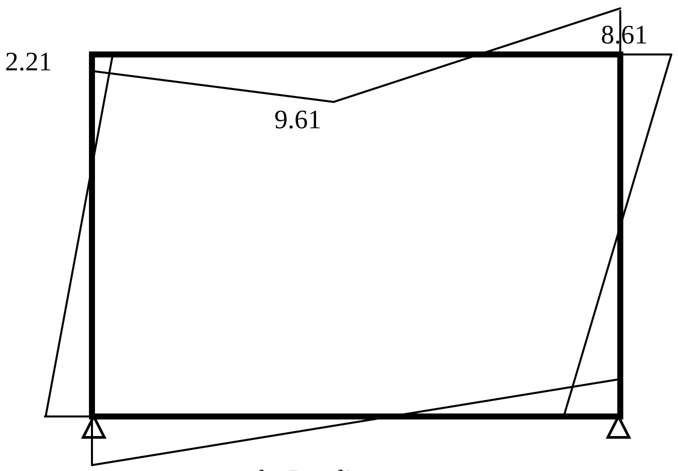
Where Q_{c1}, Q_{c2} and N_b are the shear forces on the columns and the normal force on the top beam as shown in Figure 5. From equation (1) and (2), the following equation can be concluded;

$F_h = F_{strut} \cos\theta + F_{tie} \cos\theta + (Q_{c1}+Q_{c2})$ (3)

This means that the lateral load is bigger than the summation of the horizontal components of the forces in the tie and strut (Fh >F strut cos θ + Ftie cos θ).The model is solved under the ultimate load obtained from the experimental results to determine the values of the shear forces Q_{c1} and Q_{c2} as illustrated in Table (1) and Figure 6.



a- Normal forces



b- Bending moment

Fig. 6 Straining actions for the used analytical model for tested frame IF-BST.

The values of the terms ($Q_{c1}+Q_{c2}$) have ranged from 5% to 8% of the corresponding lateral loads. So, the accuracy of the equation used to determine the ultimate lateral load (equation 3) can be modified to be more conservative and simplified by neglecting the terms ($Q_{c1}+Q_{c2}$) as following;

$$F_h \approx F_{strut} \cos\theta + F_{tie} \cos\theta \tag{4}$$

Where the tension force in FRP can be computed as shown in equation 5:

$$F_{FRP} = n_L * b * t * R * k_b * f_t \tag{5}$$

Where:
n_L: Number of FRP layers for both wall sides.
b: width of FRP.
t: thickness of FRP.

R = ratio of effective strain in the FRP, ε_{fe} to its ultimate strain, ε_{fu} (R = ε_{fe} / ε_{fu}). There are many researches that proposed expressions to evaluate the effective strain in the FRP ε_{fe}. The main factors govern the predication of FRP effective strain is the failure mode of the FRP system and the FRP reinforcement ratio. From the previous works concerned with using FRP, it was found that the less value of R is about 0.1 and not exceeds 0.75 (M. S. Murphy et al 2010 [19], and C. Pellegrino & C. Modena 2008 [20]). So, R can be assumed for the initial design equal to 0.5.

k_b =1 in case of using the bonding FRP technique,
k_b =0.7 in case of using the unbonding FRP technique,
f_t : tensile strength of FRP.
The force in strut can be evaluated as show in equation 6:
$F_{strut} = b_{strut} * t_{strut} * f_{c\ brick}$
Where :
b_{strut}: effective strut width can be assumed equal to 0.1-0.2 of the strut length as observed from cracking pattern of the experimental work.
t_{wall} :width of brick.
θ is the inclination angle of FRP as shown in figure 15.

From the previous equations numbers 4, 5, and 6, the required area of FRP, AFRP which equal to n_L * b * t can be estimated under any certain lateral load as expressed in the proposed simplified amplified equation 7:

$$A_{FRP} = \frac{F_h - b_{strut} t_{wall} f_{cbrick} \cos\theta}{R K_b f_t \cos\theta}$$

The results of both the experimental work and the proposed equations are compatible as illustrated in Table 6.

Table 1 Verification of the two proposed design equations with the experimental result

Frame	P_u (kN)	Specifications of FRP used in exp.					Qc 1	Qc2	F_h*	F_h **	Verf.* eq 3&Exp	Verf.** eq 4&Exp
		n_L	b_{FRP}	t(mm)	f_t (MPa)	F_{FRP} (eq5)						
IF-BST	265	2	50	1.2	2800	168	7	11	262.8	244.8	-0.8%	-7.6%
IF-UST	213.3	2	50	1.2	2800	117.6	5	9.4	222.5	208.1	4.3%	-2.4%
IF-BSH	278.3	4	205	0.13	3500	186.5	7.5	11.3	277.2	258.4	-0.4%	7.3%
IF-USH	191.7	4	205	0.13	3500	130.5	3.8	8.4	229.8	217.6	-19%	13.5%

Forces in kN b_{strut} assumed equal to 0.1* strut length $f_{c\ masonry}$=7 MPa. Verf.= verification
* According to the proposed accurate equation (eq 3). ** According to the proposed simplified equation (eq 4).

IV. Conclusion

Based on the solution of an analytical model for using FRP in strengthening masonry infilled frame under lateral load, two new design equations were proposed to determine the required amount of FRP needed to resist lateral loads. The first formula represents the accurate solution while the second formula is a simplified empirical design equation. Both formulas showed good agreement with the experimental result of the first phase of this research.

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