

# ANALYTICAL AND NUMERICAL STUDY OF RC FRAMES WITH URM INFILLED RETROFITTED BY CFRP

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### **ABSTRACT :**

It is obvious from experience that structures which had not been designed and constructed according to standard codes, and therefore do not have enough lateral stiffness, will undergo sever damages during intense earthquakes. As an effective rehabilitation technique, strengthening unreinforced masonry (URM) infills with fiber reinforced polymer (FRP) can improve their contribution in load-bearing action and in doing so, they can be considered as a structural element. In this article, the method of Equivalent Strut for modeling infill walls is analyzed with the aid of finite element (FE) procedure, and then by defining the compressive and tensile strut behavior, URM infills are modeled both in un-retrofitted and retrofitted states. The results of nonlinear push-over analysis show that the proposed model can give the behavior close to the experimental specimens.

**KEYWORDS:** Concrete structures, CFRP, Infill, Finite element, Non linear push- over analysis

### **1-INTRODUCTION**

One of the most important factors contributing in structural destruction is insufficient lateral stiffness (Erdem et al. 2004). According to previously done studies, the brittle and not-structural infills can play a significant role in the overall behavior of the structures, especially in the onset of earthquakes. This positive effect can last until finally stress transference between the infill and the frame becomes zero and the inertia forces from other earthquake components cause the instability of the infill. Retrofitting of infill walls to prevent their out-of-plane movements by means of FRP is one of the most promising methods for improving the ductility as well as the strength and stiffness of the buildings. This method is more feasible and less time-consuming and causes the least intervention in the occupancy, when compared to other methods. Triantafillou experimentally studied the in-plane and out-of-plane behavior of URM infills which had been retrofitted by FRP and published a report on related modes of failure (Triantafillou 1998). The effect of reinforcing material properties, the pattern of reinforcing elements' placement, and the type of loading on the behavior of URM walls were investigated experimentally by Albert et al. In this study, according to the test specimens of reference [4] and by doing FE modeling, the behavior of infilled frame is investigated and a model for defining the equivalent strut characteristics is proposed (Al-Chaar et al. 2002). Then, the modified behavior for retrofitted infill is established and used in compressive and tensile strut modeling. Finally, a comparison is made between the models and the specimens in reference (Erduran et al. 2003)

### 2- A REVIEW ON EXPERIMENTAL TESTS FOR FINITE ELEMENT MODELING

The selected material properties derived from Al-Chaar 1999, is as follows:



rable 1 material characteristic (11-Chaar et al. 2002)				
	Properties			
Material	mean compressive strength (Mpa)	mean modulus of elasticity (Mpa)		
Concrete	38.44	29.9		
Reinforcement	338.5	200		
Brick	80.96			
Prism	26.74			

Table 1 n	naterial cha	aracteristic	(Al-Chaar	et al.	2002)
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The experiment was done on half-scaled, single story, single bay RC frame with URM infill wall with the maximum drift of 9% [5]. The height of the model and the center-to-center distance of the columns are 1.5 m and 2.0 m, respectively. The dimensions of the columns and beams are  $127 \times 203mm$  and  $127 \times 197mm$ , respectively. The aspect ratio for masonry infill is 23 and the ratio of height to length is 0.75. Finally, the thickness of URM infill wall is 5.8 cm. the features of the model are depicted in Figure 1. The lower beam is fixed to the floor and the displacement is exerted to the upper beam in the cyclic way.



Figure 1 reinforcement characteristics of the models (Al-Chaar et al. 2002)

### 2-1-Nonlinear Push-Over Analysis by FE Modeling

The aforementioned specimen was modeled by commercial software DIANA; the model is two dimensional, plane stress with the same thickness application. The columns and the upper beam and stub (lower beam) were modeled by plane-stress 4-sided 8-noded elements CQ16M, and the interface between the infill wall and the surrounding frame were modeled by link elements CL12I. Both elements use second-order interpolation method. For preventing stress concentration in the location where the load is exerted, an elastic steel plate with the dimension of  $200 \times 127 \times 20mm$  was used and modeled by 8-noded elements. The schematic view of masonry wall interface with concrete frame is shown in Figure 2.



Figure 2 frame and infill elements and their interaction by link element representing the mortar

Masonry infills can be modeled into two forms: micro modeling and macro modeling. In micro modeling, each



brick is modeled separately with the surrounding mortar defined by link elements. So the crack initiation and propagation can be modeled exactly. In macro modeling, on the other hand, the masonry infilled is modeled by a uniform membrane to which the masonry stack and prism properties are attributed. Link elements are only used to model the interface between the masonry indfill and the frame. Since in this analysis, only the stresses of the infill after loading are of importance, the masonry was modeled according to macro procedure.

#### 2-2-The Material Model

The concrete is modeled on the basis of Modified Maekawa which incorporates the Multi-Axial Damage Plasticity Model in compression and Crack Model Based on Total Strain in tension. The main advantage of this model over the others is that it can be defined based on engineering parameters including tensional, compressive strength and fracture energy and can cover all types of lading, while other models are not capable of doing so (DIANA, release 9.1 2005). Tensional softening of concrete is shown in Figure 3.



Figure 3 tensional softening in Modified Maekawa model (DIANA, release 9.1 2005)

The parameters necessary for defining concrete is listed in Table 2. In this table,  $f_c$  is the compressive strength,  $f_t$  is the tensional strength,  $g_f$  is the fracture energy and  $W_{cr}$  is the width of crack bound of concrete.

f <sub>c</sub> (Mpa)	f <sub>t</sub> (Mpa)	g <sub>f</sub> (Mpa)	w <sub>cr</sub> (mm)	ν
38.44	3.8	240	10	0.2

Table 2 input data for defining Modified Maekawa model

For defining the masonry that has anisotropic behavior, Rankine-Hill model was used which has been formulated by Lourenco in 1996. This model incorporated the multi-surface plasticity with Rankine tensional softening and hardening model and Hill yield criteria compressive softening model (DIANA, release 9.1 2005). This model is capable of modeling different strengths of parallel and perpendicular directions of the head joints and the bed joints. The input data necessary for modeling the masonry infill is presented in Table 3.

Tuble 5 mput untu for defining mubbing mit						
	tensile loading-Rankine criteria					
f <sub>tx</sub> (Mpa)	f <sub>ty</sub> (Mpa)	$\alpha_{\tau}$	$\alpha_{\rm h}$	g <sub>ftx</sub> (Mpa)	g <sub>fty</sub> (Mpa)	
0.25	0.35	1	1	0.00034	0.001	
compressive loading-Hill criteria						
f <sub>cx</sub> (Mpa)	f <sub>cy</sub> (Mpa)	β	γ	g <sub>fcx</sub> (Mpa)	g <sub>fcy</sub> (Mpa)	kp
0.25	26.7	-1	3	15	20	0.0012

Table 3 input data for defining masonry infill

In the above table,  $f_{tx}$  and  $f_{ty}$  are masonry tensile strengths in x and y-directions, respectively.  $a_r$  is the coefficient for determination of shear contribution in tensile failure.  $a_h$  is the coefficient of element area dependency to the equivalent length.  $g_{fix}$  and  $g_{fiy}$  are the fracture energies,  $f_{cx}$  and  $f_{cy}$  are the compressive strengths in x and y-directions, respectively. b is the coefficient of compressive stresses' combination and g



is the coefficient for determination of shear contribution in compressive failure. The Poisson coefficient is assumed to be 0.15 and the Young modulus is 8000 MPa. Since only compressive strength was available by Al-Chaar et al. 2002, other parameters for defining material is derived from studies done by Lourenco for brick walls (Lourenco 1997). The behavior of link elements is according to two dimensional plane stress contact surface model after Van Zijl (Van Zijl 2000). This model is Combined Cracking-Shearing-Crushing multi-surface plasticity and capable of modeling mortar joints.

#### 2-3-Finite Element Analysis

In this analysis, loading procedure is displacement-controlled with the maximum drift of 7.5% and the solution uses iterative Newton-Raphson method with convergence criterion of internal energy. The results of experimental and numerical analysis are compared in Figure 4. Good agreement between the two results has been obtained. It is noteworthy that the numerical curve inclines after displacement of 9 cm.



Figure 4 load-displacement curve of infilled frame

Figure 5, shows the distribution of diagonal compressive stresses in infill wall. In this figure, corner-crushing mode caused by in-plane behavior of infill can be observed from propagation of compressive stresses at the loading corners on the infill.

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Figure 5 distribution of diagonal compressive stresses in infill and determination of equivalent strut width

In this step, the infill has reached to its ultimate capacity and in the following steps, fails to participate in load-bearing action and the load-displacement curve inclined afterwards. Sliding between the infill wall and the frame can be observed from relative displacement at their mesh interface. This sliding which has been modeled by link elements is shown by an arrow in Figure 5. From this model, the width of equivalent strut is obtained equal to 25.9 cm. So, in analytical simulation, the infill wall can be modeled as a rectangular with the effective width of 25.9 cm and the thickness equal to the thickness of the infill wall.

### **3-ACCURACY OF INFILL WALL SIMULATION METHODS**

Equivalent strut width of the infills can be calculated according to different formulas obtained by analytical and numerical analyses (Mainstone, 1971, Drysdale, 1994, El-Dakhakhni, 2001). The results of finite element analyses of the model shows that the formula for determination of equivalent strut width in the infills proposed by El-Dakhakhni, 2001 gives more realistic results. Hence, in the second phase of this paper, the abovementioned formula was used. According to this model, the equivalent width of diagonal strut which



represents the width of diagonal compressive stresses distribution can be calculated as follows:

$$A = \frac{(1 - a_c)a_cht}{\cos q}$$
(1)  
$$a_c h = \sqrt{\frac{2(M_{pj} + 0.2M_{pc})}{tf'_{m-0}}} \le 0.4h$$
(2)

In which A is the area of equivalent diagonal strut,  $\theta$  is  $\tan^{-1}(\frac{h}{l})$ , h is the height of the columns, l is the length of the beams,  $a_c$  is the ratio of contact length between the columns and the infill to the height of the column,  $M_{pj}$  and  $M_{pc}$  are the plastic moments of the joints and the columns, respectively, t is the infill wall thickness,  $f'_{m-0}$  is the compressive strength of infill panel parallel to bed joints which can be considered equal to in which  $f'_{m-90}$  is the compressive strength of infill panel perpendicular to bed joints. Formula 1 gives  $143cm^2$  as the equivalent strut area. By assuming that the strut thickness is equal to the infill thickness, the width of the diagonal strut would be 24.65 cm which is close to the width derived from numerical simulation. Therefore, in the following nonlinear push-over analyses, the URM infill wall was modeled as an equivalent strut according to the proposed model after El-Dakhakhni, 2001.

#### 3-1-A Review On Experimental Tests For Modeling Retrofitted Infill Walls

In the following, a model for simulating infilled walls retrofitted with FRP is proposed. In order to verify the capabilities of the proposed model with the actual behavior of strengthened URM infills, the seven 2-story, one-bay 1/3 scaled specimens tested by Erduran et al. as selected analyzed. In these analyses, the first specimen was an infilled frame as the control specimen, and the 6 remainder specimens were retrofitted by FRP and tested under cyclic loading.

The main purpose of the proposed retrofitting technique is reducing inter-story drifts. In doing so, FRP strips were pasted on the infill wall and anchored to the frame at both ends. During the process of loading, one of the diameters of the infill is in tension and the other is in compression. Since the diagonal compressive behavior of the URM infill and diagonal tensile behavior of FRP strips, the overall behavior of the infilled frame is improved dramatically. Figure 6 and Figure 7 show the specifications and the retrofit method of the infilled frame, respectively. The infill wall is made up of clay bricks and the sum of the plasters and bricks sides' thickness is 5 cm. The FRP strips have been pasted on both sides of the infill and connected to the frame by some special anchors.



Figure 6 reinforcement specifications



Figure 7 retrofit method by FRP strips [12]



Table 4 includes material properties used in the specimens.

		1 23			
Material	Properties				
	Mpa	Mpa	Gpa		
Concrete	Control specimen: f'c=19.5	Retrofitted specimen: f'c=12	E=30		
Reinforcement	f <sub>y</sub> =388	f <sub>u</sub> =532	E=200		
CFRP	f <sub>t</sub> =3430	$\epsilon_u = 1.5\%$	E=230		

 Table 4 material properties of experimental specimens [12]

In the following, the behavior of proposed hinge model for un-retrofitted and retrofitted infill walls done by SAP2000 commercial software is validated against the abovementioned experimental tests.

#### 3-2-Nonlinear Push-Over Modeling And Analysis

For simplified modeling the retrofitted infilled frames, the infill itself which carry a majority of compressive forces in the combined system. Besides that, since the FRP strips tolerate a considerable amount of tensile forces, modeling the infill wall with two cross diagonal struts seems to be logical. In this part, the specimens tested by Erduran et al. 2003 are modeled with the aid of equivalent diagonal struts procedure. As illustrated in Figure 8, elements 7 and 8 represent compressive action of infill wall and elements 9 and 10 are representatives of FRP strips tensional action. In this model, tensile strength of masonry infill wall was ignored and the modeled was pushed up to 3 cm displacement at the top.



Figure 8 modeling of retrofitted infill wall with tension-compression behavior in tested 2-story frame

The behavior of the proposed tri-linear model for compressive diagonal struts after El-Dakhakhni is illustrated in Figure 9. The parameters necessary for building this model are initial, secondary, and ultimate displacements, and the compressive strength of URM infill wall.



Figure 9 the behavioral model for compressive diagonal strut

In order to define the behavior of the tensile struts, different effects contributing to this behavior should be taken into account simultaneously. The FRP strips used in the Erduran's experiments had fibers in a single direction and were 200 mm in width. According to standard tests done on 25-mm wide FRP strips, their tensile strength is 1000 MPa (Erduran et al. 2003).



Regarding the fact that the tensile strength of the struts is the result of brick infill, 10-mm plaster and FRP strips' capacity acting simultaneously, the tensile strength of FRP strips is not the same as the tensile strength of the reinforced infill wall. Furthermore, it can be concluded from previously done experiments that the tensile strength of struts in the infill is controlled by the capacity of the anchors connecting the FRP strips to the frame (Erduran et al. 2003). Therefore, the proposed behavioral model for tensile struts should not only consider the overall behavior of the infilled frame, but also undertake the effect of anchors on the system. After numerous analyses to calibrate the model to the results of related experiments, the three-linear behavioral model foe retrofitted frames was proposed which has been depicted in Figure 10.



Figure 10 proposed model for diagonal tensile strut

In the above figure, point A is the condition in which initial yielding in composite material takes place and the tensile stiffness of the strut decreases to 50%. At point B, the initial failures in anchors happen which is accordingly, the point of maximum axial strength of the strut. Hence the model can be defined base on parameters: initial stiffness, stiffness after initial yielding, stiffness after the ultimate strength, yield and failure loads.

The results of the analytical and experimental analyses have been compared for un-retrofitted and retrofitted infilled frames in Figures 11 and 12, respectively. As it is obvious from Figure 11, failure of compressive strut and quitting from load-bearing action is the main cause of the sudden drop in strength. The intensity of this drop, however, reduces in several-story buildings, because not all the struts fails at the same time.



According to Figure 12, after reaching the load of 60 KN, the compressive stiffness of the system decreases to half because of the failure in compressive struts. Contrary to the previous model, the tensile struts continue load bearing action up to 120 KN. Afterwards, the model undergoes the lateral displacement up to 11mm and finally, the analysis terminates. It is noteworthy that the behavior of the structure between points A and B cannot attributed to the real and actual behavior since in this phase, the model undergoes some failures. Finall, it can be concluded that the proposed model can capture the behavior of the un-retrofitted and retrofitted infilled frames to an acceptable degree.



#### 4-CONCLUSIONS

According the analyses results obtained from the numerical simulation with DIANA, it is obvious that the elements and the material behavior models can yield acceptably accurate results in terms of infilled frame behavior. Also by comparing the results of numerical simulation and the proposed simplified models for strut width determination, the model after El-Dakhakhni has proved its accuracy over other models.

The proposed behavioral models for tensile and compressive struts showed good agreements with experimental results. In addition, in un-retrofitted infilled frames, failure of the compressive strut follows by a 60% decrease in load-bearing capacity. While in the retrofitted specimens, the tensile struts continue bearing load up to 120 KN. Finally, the proposed retrofitting procedure will result in a higher strength as well as stiffness.

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