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PURE SHEAR TESTS ON FRP STRENGTHENED MEMBRANE ELEMENTS

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Abstract: As a response to corrosion problems in reinforcing steel, and to increase the efficiency of strengthening systems in terms of time and ease of application, alternate materials such as Fiber Reinforced Polymer (FRP) composites have grown more popular in civil engineering. While research related to the flexural behavior of FRP-strengthened elements has reached a mature phase, the study on shear behavior is still in a developing stage. This paper presents the results of an on-going project, which aims to develop a rational model to evaluate the behavior of the FRP strengthened reinforced concrete element subjected to pure shear. A series of large-scale tests were conducted using the Universal Panel Tester at the University of Houston (UH). Preliminary test results were presented, and the research methodology on modifying the SMM model to account for the effect of FRP was also addressed.

Keywords: fiber reinforced polymer, reinforced concrete (RC), shear failure, strengthening, analytical model.

1. Introduction

Fiber Reinforced Polymers (FRPs) have been widely used in civil engineering applications for new construction, and for repair and strengthening of existing structures for more than three decades. Although extensive research activities have been conducted on FRP RC members under flexural and axial load, the research on shear behavior of such members is still in a developing stage. Most current analytical models for prediction of shear behavior for FRP RC provide a large scatter when compared with the experimental results [1]. These models were mostly developed based on results of simply supported beam tests. Such arrangements cannot give a full understanding of the true pure shear behavior due to the presence of flexural moments and other non-shear related effects such as the height of the beam (h) and the axial stress due to bending.

An efficient method to assess the overall response of an RC member is to identify the characteristic behavior and the contribution of each element/material constituting the structure. For example, an element from a girder strengthened by FRP sheets that is subjected to shear stress field can be isolated and the behavior of that specific element can be predicted by taking into account the inherent characteristics and material laws of the constituents that lead to understanding the global shear response of the girder (Fig. 1). To assess the behavior of this shear element, a set of equilibrium equations, compatibility conditions, and materials laws are required for steel and FRP reinforcements in the longitudinal (l) and transverse (t) directions as well as the concrete in tension and compression in the principal directions 1 and 2, respectively.

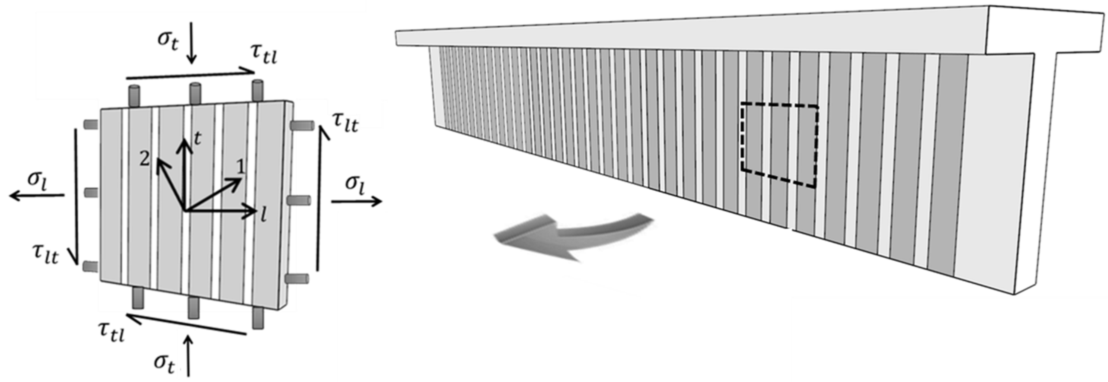

Fig. 1. Beam Shear Element with In-plane Stresses

Based on this approach, researchers from the University of Houston (UH) have developed a series of truss models to predict the shear behavior of un-strengthened RC members, of which the most recent one is the Softening Membrane Model (SMM). The SMM has been proven to be able to predict the whole stress-strain curve of the RC member under pure shear. However, in order to apply SMM in calculating the shear behavior of FRP RC element, a series of equations in terms of stress equilibrium and material laws have to be modified to account for the effect of FRP to the overall behavior of the whole element.

This paper presents the experimental and analytical investigation of an on-going project on developing a rational model, SMM-FRP, in order to evaluate the behavior of the FRP strengthened RC element subjected to pure shear load. A series of full-scale panels were tested under pure shear loading, using the Universal Panel Tester housed at the University of Houston [2]. Preliminary test results were presented, and the research methodology on modifying the SMM model to account for the effect of FRP was also addressed.

2. Experimental program

In order to evaluate the shear behavior of FRP strengthened RC members and to investigate the main factors that influence the behavior, six full-scale tests on FRP strengthened RC panels have been conducted. The experimental results will be used to calibrate the proposed analytical model for FRP strengthened RC members based on the SMM model. The tests are conducted using the state-of-the-art Universal Panel Tester at the University of Houston.

The Universal Panel Tester (UPT)

The UPT was built in the 1980s to study the in-plane and out-of-plane behavior of RC elements. It can accommodate test specimens with dimensions of 1400×1400 mm and the thickness can be up to 406 mm. Figure 2 shows the north view of the panel tester. The UPT is capable of applying various combinations of in-plane and out-of-plane loads to the specimen through 40 in-plane jacks with a capacity of 1100 kN per jack and 10 out-of-plane jacks with a capacity of 670 kN per jack. All of these jacks are fixed onto a giant 4.8×5.8 m steel reaction frame, and are controlled by a sophisticated hydraulic system in order to accurately simulate the stress condition that the specimen is subjected to. The UPT was initially designed to test specimens using only load control mode. Later in 1993, a closed-loop servo-control system was designed specifically for the UPT to conduct tests using strain control mode [3]. By using the strain control mode, the post-yielding behavior can be captured more accurately. Up to date, the UPT is unique to the world because it can test the full-size RC panel using both load control and strain control modes.

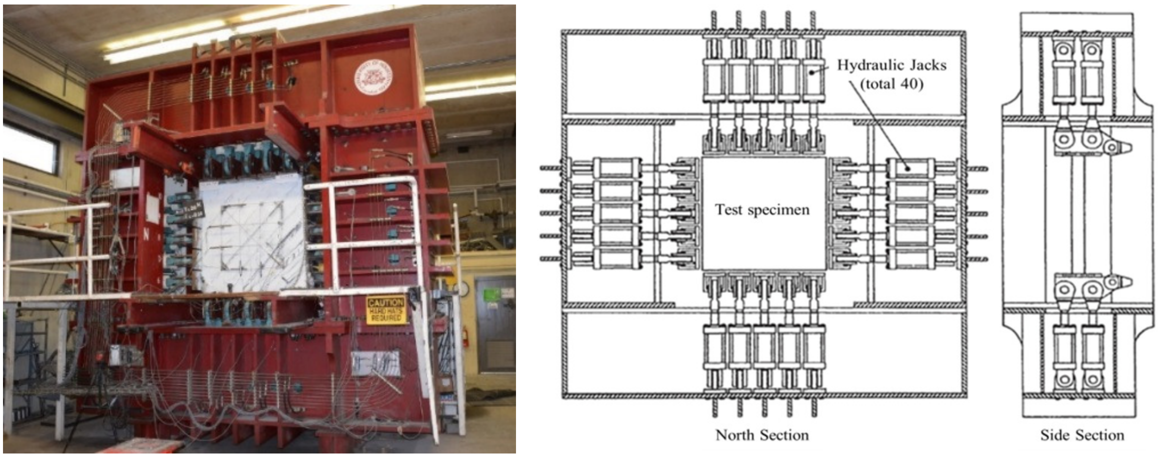

Fig. 2. The North View and section of the Universal Panel Tester

Test specimens and instrumentation

The test specimens (panel elements) are 1.4 m RC square elements, with a thickness of 178 mm as shown in in Fig. 3. The concrete strengths for six tested specimens are in average 46.5 MPa. The mild steel reinforcement consists of grade 60 (426 MPa) bars spaced at 188 mm in longitudinal and transverse directions. The externally applied FRP reinforcements are unidirectional carbon fiber sheets as strips attached on the surface of the panel specimens, which are typically used for shear strengthening. The FRP strips are oriented at 45 degrees to the principal stress directions. The strips have a width of 144 mm, and 189 mm center-to-center distances. The wet lay-up system is used for installation of FRP sheets. The RC specimens are first grinded, sandblasted, and then power washed to provide proper concrete surface conditions that would develop the necessary bond strength between the FRP sheets and concrete substrate. First, putty and primer are applied on the surface; the sheets are then impregnated by epoxy resin and applied in-situ. Specimens are cured at least 48 hours before testing. Pull-off tests are carried out to verify proper bond strength in accordance to ASTM standard D7522 [4].

Shear tests are performed in a way that equal tensile and compressive loads are applied until failure in the horizontal and vertical directions respectively, in order to create a pure shear condition at an angle of 45 degrees.

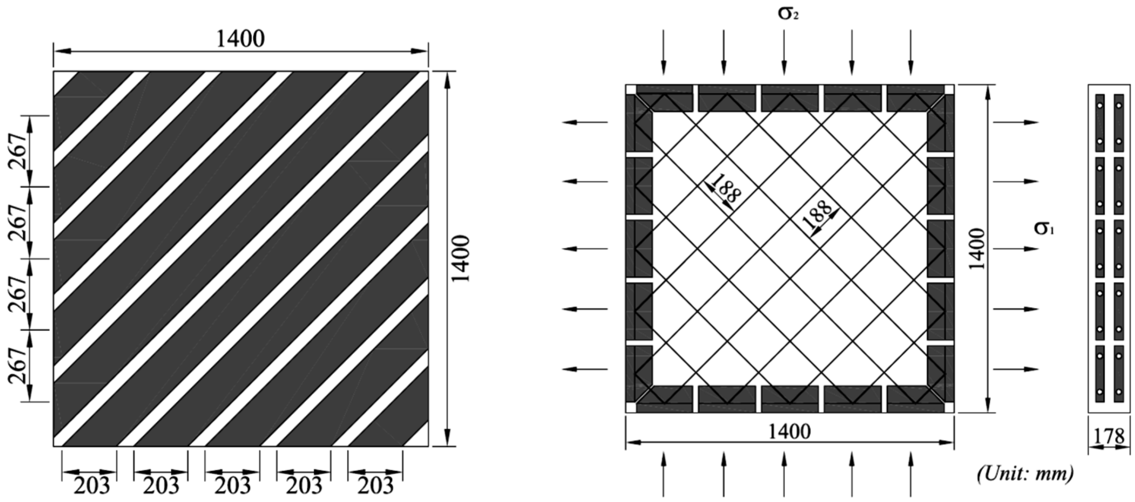

Fig. 3. Test Panels (dimensions are in inches)

Standard material tests have been conducted in order to obtain the mechanical properties of materials used for the panel tests. In Table 1, the properties of materials are reported, where f_y and E_s are the yield stress and Young's modulus of steel, respectively. $Fu_{,FRP}$ and E_f, are the ultimate strength and Young's modulus of FRP, respectively.

Linear Variable Differential Transducers (LVDTs) are used to measure the developed strain on both sides of the tested panels. One side of the specimen (North) is instrumented symmetrically with 10 LVDTs. Four of the LVDTs are aligned horizontally, and another set of 4 LVDTs are aligned vertically, while the remaining two are aligned along the diagonal directions as shown in Fig. 4. On the other side of the specimen (South), two horizontal and two vertical LVDT's are used. The LVDTs are attached to the panel through brackets, which in turn are screwed into threaded bars. The threaded bars and the brackets are aligned on the perimeter of a square with dimensions of 800×800 mm. The difference between the dimensions of the panel and the instrumentation area is to ensure that the stresses are uniform within the area where measurements are recorded.

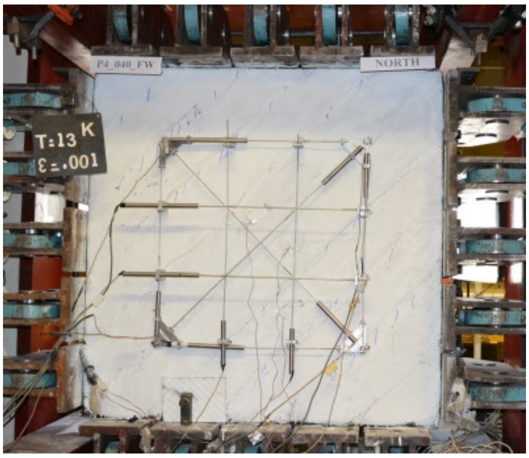

Fig. 4. Instrumentation of Panel Element (North side)

Test matrix

In order to investigate the effects of different parameters on the shear behavior of FRP strengthened RC members, the following two variables are considered: (1) FRP sheet thickness, and (2) Wrapping scheme. The panels are strengthened with FRP sheets of two different thicknesses (0.6 mm and 1.0 mm). Previous research studies have indicated that there may be a limit with respect to axial rigidity of the applied materials beyond which no increase in shear capacity is expected [5]. When the thickness of the FRP sheets applied to the beam increases, the ultimate shear strength gain is limited by premature debonding from the concrete substrate [6]. Also, the disproportionate strength gain when the FRP thickness (FRP layers) increases, is explained by the fact that the ultimate failure is primarily governed by the concrete cracking, splitting, and losing aggregate [7]. Current design guidelines fail to incorporate such behavior for strengthened beams when the thickness of FRP laminates is high. The design guidelines are based on Triantafillou's [8] statement that the contribution to shear strength will increase linearly with low values of axial stiffness. Therefore, the current design guidelines are satisfactory only when a small amount of FRP material is applied [9].

The second variable includes the wrapping scheme, which affects the confinement effect of the FRP sheets and the potential for debonding. Three common wrapping schemes in shear strengthening have been adopted: (a) full wrap, (b) U-wrap with FRP anchor, and (c) side bonding (Fig. 5). The full wrapping is used to ensure that debonding is isolated and FRP will reach its ultimate strain, while the side bonding scheme is used to evaluate the behavior up to the debonding point. The U-wrap with FRP anchor is used to simulate the real case of shear strengthening with FRP in T-beams, wherein full wraps cannot be used.

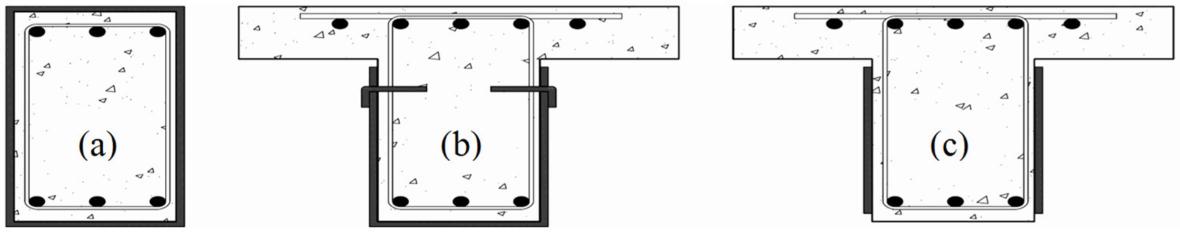

Fig. 5. Wrapping schemes for externally bonded FRP strengthened RC members (a) Fully wrap, (b) Side bond with FRP anchor, (c) Side bonding

The FRP anchors are made by a bundle of the same carbon fiber as the FRP sheets to provide compatibility between the materials used. After saturating the FRP anchor into epoxy resin, one end of the anchor was inserted through a pre-drilled hole on the concrete surface, and the fiber on the other end was then spread on top of the FRP sheet. More details about FRP anchors can be found elsewhere [10].

The test program is mainly designed to identify the necessary data points for the development of the required constitutive relations and the verification of the SMM-FRP model. With the combination of these test variables, 6 panel specimens were tested. The test matrix is detailed in Table 1.

Table.1. Test Matrix and material properties

Specimen	$f'c$ [MPa]	ρ_s [%]	E_s [MPa]	ρ_f [%]	$f_{u,FRP}$ [MPa]	E_f [MPa]	Wrapping Scheme	Anchorage method
REF_P4	45.5	0.76	190	–	–	–	–	–
P4_040_SB	48.6	0.76	190	0.87	876	72	Side Bonding	–
P4_040_FA	46.7	0.76	190	0.87	876	72	U-Wrap	FRP anchor
P4_025_FW	48.2	0.76	190	0.54	827	83	Fully Wrap	–
P4_040_FW	45.6	0.76	190	0.87	876	72	Fully Wrap	–
P4_025_FA	44.7	0.76	190	0.54	827	83	U-Wrap	FRP anchor

The specimens are identified using transversal ad longitudinal steel rebar size (#4), FRP thickness (0.025 in. (0.6 mm) and 0.040 in. (1.0 mm), and wrapping schemes (Full Wrap, Side Bond, and U-wrap with FRP Anchor). As an example: P4-025-SB stands for the specimen with #4 transversal rebar, 0.025 inch thick FRP, and the side bond wrapping scheme method.

3. Behavior of test panels

The experimental shear stress,τ_{lt}, shear strain, γ_{lt}, curves are shown in Fig. 6. Each of these curves exhibits three stages; the elastic stage before concrete cracking, the post-crack stage after concrete cracking, and the plastic stage after steel yielding. Before the concrete cracked, the behavior of the panels was elastic and the $\tau_{lt} - \gamma_{lt}$ relationship was linear. After the concrete cracked, the slope of the curve suddenly reduced. The maximum applied shear stress was reached when the concrete began crushing. After the concrete crushed, the $\tau_{lt} - \gamma_{lt}$curves declined with an increase of deformation until the FRP strengthening system failed.

In Figure 6a, it can be observed that the application of FRP increased the shear capacity of the RC panels (REF_R4) by 30%. Also, with the increase of the FRP reinforcement ratio, ρ_f, the shear capacity increased. Figure 6b, shows that the wrapping scheme has a clear effect on the shear capacity.

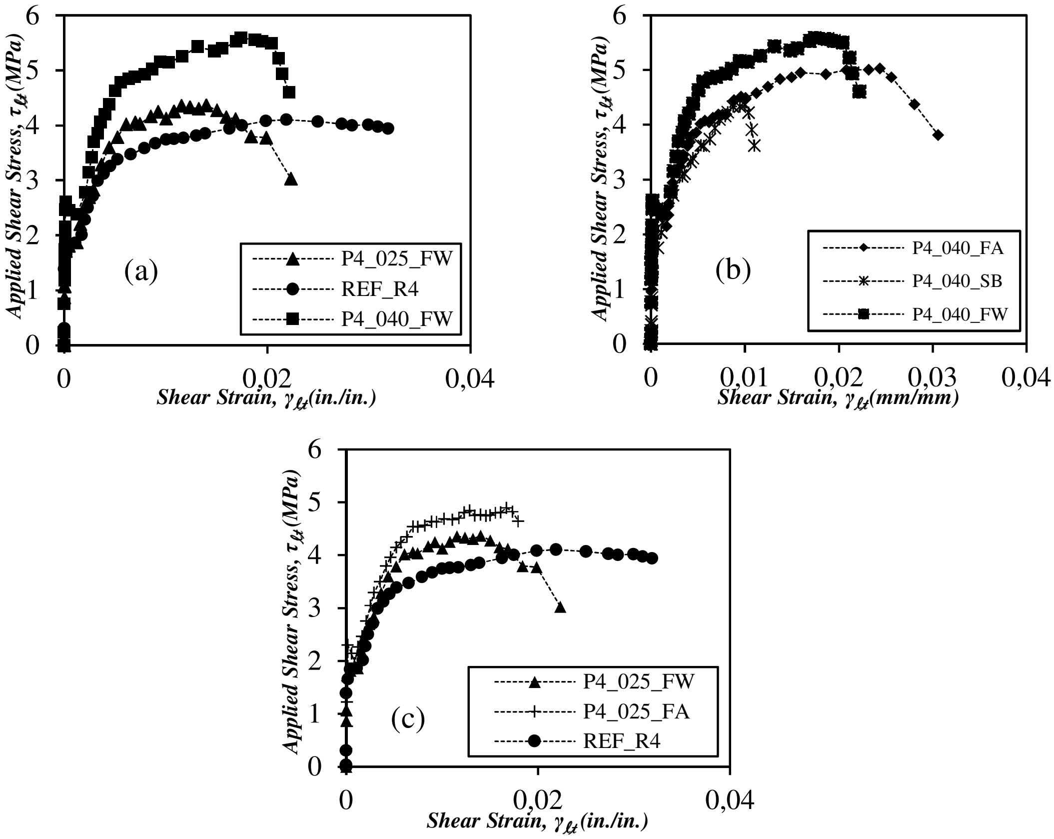

Fig. 6. Shear stress- shear strain curves

In the case of “Side Bonding”, increase in shear capacity was limited to the debonding mode of failure in which the strains are lower than the ultimate strain of FRP. At these lower strain levels, the FRP is not able to utilize its full tensile capacity, effectively lowering the efficiency of the strengthening system. In the case of “Fully Wrap”, the mode of failure was FRP rupture; where the fibers reached their ultimate strain value and fractured at the point of maximum stress. Also, the panels strengthened with “U-Wrap with FRP anchor” showed increase in shear capacity. In these panels the modes of failure were either FRP rupture or FRP anchor failure. Figure 6c compares the two wrapping schemes of Fully Wrap and U-wrap with FRP anchor for the smaller FRP reinforcement ratio; both show an increase in shear capacity and decrease in ductility due to presence of FRP sheets.

4. Theory of SMM_FRP

The SMM model [11] provides a theory for the behavior of reinforced concrete membrane elements. The theory satisfies Navier’s three principles of mechanics of materials, known as: stress equilibrium (Eqn. 1–3), strain compatibility (Eqn. 4–6), and the constitutive laws of materials. Pang and Hsu [12] gave the stress equilibrium and the strain compatibility equations in SMM. In the SMM-FRP model, the stress in the FRP strip was considered similar to the steel reinforcement (Figure 7). The crack was assumed to occur along the principal direction

2 for applied stresses. Therefore, the contribution of FRP reinforcement was added as a new parameter in longitudinal and transverse directions in the stress equilibrium equations, as shown in Eq. (1) and Eq. (2).

$$\sigma_l = \sigma_1^c cos^2\alpha_1 + \sigma_2^c sin^2\alpha_1 - \tau_{12}^c 2sin\alpha_1 cos\alpha_1 + \rho_l f_l + \rho_{fl} f_{fl} \tag{1}$$

$$\sigma_t = \sigma_1^c sin^2\alpha_1 + \sigma_2^c cos^2\alpha_1 + \tau_{12}^c 2sin\alpha_1 cos\alpha_1 + \rho_t f_t + \rho_{ft} f_{ft} \tag{2}$$

$$\tau_{lt} = (\sigma_1^c - \sigma_2^c) sin\alpha_1 cos\alpha_1 + \tau_{12}^c (cos^2\alpha_1 - sin^2\alpha_1) \tag{3}$$

The strain compatibility equations are derived as follows:

$$\varepsilon_l = \varepsilon_1 cos^2\alpha_1 + \varepsilon_2 sin^2\alpha_1 - \frac{\gamma_{12}}{2} 2sin\alpha_1 cos\alpha_1 \tag{4}$$

$$\varepsilon_t = \varepsilon_1 sin^2\alpha_1 + \varepsilon_2 cos^2\alpha_1 + \frac{\gamma_{12}}{2} 2sin\alpha_1 cos\alpha_1 \tag{5}$$

$$\frac{\gamma_{lt}}{2} = (\varepsilon_1 - \varepsilon_2) sin\alpha_1 cos\alpha_1 + \frac{\gamma_{12}}{2} (cos^2\alpha_1 - sin^2\alpha_1) \tag{6}$$

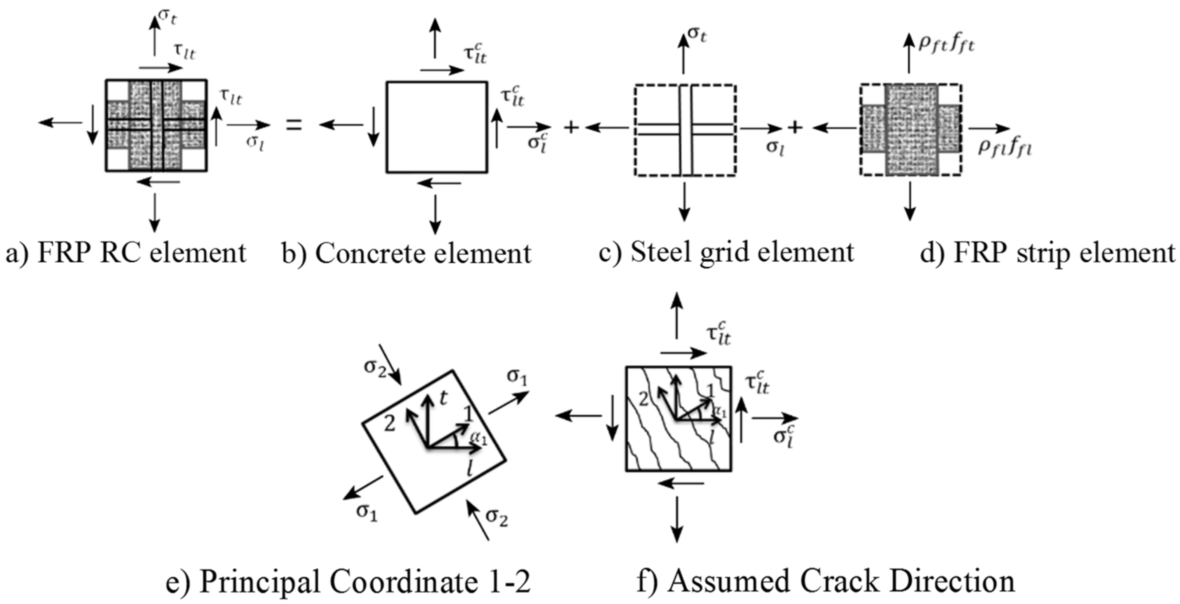

Fig. 7. FRP-RC element subjected to in-plane stresses

In order to take into account the effect of FRP in the SMM, new constitutive laws should be developed for concrete, steel, and FRP. These new constitutive laws should consider the effects of various parameters such as stiffness of FRP, wrapping scheme, spacing of FRP, reinforcement ratio, and the bond. The new constitutive laws include: concrete in tension ($\sigma_1^c - \varepsilon_1$), concrete in compression ($\sigma_2^c - \varepsilon_2$), concrete in shear ($\tau_{12}^c - \gamma_{12}$), steel in tension/compression ($f_s - \varepsilon_s$), and FRP in tension ($f_f - \varepsilon_{fe}$). Preliminary studies on the new constitutive laws were presented elsewhere [13].

Further investigation is needed to develop and evaluate the new constitutive laws in order to develop an analytical model that accurately evaluates the behavior of the FRP strengthened RC elements subjected to pure shear. Verification of the new SMM-FRP model with the presented experimental test results will be presented elsewhere.

4. Conclusions

This paper presents experimental results of the behavior of RC members externally strengthened with FRP sheets subjected to pure shear loads. The preliminary experimental results indicate that the externally bonded FRP sheets enhance the shear capacity of the RC members. Wrapping scheme was found to have a clear effect on the shear gain of the strengthened members. Different failure modes were observed based on different wrapping schemes. Furthermore, FRP anchor was shown to improve utilization of the tensile capacity of the FRP sheets in strengthened RC members, while preventing premature failure due to debonding until the crushing of concrete.

The basic details of the SMM model were introduced and modifications were made to consider the presence of FRP sheets and their effect on shear behavior. Further effort will be made on developing new constitutive laws, which can increase the accuracy of the SMM-FRP model.

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