Fracture Mechanics Modeling of a Shear-Cracked RC Beams Shear-Strengthened with FRP Sheets

Shahriar Shahbazpanahi, Alaleh Kamgar

***Abstract*—**So far, the conventional experimental and theoretical analysis in fracture mechanics have been applied to study concrete flexural- cracked beams, which are strengthened using fiber reinforced polymer (FRP) composite sheets. However, there is still little knowledge about the shear capacity of a side face FRP- strengthened shear-cracked beam. A numerical analysis is herein presented to model the fracture mechanics of a four-point RC beam, with two inclined initial notch on the supports, which is strengthened with side face FRP sheets. In the present study, the shear crack is forced to conduct by using an initial notch in supports. The ABAQUS software is used to model crack propagation by conventional cohesive elements. It is observed that the FRP sheets play important roles in preventing the propagation of shear cracks.

***Keywords*—**Crack, FRP, shear, strengthening.

I. INTRODUCTION

SEVERAL years after being built, concrete members may need strengthening due to extra load, cracks, environmental factors, and damages. FRP composite sheets have been applied mainly to improve the flexural capacity, to provide shear strengthening, and to prevent crack growth in the soffit or/and side face reinforced concrete [1], [2]. Studying the effects of FRP composite sheets in shear span plays an essential role in predict the growth of the crack [3], [4]. Numerous experimental, and theoretical analysis have been conducted to study the shear capacity of reinforced concrete (RC) beams which are shear-strengthened using FRP composite sheet [5], [7].

In fracture mechanics a crack is assumed to start when there is a notch or a stress concentration in the tension zone [8], [9]. To model crack propagation, previous studies have demonstrated that the stress-deformation of concrete has a nonlinear softening behavior [10], [11]. With respect to this behavior, the modeling of crack can be done by cohesive zone model (CZM). For the first time, Hillerborg et al. [12] used CZM to calculate softening fractures of concrete beams. A large and variable fracture zone dimension was introduced in front of the main crack by [12]. This fracture zone is called a fracture process zone (FPZ). The FPZ still has an ability to transfer normal and shear stress to close the crack [13].

So far, the method suggested by [12] has been applied more widely due to its practicality, accuracy, and cost-effectiveness in modeling interfacial fractures [14].

In the other hand, there have been some investigations on the fracture mechanics of concrete beams [15], with an initial notch, that have flexural strengthening achieved by using FRP composite sheets. However, to the best of our knowledge, the fracture mechanics modeling of a shear-crack beams which shear-strengthened with FRP a composite sheet has not been studied in the literature. As concrete is relatively weak in shear, obtaining the effect of the FRP on a shear-crack are of particular importance [16].

In this study, a numerical analysis is presented to model the fracture mechanics in a four-point RC beam, with two inclined initial notch on supports, which is strengthened with side face FRP composite sheets. It is shown that the FRP sheets have positive effects on the fracture toughness and they play important roles in on preventing the propagation of shear cracks.

II. METHODOLOGY

Let us consider a four-point loading RC beam. Shear cracks appear along the shear span in an intermediate position, between the loading point and the support, depending on the longitudinal reinforcement amount. Initially, a shear crack follows a vertical trajectory and then turns toward the loading point. But in the present study, the shear crack is forced to conduct by using an initial notch in supports. Since shear force is large and flexural moment is small in the supports, this moment can be ignored to study shear cracks in Mode II. The shear crack angle has an important effect on the shear capacity and fracture resistant.

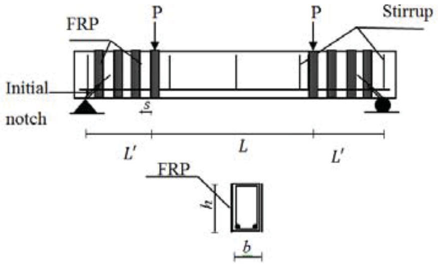

Fig. 1 FRP shear-strengthened beam with two inclined initial notches

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An angle of 45° has been used to design RC beams although, actual shear cracks angle is seldom reported. Thus, the assumptions that the shear crack is 45° and that it starts from the supports, are not far from reality.

Fig. 1 shows an FRP-strengthened beam with two inclined initial notches. These notches have shear cracks angles of 45° and are located on the supports. The four-point loading RC beam has a rectangular cross-section with depth h and width b. The lengths of the initial notches are a_0.

An FRP sheet has a thickness t. The distance of the steel stirrups is selected very large to make the beam weak in shear. Also, for shear failure to happen, the locations of loads are selected close to the supports. The 3D finite element model of four-point loading RC beam with tow inclined initial notches is developed in this research by aid of ABAQUS software. Dynamic explicit non-linear analysis is carried out.

The finite element model of concrete and steel used in the analysis are shown in Fig. 2. Elements C3D8R, T3D2 are implemented for modeling of concrete and reinforcement/ hooks, respectively. The ABAQUS software is used to model crack propagation by conventional cohesive elements (COH2D4P). In the present study, the stress–slip between FRP and the concrete are modeled using the approach introduced by [17]. Bonding between truss elements to model steel bars and concrete is assumed to be perfect. The FRP behavior is elastic but elastic–perfect plastic is considered when modeling the behavior of the steel bars.

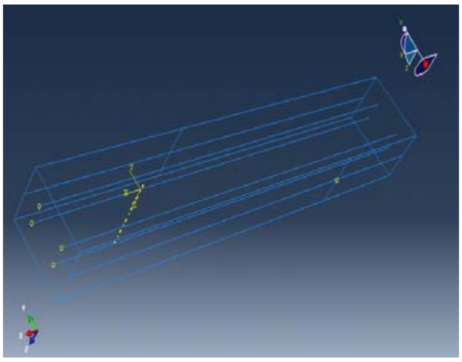

Fig. 2 Three dimension finite element model of concrete beam and steel bars by ABAQUS software

III. Results And Discussions

A simply supported FRP shear strengthened beam under four-point load is considered to study the fracture mechanics in the beam that was tested by [18]. The total length, depth, width, and compressive strength are 3460 mm, 250 mm, 150 mm and 27.54 Mpa, respectively. The distance between two-point load positions, L, is 1700 mm to cause the shear failure in (Fig. 1) while L' is 370 mm. The space of steel transverse was selected 610 mm so that it has no effect on the shear capacity. The steel bars and stirrups have 169 mm^2 and 45 mm^2 cross-sectional areas, respectively. Modulus of elasticity, thickness, width and length of FRP are 151.7 GPa, 1.19 mm, 50 mm, 150 mm, respectively. The spacing of FRP in Fig. 1, is 51 mm. Maximum shear slip stress between FRP and concrete, τ_{max}, is 6.65 Mpa, while ε_{f_c}, the effective strain for FRP sheet, is 0.004. Plain concrete fracture toughness, $K_{C_{II}}$, is 6.65 Mpa.mm$^{1/2}$.

Table I shows the ultimate shear capacity of RC beam using the proposed method as well as the model and the experimental data of [18]. It can be seen that the result of the proposed method is close to other results.

TABLE I
RESULTS FOR SHEAR CAPACITY BY PRESENT STUDY AND PREVIOUS RESEARCHES

Experimental	ACI [19]	Colotti et al. [20]	Matthys and Triantafillou [21]	ABAQUS software
55.46	68.16	55.18	63.98	**54.71**

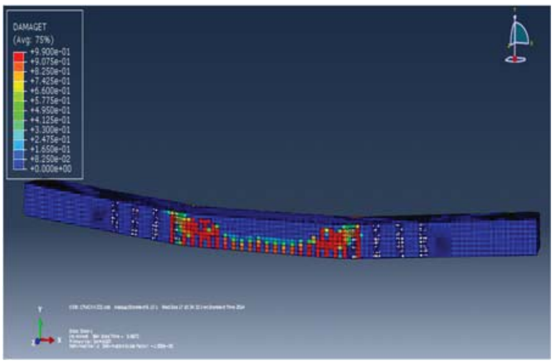

Fig. 3 Crack paths by ABAQUS software with FRP and without FRP sheets

Fig. 3 illustrates the beam with 7652 initial meshes for crack path in beam with FRP sheets (Fig. 3), and in the control beam (Fig. 3), at 28.0 kN load by ABAQUS software. The main diagonal shear-crack is formed at the notch in the control beam (Fig. 3) while shear-crack does not appear in beam with FRP sheets (Fig. 3). It is interesting to observe that the shear crack propagation is controlled with FRP sheets. It can be observed from Fig. 3 that flexural cracks occur at mid-span perpendicular to the axis beam with FRP sheets while flexural crack does not appear in the control beam.

Fig. 4 compares the present numerical model results and experimental data of load versus mid-deflection on control and shear-strengthened beams. It is seen that the stiffness in present study is slightly more than experimental observation (approximately 8.7%). This error may be acceptable because crushing, nonlinear behavior of bulk concrete and plastic deformation are neglected in fracture mechanics.

Ultimate the shear load capacity in the beam with CFRP sheet increases 82.6% compared to the control beam. The numerical results show that the failure in the beam with the CFRP sheet occurs with CFRP sheet being ruptured, but it was reported to with shear crushing and CFRP sheet debonding.

Figs. 5 and 6 showed the parameter study the present model, such as effect of the number and the thickness of FRP sheets on the shear load capacity. Fig. 5 shows how the shear capacity is affected by different number of FRP sheets, "n". It can be seen that, initially, shear capacity decreases. This may be due to the crack growth. After this initial decrease, the stress-free region appears in the concrete and its slip is more pronounced.

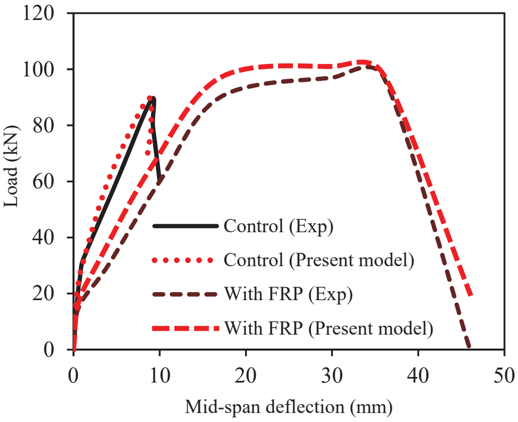

Fig. 4 Load–deflection curves for composite strengthened beams

These conditions, which load falls as crack growth, is called stabilization. Another observation is that loading capacity is increased, as expected, by increasing numbers of FRP sheets. This observation verifies the rationality and efficiency of the method.

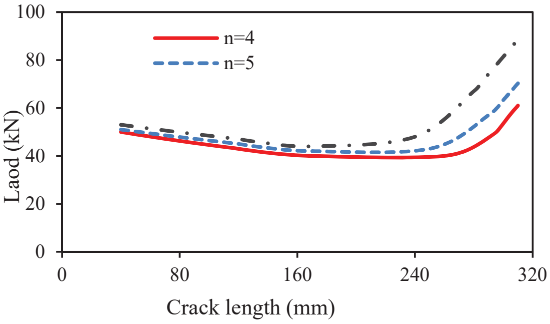

Fig. 5 Shear load vs. crack length with different number of FRP sheets

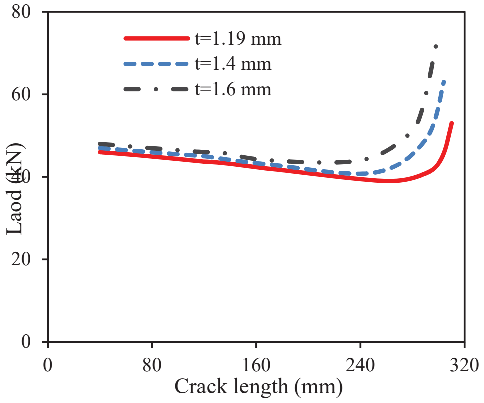

Fig. 6 Shear load vs. crack length with different thicknesses

Fig. 6 illustrates the shear load-crack length with different thicknesses of FRP sheets. When the thickness increases to 1.6 mm, the shear load slowly drops due to the crack propagation. After this drop, the shear load recovers due to the effect of FRP sheets as the influence of the thickness of the FRP sheets on the fracture resistance prevails.

IV. CONCLUSION

In this study, a numerical analysis is presented to obtain the fracture mechanics of a four-point RC beam with two inclined initial notches on supports shear-strengthened with FRP sheets. It is interesting to observe that the shear crack propagation is controlled with FRP sheets. It is seen that the FRP sheets have important effects on the prevention of the propagation of shear cracks. The proposed method shows acceptable similarity to experimental data.

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