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# Numerical and experimental study of failure mode of CFRP strengthened concrete under tension and shear loading

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**ABSTRACT:** Today, the use of carbon fiber reinforced polymers (CFRP) is used as an efficient method for the reinforcement of concrete structures. Concrete structures strengthened with CFRP sheets may have a failure due to debonding mechanisms. In this study, the bond strength and failure mode of CFRP strengthened concrete in tensile and shear stresses are investigated using nonlinear finite element and experimental methods. Because in the study of mechanical behavior of concrete strengthened with CFRP sheet, the assumption of homogeneity of concrete leads to unrealistic results, so in this study, a mesoscale model is used to model concrete. The mesoscopic model of concrete includes three-phase inhomogeneous material consisting of aggregate, mortar, and Interfacial Transition Zone (ITZ). Tests performed include "pull-off" and "twist-off" to determine tension and shear bond strength. The results show that the tension and shear strength of the finite element model is 18% and 13% higher than the results of the "pull-off" and "twist-off" tests, respectively, which are due to laboratory influencing factors and ignoring They are acceptable in numerical modeling of this difference. Also, the tensile strength of the numerical and experimental models is 34% and 33% lower than the shear strength, respectively. According to the obtained results, the debonding in the CFRP strengthened concrete sample was from the substrate concrete. The results show that the micro-cracks, followed by debonding in the mortar and ITZ phases of concrete, due to high porosity and lower strength than the aggregate phase, spread easily.

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## 1. INTRODUCTION

Nowadays, fiber-reinforced polymer sheets have been known to be one of the most effective composite materials that are used to increase the strength and durability of concrete structures. Owing to the lightweight, corrosion resistance, high tensile strength, and ease of application without any interruption of the services, the use of these sheets has become very widespread. One of the recent developments in the reinforcement industry is the use of fiber-reinforced polymer reinforcing sheets (FRP) which are used for strengthening concrete, steel, masonry, and even wooden structures [1]. Fiber-reinforced composites are widely used in engineering applications today. In the study of the behavior of layered composites, several different failure mechanisms can be seen that transverse cracking and consequent debonding is one of the most common failure mechanisms [2]. Reviewing the research conducted in this field, it can be seen that in most studies, concrete is considered as a homogeneous material. While the mechanical behavior of concrete is influenced by the properties of its components and in evaluating the behavior of concrete strengthened with CFRP sheet, the assumption of homogeneity of concrete leads to unrealistic results. Therefore, to study more precisely the behavior of concrete, it is necessary to consider the heterogeneity of its internal structure properly. Therefore, in this study, the mesoscale has been used for modeling concrete, and the bond strength and failure mode of CFRP strengthened concrete in tensile and shear stresses are investigated using nonlinear finite elements in ABAQUS software. Finally, the results obtained from the finite element method are compared with experimental results. The experimental methods used in this study include "pull-off" and "twist-off" tests, which are used to determine the tensile and shear bond strength, respectively.

## 2. METHODOLOGY

### 2.1. Experimental method

"Pull-off« test, one of the most accurate methods for assessing tensile bond strength, is a simple and repeatable test. The two main parameters studied in the "pull-off« test are the bond strength and the mode of failure. The "twist-off« test is an accurate widely used method in determining the strength of concrete and determining the shear bond strength of repair layers both in the laboratory and at the site and is considered as a fast, accurate, and low-cost technique with partial failure [3]. The shear stress required for debonding can be calculated using Eq. (1).

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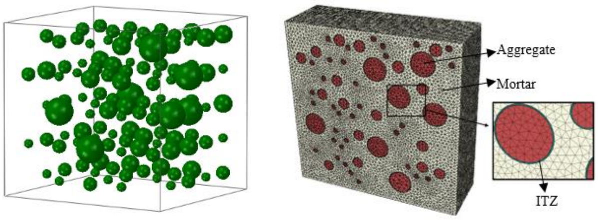


a. Distribution of aggregates

b. Aggregate, mortar, ITZ transmission area

**Fig. 1. Meso-scale model of concrete.**

$$\tau = \frac{T \cdot r}{J} \qquad (1)$$

Where $\tau$ = the shear stress due to twist-off, $\left(\frac{N}{m^2}\right)$, $T$ = the torsional moment, (N.m), $r$ = the radius of the metal plate, (m), $J$ = the polar moment of inertia $(m^4)$.

## 2.2. Numerical method

To evaluate concrete at mesoscale, it is necessary to make a random geometry of the concrete sample. This geometry, which consists of aggregates with random shape, size, and distribution, should be made as similar as possible to real concrete specimens. The basis of this geometry is the random distribution of aggregates and filling the space between them with a cement (mortar) matrix. Fig. 1 shows a concrete sample with dimensions of 150 × 150 × 150 mm produced by coding in the MATLAB program. The model produced includes spherical aggregates, mortar, and interfacial transition zone (ITZ). The volume percentage of aggregates is 30% ($\rho_{agg}$ =30%), the minimum distance between the two aggregates is 0.5 mm, the minimum distance between the aggregates and the concrete sample boundary is 0.5 mm. Based on these past results, the present study uses 0.1 mm thick solid elements to represent ITZ as a separate phase with tensile and compressive strength approximately 75% of the mortar's as suggested in Xiong and et al. [4].

To accurately simulate the "pull-off" and "twist-off" tests, in the numerical model, a partial core was created on the cubic sample of concrete and CFRP sheet, with diameters and depths of 50 and 5 mm, respectively. The produced model includes cubic concrete (in mesoscale) with dimensions of 150 mm, a CFRP sheet with a thickness of 0.35 mm, and a circular metal disk with a diameter of 50 mm. The intended mesh size in the core is 1 mm and has increased to 5 mm in areas farther away.

## 3. RESULTS AND DISCUSSIONS

Fig. 2 shows the distribution of damage in the area of concrete failure in tensile loading.

As shown in Fig. 2, the damage caused in the aggregates phase is minimal and in the other two phases of concrete (mortar and ITZ), complete damage is observed. Due to the weaker phases of mortar and ITZ compared to the aggregate phase, micro-cracks and tensile damage of concrete first occur in these two phases. Then, with the spread of micro-cracks, the damage caused in the concrete also spread, which eventually leads to the failure of the concrete. However, the amount of damage caused in the aggregate phase due to the high strength and stiffness is less than the other two phases. According to Fig. 2, the value of the damage index in the aggregate phase is close to zero. Fig. 3 shows the distribution of damage in the area of concrete failure in torsional loading.

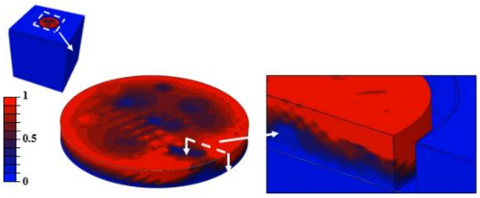


**Fig. 2. Damage propagation in the concrete core under tension loading.**

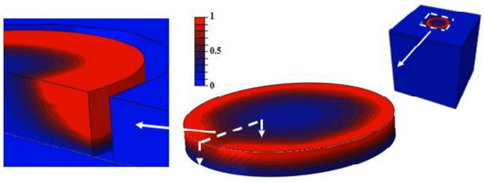


**Fig. 3. Damage propagation in the concrete core under torsion loading.**

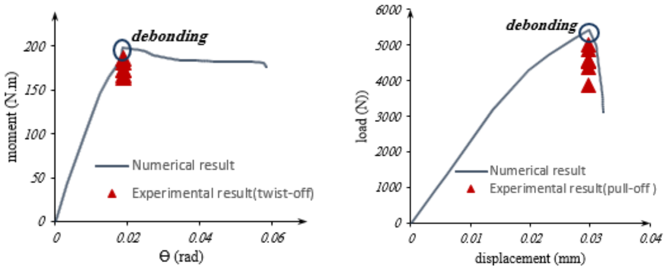
The propagation path in CFRP strengthened concrete specimens depends on the characteristics of the substrate concrete, CFRP sheet, and the interface zone (adhesive matrix). In the sample under net shear force, the main compressive and tensile stresses are at a 45-degree angle, and since the brittle materials, such as concrete, failure sheets are perpendicular to the tensile stresses and core failure has a failure angle of about 45 degrees in the "twist-off" test. As shown in Fig. 3, the failure surface in the concrete sample strengthened with the CFRP sheet Occurs in a plane with an approximate angle of 45 degrees. Fig. 4 shows the load-displacement curve obtained from the numerical model under tensile and torsional loading.

To compare the numerical and experimental results, Table 1 presents the bond strength obtained from these two methods.

It should be noted that the surface areas of a concrete specimen are different from the internal strength due to the contact with mold oils, insufficient hydration of cement on the concrete surface, and also the impact of environmental damaging factors. these factors reduce the strength of the concrete surface areas. Due to the mentioned factors are ignored in the numerical model, so the bond strength obtained from the numerical model is higher than the experimental model.

## 4. CONCLUSIONS

According to the results, due to the high strength of the aggregate phase of concrete, the highest amount of stress has occurred in this phase. Also, in this phase, the criterion



a. Shear loading (torsional) b. Tensile loading

**Fig. 4. load-displacement curve.**

**Table 1. Result of the numerical and experimental model (numerical/experimental).**

| load type | Average bond strength | Failure mode | %Difference between num./ exp. |
|---|---|---|---|
| tension | 2.76/2.32 | Concrete substrate | 18 |
| torsion | 8.09/7.1 | Concrete substrate | 13 |

of damage is the lowest compared to the other two phases (mortar and ITZ). The ITZ around the aggregates as well as the mortar phase is weaker than the aggregate phase due to its high porosity and low strength. Therefore, micro-cracks, followed by damage and failure, easily grow in these two parts. According to the results under uniaxial tensile loading, the stresses generated in the CFRP sheet are often concentrated in the center strip of the sheet and reduced around. However, under torsional loading, the greatest amount of stress is concentrated around the CFRP sheet. Based on the results of bond strength and failure mode predicted in the finite element model and its proper adaptation to the experimental results, the use of the CZM model in ABAQUS for CFRP-concrete bond seems to be a suitable model.

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