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To cite this article: Ali Oday Hilal *et al* 2021 *IOP Conf. Ser.: Mater. Sci. Eng.* **1090** 012105

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Behavior of FRP sheet-concrete bond in high strength concrete samples

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Abstract. The main goal of the present work is to investigate the effect of concrete compressive strength on the behavior of FRP sheet-concrete bond. For this purpose, a model of single shear test was selected and modeled using ANSYS program to study the "FRP-concrete bond". The formulated model was used in the analysis process and it gave results of good correspond with the available actual test results. It was found that the increasing in concrete strength leads to increasing in the bond capacity and the greater concrete strength the better utility of the FRP sheet. All studied models were failed in the same way by debonding the FRP sheet due to concrete failure.

Keywords: High strength concrete, FRP sheet-concrete bond, bond capacity, FEM, Single shear test.

1. Introduction
The ″FRP sheet-concrete bond″ is an affair that is in need to discuss. The bond function is to transfer the stress between concrete and FRP to develop working of composite. The externally reinforcing structural element successes due to the totality of the bond occurs between the surface of concrete and FRP material. The primary considerations that need to achieve a good bonding include epoxy quality, surface preparation, and application of laminate. Although, the efficient bond depends mainly on the work quality and less on the material quality.

Design contra debonding failure is the most important point in the field of using FRP plates or sheets in strengthening structures. "There are various debonding failure modes such as separation of cover, debonding of plate, interfacial debonding, intermediate flexural crack formed interfacial debonding, and

critical diagonal crack forrmed interfacial debonding. Therefore, the FRP sheet-concrete bond behavior is one of the major factors influencing debonding failures in FRP strengthened structures" [1]. The behavior of bond between the concrete surface and FRP laminates is thus the main issue of strain compatility. Some works showed that the strain compatibility appeared to occur through the full depth of the section [2, 3], whereas other works have showed that there is no strain compatibility takes place closely to failure [4, 5]. The adhesive characteristics and properties are important factors that developing composite behavior [6]. "The adhesive transfers stresses and this transferring is related to on its bond with concrete and FRP, the internal shear stress, and its other characteristics such as stiffness, flexibility, and viscosity" [7]. Some studied have proposed bond models for epoxy and polyurethane adhesives [8-10]. Low creep of concrete has also been noticed as a desirable characteristic [11].

The main factors affecting the composite action have been reported as compressive strength of concrete, effective length of bond, FRP axial stiffness, width ratio of FRP-to-concrete, adhesive axial stiffness, adhesive compressive strength [12]. The interface stresses affect bond behavior and failure mode. Large loads which occur in the tension zone will result great shear stresses in concrete which cause high interface stresses producing failure [7]. These stresses are corresponding to FRP tensile capacity, concrete tensile capacity, concrete surface preparation, thickness and strength of adhesive, and the FRP width to thickness ratio.

Many researches have been dealt with bond strength and bond stress between concrete and FRP sheets or strips [13-18] and various models have been suggested for that bond. Some models were resulted in empirical equations calibrated with test results, and others were dealt with fracture mechanics theories and they contain with many variables calibrated with test results. In all models, the stress state is simulated by a "shear test" or "pull-off test" on a concrete prism (block) with bonded FRP strip, as shown in figure 1, in which one or two FRP strips externally bonded to one or two sides of a concrete block by an adhesive resin (epoxy), then a tensile force is applied to the FRP strip from one side of the concrete block "single shear test" or from two sides of the concrete block "double shear test" using hydraulic machine.

(a) Single shear test   **(b)** Double shear test

Figure 1. Bond test.
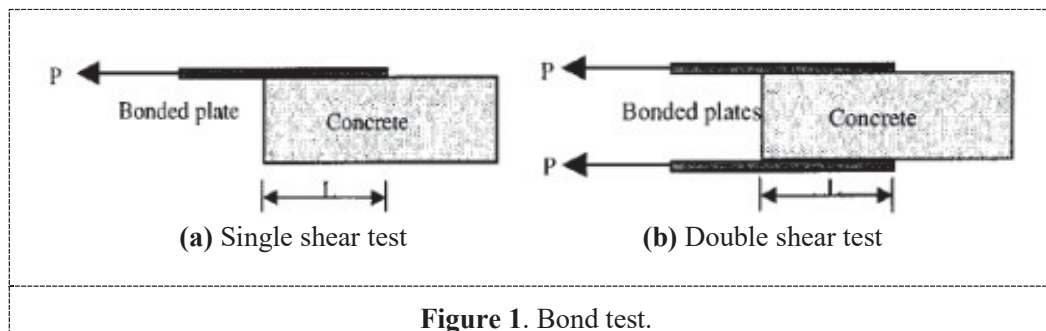
2. Finite Element Modeling
In order to study the behavior of FRP sheet-concrete bond, a model of "single shear test", as shown in figure 2 (a concrete block bonded with FRP sheet from one side), is selected and modeled using ANSYS program [19]. A direct tensile force is applied to the FRP sheet increasingly up to failure. This model was adopted by many codes and researchers to calculate or study the strength, stress and effective length of the bond between concrete and FRP sheets or strips [14,15,16].

Figure 2. Single shear test.
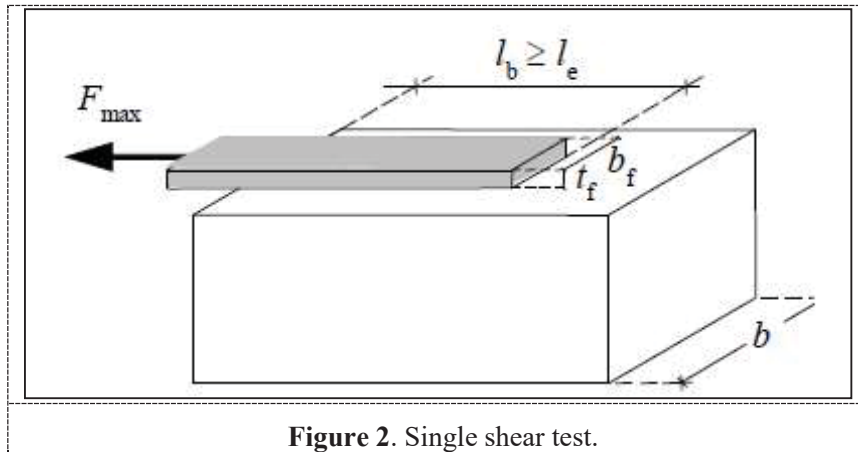
2.1. Materials Modeling
The concrete is a brittle material and had different behavior in compression and tension. A typical stress-strain curve for normal weight concrete is shown in figure 3. The concrete is assumed as a homogeneous and initially isotropic material and its properties that used in ANSYS program are the concrete modulus of elasticity (E_c), concrete ultimate compressive strength (f'_c), concrete ultimate tensile strength (rupture modulus, f_r), concrete Poisson's ratio (v), and shear transfer coefficients (β_t) and (β_c). Concrete Poisson's ratio (v) has been recorded to be remained approximately constant within 0.15 to 0.22 up to a 80% f'_c stress level. Then, after this level, the ratio increases rapidly (values greater than 1.0 have been measured). In the current work, a value of 0.2 is adopted for all concrete types [20]. β_t and β_c are assumed to be (0.3 and 0.7), respectively.

For concrete of high strength, the model of (Hsu and Hsu 1994) [21] is adopted to compute the multi linear isotropic stress-strain curve for the concrete as,

$$f_c = f'_c \cdot \frac{\eta\beta(\varepsilon/\varepsilon_o)}{\eta\beta - 1 + (\varepsilon/\varepsilon_o)^{\eta\beta}},$$
(1)

$$\beta = \left(\frac{f'_c}{65.23}\right)^3 + 2.59,$$
(2)

$$\varepsilon_o = 1.29 \times 10^{-5} f'_c + 2.114 \times 10^{-3},$$
(3)

where f is stress at certain strain, ε is strain at certain stress, ε_o is strain at the concrete ultimate strength f'_c, η is a parameter based on material strength ($\eta = 1$ for $0 < \varepsilon < \varepsilon_o$) and β is a parameter depends on the shape of the stress-strain curve.
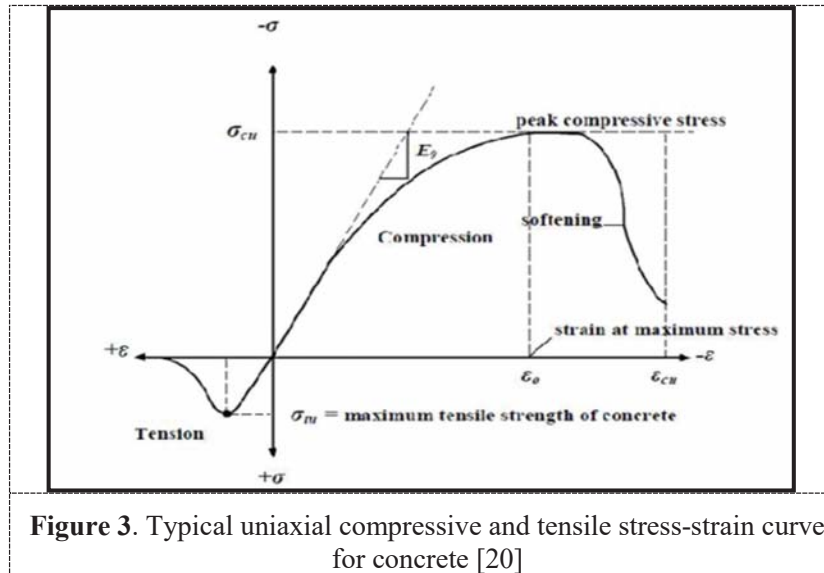
Figure 3. Typical uniaxial compressive and tensile stress-strain curve
for concrete [20]

"FRP materials compose of two constituents. First one is the reinforcement, which is embedded in the second one which is a continuous polymer known as the matrix. The FRP composites are considered as orthotropic elastic materials in the model of finite element; so their properties are different in both directions" [22]. In the present study, the contributions in shear and lateral FRP stiffness are negligible (since strips are at most loaded in the longitudinal direction), the value of 0.3 has been taken for Poisson's ratio, and linearly elastic stress-strain relationship behavior, figure 4, is considered for FRP sheets which do not exhibit any plastic behavior before rupture.

The SOLID65 and SHELL41 elements are used to model the concrete and FRP sheets, respectively. In this study, the SOLID65 element is also used to model the epoxy material (because this element contains 8 nodes, four nodes to contact with concrete and four nodes to contact with the FRP sheet) and the linearly elastic stress-strain relationship behavior is considered for the epoxy material to insure the integrated transmission of loading from the FRP sheet to concrete. It is worth mentioning that the authors, in another study in progress, used an interface element with a bond-slip model to represent the epoxy material. It is hoped that a comparison will be made between the results of the two studies.
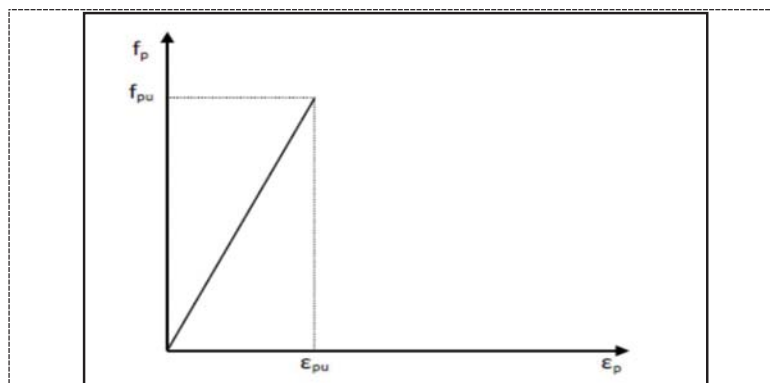

Figure 4. Idealized stress-strain relationship for FRP strips [19].

2.2. Materials Details

A concrete prism with dimensions of (150×150×350mm) bonded with an FRP sheet of (95mm) length and (25mm) width is selected in the present study to represent the single shear test. Figure 5 depicts a typical FE model in ANSYS program that used in this study. The epoxy with nominal thickness of (1mm) is considered along the FRP sheet to achieve full integrity between the two materials. Table 1 shows the chosen materials properties of the FRP sheets and epoxy that used in the current work.
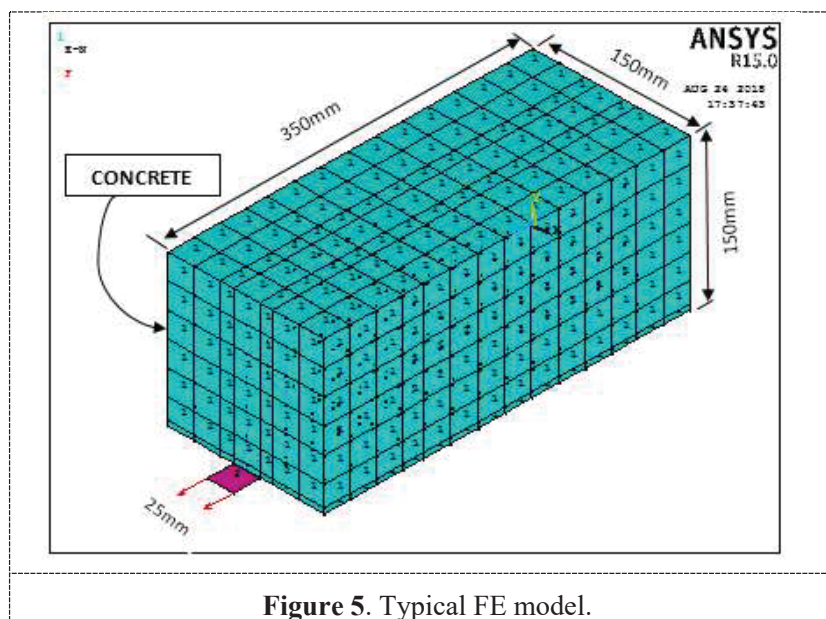

Figure 5. Typical FE model.

Table 1. FRP and epoxy properties

Material	Elasticity modulus (GPa)	Tensile strength (MPa)	Poison's ratio
FRP	256	4114	0.3
Epoxy	36.1	39.4	0.3

3. Verification of Formulated Model

To verify the validity and accuracy of the present formulated finite element model, the obtained analytical results from this model are compared with the experimental results of specimens tested by Jain [15] and Zhao [16]. The results of this comparison are showed in figure 6. The analytical results of the formulated model show good agreement with the experimental values.
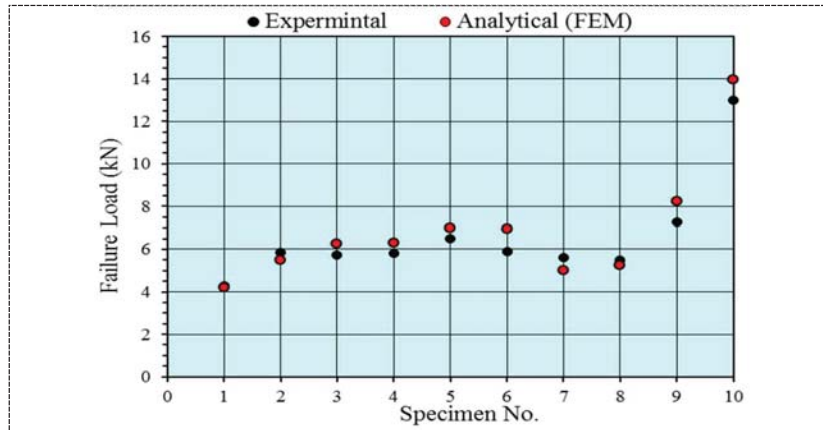
Figure 6. Comparison of available test and present FEM results.

4. Results and Discussion

The compressive strength of high strength concrete is considered to be greater than 55MPa [23]. In order to investigate the effect of variation of concrete compressive strength on the bond between the concrete and FRP sheet and hence to understand how and how much this bond would change accordingly, different compressive strengths ranged between 60MPa and 100MPa are used. Five specimens with different $f'c$, ranged from 60 to 100MPa with an increment of 10MPa, are modeled and analyzed using the formulated model for each specimen. Each analysis process included investigating the bond capacity, stress distribution and crack distribution. The stress value and its distribution are very important in this study to determine the case of failure of each model and to understand the condition of stress transferring from one material to another.

4.1. Bond Capacity

Table 2 and figure 7 show the bond capacity (ultimate failure load) for different compressive strength using the formulated FEM model. It can be noticed from figure 7 that the relationship between bond capacity and concrete compressive strength is nonlinear. The bond's strength increases by about 4.3, 4.5, 7.4 and 12.5 % as the compressive strength increases from 60 to 70, 70 to 80, 80 to 90 and 90 to 100MPa, respectively. It is obvious that the increasing in compressive strength causes an increasing in the bond capacity and by the way an increase in bond capacity ratio.

Table 2. Bond capacity of models with different concrete compressive strength

$f'c$ (MPa)	Bond Capacity (N)
60	7213
70	7525
80	7864
90	8444
100	9500

Figure 7. Bond capacity of different high strength concrete models.
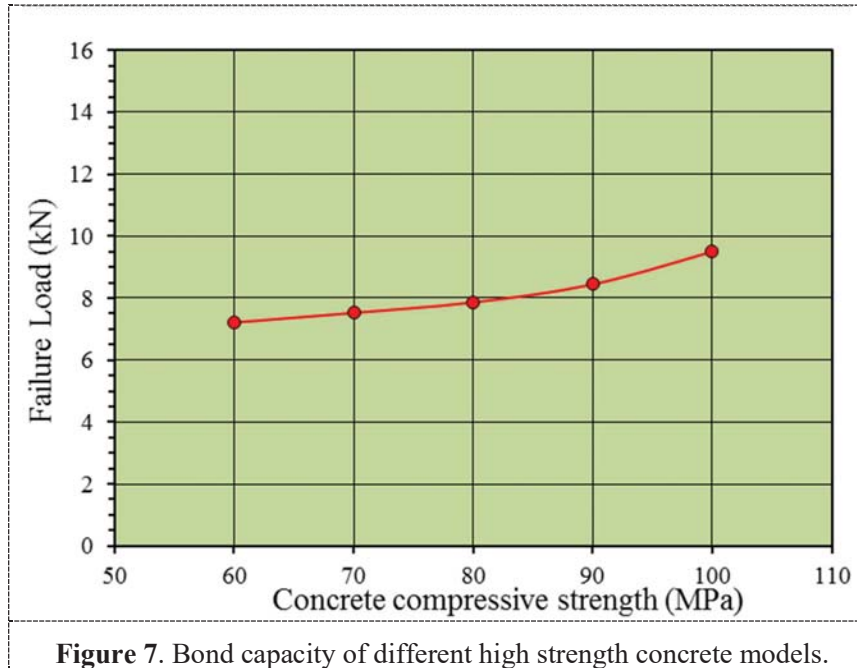
4.2. Stress Distribution

Figure 8 shows the stress distribution in the FRP sheet, concrete and epoxy layer for models with $f'c$ = 60, 80, and 100MPa. Within the contact region between the concrete and FRP sheet, the maximum stress in FRP sheet is equal to 987, 1029, 1107, 1175 and 1275 MPa for models with compressive strength of 60, 70, 80, 90 and 100 MPa, respectively. As the compressive strength increases, the maximum stress of FRP sheet increases linearly. The FRP sheet undergoes greater stresses as the compressive strength increases. For all models, the maximum stress in FRP sheet is less than the peak strength of FRP sheet, which equals 4114MPa. The FRP maximum stress occurs at points, within the contact region, closest to the loaded end. The FRP stress decreases gradually in a fast manner as moving far away from the loading side through approximately one quarter of the contact region length then it decreases slowly along the rest length of the contact region.

For concrete, the maximum stress is equal to 46.6, 52.5, 55, 61 and 67 MPa for models with compressive strength of 60, 70, 80, 90 and 100MPa, respectively. For all models, this maximum stress occurs at points contacted to FRP sheet and nearest to the applied tensile load. The strees in cocrete decreases gradually as moving towards the end of the contact area with the FRP sheet. In general, the concrete stress at all points along and adjacent to the contact area, except the farthest small part from the loading side, exceedes both the ultimate tensile strength and the ultimate shear strength of concrete that specified by the ACI code [20] as $(0.1f'_c)$ and $(0.167\sqrt{f'_c})$, respectively.

The stress distribution manner along the epoxy layer is the same for all models. The peak stress, which equals to the maximum stress, occurs at the end nearest to the loading side then the stress decreases in a fast manner to about 8-22 % of the maximum stress (corresponding on the value of compressive strength) near the mid length of the epoxy layer. The stress returns to increase through the rest layer length until it reaches, at the other end, a value close to the maximum stress. That is the stress at the ends of the epoxy layer is greater than the stress at the middle. This was strange and incomprehensibl
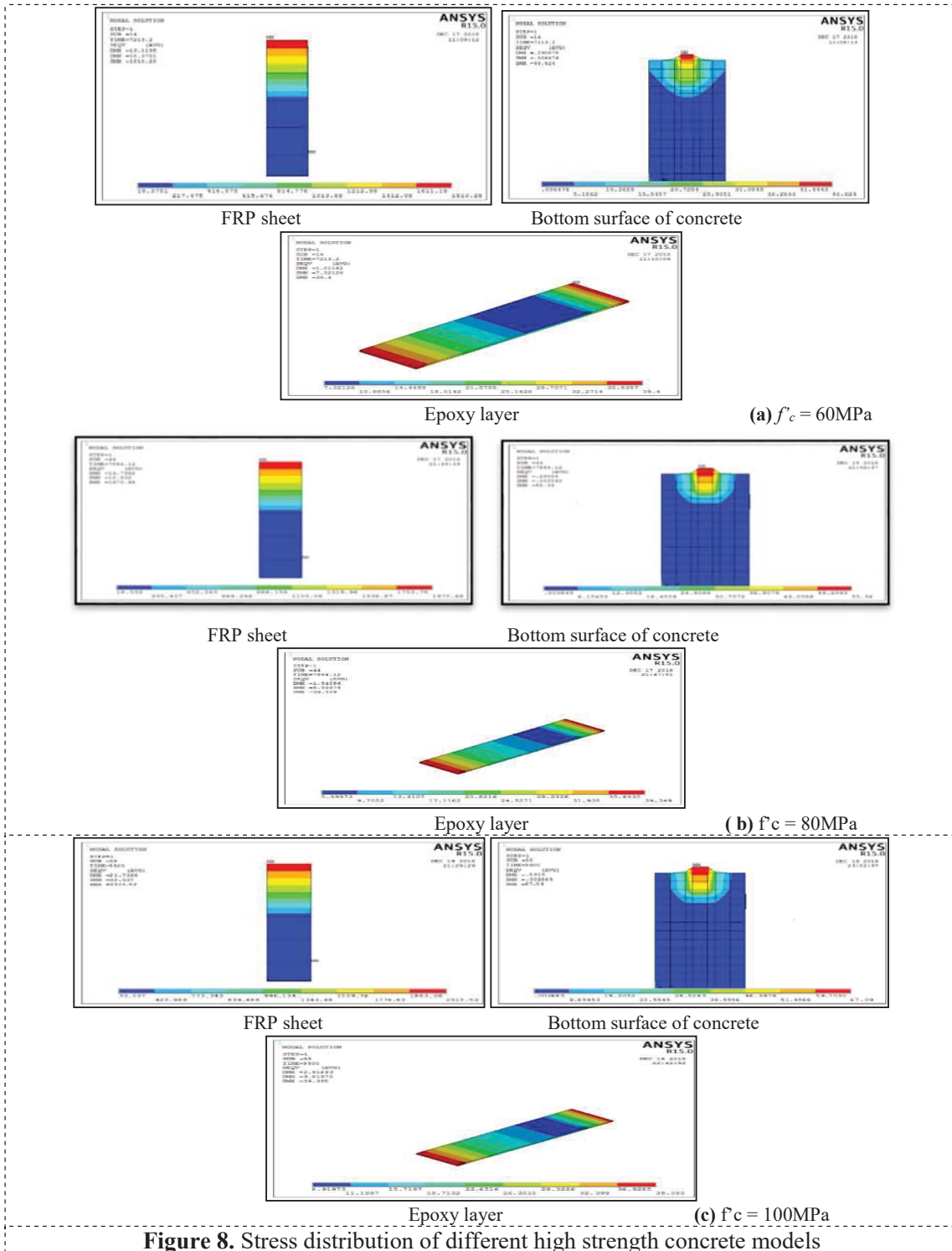
FRP sheet

Bottom surface of concrete

Epoxy layer **(a)** f'_c = 60MPa

FRP sheet

Bottom surface of concrete

Epoxy layer **(b)** f'c = 80MPa

FRP sheet

Bottom surface of concrete

Epoxy layer **(c)** f'c = 100MPa

Figure 8. Stress distribution of different high strength concrete models

4.3. Crack Distribution

Figure 9 shows the crack distribution for models with $f'c$ = 60, 80, and 100MPa. It can be noticed that for model with f'_c = 60MPa, the cracking of concrete starts in the region adjacent to the contact area, with the FRP sheet, near the side face of the concrete block. Cracks concentrate around the sides of fiber sheet and propagate towards the side face of concrete. As loading is increased, additional cracks are appeared along the contact region until failure is occurred. The size of the cracks decreases as moving to the far end of the contact region. The stress in concrete in the cracked regions is much greater than the ultimate shear and tensile stress of concrete, as was found in stress distribution, causing concrete to crack. Firstly, cracking of concrete tends to debond the FRP sheet from its place at the loaded end, then this debonding of FRP is continued and propagated to the other FRP end and lately the separation of FRP sheet from the concrete is occurred due to concrete failure. For model with $f'_c \geq$ 70MPa, it is also noticed that the cracking of concrete starts in the region adjacent to the contact area, with the FRP sheet, near the side face of the concrete block. Cracks concentrate around the sides of FRP sheet and propagate towards the side face of concrete, but these cracks disappear approximately at the half-length contact region. At other regions (non-bonded or far from the FRP sheet) the stress in concrete is close to zero so no cracking is observed. It can be concluded that, all high strength concrete models are failed in the same way by debonding of the FRP sheet due to concrete failure.

(a) f'_c = 60MPa

(b) f'_c = 80MPa

(c) f'_c = 100MPa

Figure 9. Crack distribution of different high strength concrete models.
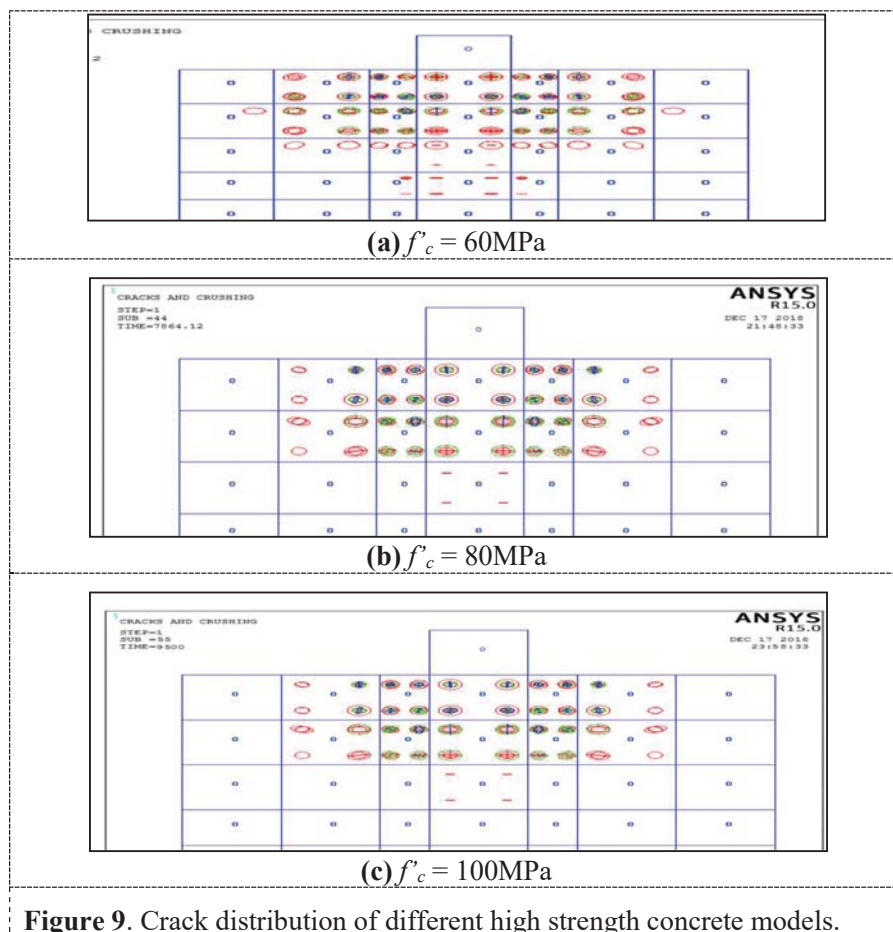
5. Conclusions

The most important conclusions that can be concluded from the current work are the followings:

- The increasing in concrete strength leads to increasing in the bond capacity.

- The relationship between bond capacity and concrete strength is approximately a linear relationship.

- The FRP sheet undergoes greater stresses as the concrete strength increases. Thus, the greater concrete strength the better utility of the FRP sheet.

- All studied models are failed in the same way by debonding the FRP sheet due to concrete failure. Therefore, changing the compressive strength has no effect or does not change the failure mode.

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