



# EXPERIMENTAL ASSESSMENT OF THE MECHANICAL PROPERTIES OF STEEL-FIBER COMPOSITE BAR (SFCB) REINFORCEMENT

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## ABSTRACT

The Steel-fiber reinforced polymer (FRP) composite bar (SFCB) is a recently proposed bar, it has a steel inner and an exterior layer of FRP, and an adhesive resin to bond the two materials. The SFCB bar used in this paper was made by using a handmade technique; this technique includes a manufacturing procedure that was described in this paper. SFCBs were tested using the standard uniaxial tensile test (ASTM A370) to figure out their mechanical properties and stress-strain relationship and compare them with the normal steel bars. Moreover, the bonding test was conducted to comprehend the bonding performance of SFCB in the concrete and to compare it with the normal steel performance, the bonding test was conducted according to ACI 440.3R-12. The experimental results illustrated that the values of yielding and ultimate tensile strengths of SFCB were slightly less than that of the conventional steel with percentages of 4% for both, the modulus of elasticity values which were found theoretically in good agreement with the test results values, the behaviour of SFCB stress-strain curve was slightly different than the conventional steel behaviour, with a stable post-yield modulus. Also, the results showed that the SFCB/Steel (SFCB/Steel) ratio between the bond strength of SFCB and the bond strength of steel bar was approximately 0.86, which means that the SFCB had lesser bond strengths than the normal steel with a percentage of 14%, the results also showed that the SFCB had less slip than the steel bar with a percentage of 10%.

## KEYWORDS

Steel-fiber composite bar (SFCB), Fiber Reinforced Polymer (FRP), stress-strain relationship, Bonding test, Mechanical properties.

## 1. INTRODUCTION

The most broadly structural frame utilized to construct buildings in the world, is steel-reinforced concrete (RC) frame, due to the high tensile and compressive strength that the combination of concrete and steel rebar generates [Liu and Pelecanos \(2019\)](#) & [Ma G. et al. \(2019\)](#). Many of these buildings are situated in areas with sporadic earthquake activities, therefore the reparability of structures after earthquakes and the design of buildings with controllable stiffness have been progressively developed to mitigate the seismic effects. Much previous research indicated that the structural systems with certain post-yield stiffnesses, which is the stiffness that happens after the yielding phase, performed more effectively in terms of reducing the residual deformation after earthquakes. Many exploratory research was utilized to achieve structural systems with controllable stiffness and to ensure post-yield stiffness after yielding using various ways [Wu et al., \(2012\)](#) & [Lin et al. \(2021\)](#).

One of these raised techniques was the steel-fibre-reinforced polymer (FRP) composite bar (SFCB), which is a new reinforcing bar, produced by wrapping an FRP sheet on the conventional steel bar, SFCB behaviour is a combination of the elastic-plastic behaviour of the steel and linear elastic behaviour of the FRP sheet, with a stable post-yield stiffness behaviour. [Wu et al. \(2009\)](#), was the working group that proposed using an SFCB to create new damage-controllable structural buildings with a noticeable post-yield stiffness, as the stiffness of normal steel after yielding approaches to zero and the deformations increase enormously, which leads to uncontrollable damage in the reinforced concrete structures [Wu et al., \(2012\)](#) & [Ma G. et al. \(2019\)](#).

The SFCB combines the advantages and overcomes the limitations of the inner steel bar and outer FRP, as it is composed of both materials. As a result, it has high ultimate strength, strong ductility, excellent corrosion resistance, a higher elastic modulus than common FRP bars, and stable post-yield stiffness which means high stiffness [Zhao et al. \(2020\)](#) & [Ding et al. \(2021\)](#). However, many previous studies examined the SFCB tensile strength, these studies showed that the stress-strain curve of SFCB had bilinear behaviour prior to fibre fracture and stable post-yield stiffness with minimal residual strain at the phase after yielding and before fibre fracture, which means that concrete structure reinforced by SFCB have a manageable post-yield stiffness and excellent reparability [Zhao et al. \(2020\)](#).

Furthermore, many studies have been conducted to investigate the other mechanical properties of SFCB, like the bond strength between SFCB and the concrete as it is a crucial component of SFCB behaviour since it influences the serviceability, ductility, and capacity of concrete

structures. The steel-FRP interface and the SFCB-concrete contact are two of the key interfaces for SFCB inside concrete constructions. Actually, the performance of SFCB is directly impacted by the bonding of these interfaces [Ma G. et al. \(2019\)](#) & [Tang et al. \(2019\)](#).

The following are some of these previous studies: Guowei Ma et al., 2019, examined seven glass FRP bars and four SFCBs to test each bar's tensile strength. Results revealed that the SFCB enabled a more balanced tensile behaviour and overcome the low elastic modulus of FRP bars by introducing elastic modulus more than Glass FRP (GFRP) with a percentage of 169%. In the meantime, pullout tests were conducted to assess the bond strengths of the Glass FRP and FRP bars, and surface treatments with sand-coating and spiral winding were used. The results illustrated that GFRP and FRP bars had a good level of bonding strength and sand-coating treatment provided the maximum amount of bonding capacity.

Debo Zhao et al., 2020, performed the pull-out tests to examine the bonding of SFCBs in the concrete and the tensile test for the SFCB itself to examine its tensile strengths. The results demonstrated that the pultrusion process can ensure a successful collaboration between the FRP outer layer and the steel inner core, as well as rebar diameter, have a significant influence on the strength of the SFCB-concrete interface and the bond failure mode, as the SFCB diameter increased, bond strength dramatically decreased. The modulus of Elasticity test result values of SFCB, E1, and E2 were close to the theoretical values.

Wenjie Ge et al. in 2020, conducted standard pullout experiments to test the bond-slip behaviour of steel bar, Basalt FRP bar (BFRP), and SFCB with the concrete. SFCB exhibits an equivalent bond behaviour to that of normal steel bars, as evidenced by the ratio of bond strength between SFCB and conventional steel bars being almost equal to 1.0. also, the bond strength of BFRP bars to steel bars ratio is all roughly equal to 1, which showed that the bond strengths of SFCBs/BFRP bars and steel bars are quite similar. The mechanical qualities of SFCB that the test result showed were comparable to the results that were predicted theoretically.

Shu-Hua Xiao et al. in 2021, experimentally studied the flexural behavior of 10 concrete beams reinforced with SFCBs and GFRP bars. According to the test results, the ultimate bearing capacities of the reinforced concrete beams with SFCBs and GFRP bars were increased by roughly 20.6%, 45%, and 69.1% when compared to the reinforced concrete beams with normal steel reinforcement. The load-deflection curve of the reinforced concrete beams with SFCB and GFRP bars also clearly showed secondary stiffness (post-yield), indicating good performance for the tested beams. Additionally, when the thickness of the exterior protective layer of FRP rose,

the maximum load, ductility, and energy absorption capacity of concrete beams reinforced by GFRP bar and SFCB improved as well.

Wenjie Ge et al. 2021, studied the influence of chloride corrosion conditions on the mechanical behavior of the SFCB under chloride corrosion. The effect of chloride concentration, corrosion time, and fiber type were the variables that had been examined. The test results revealed that SFCB had a relatively good strength retention ratio and steady post-yield stiffness (maximum tensile strength of the deteriorated specimen in comparison with the uncorroded one). Additionally, the ratio of strength retention over time is negatively impacted by the duration of corrosion and sodium chloride concentration.

Finally, as shown in Fig. 1 the stress-strain relationship of SFCB has two segments; the first segment is a linear ascending segment before the yielding of the inner steel core, and the second one is a hardening segment before the outer layer of FRP fracture. The last segment is crucial for the safety design and early detection of structural deterioration Sun et al. (2017).

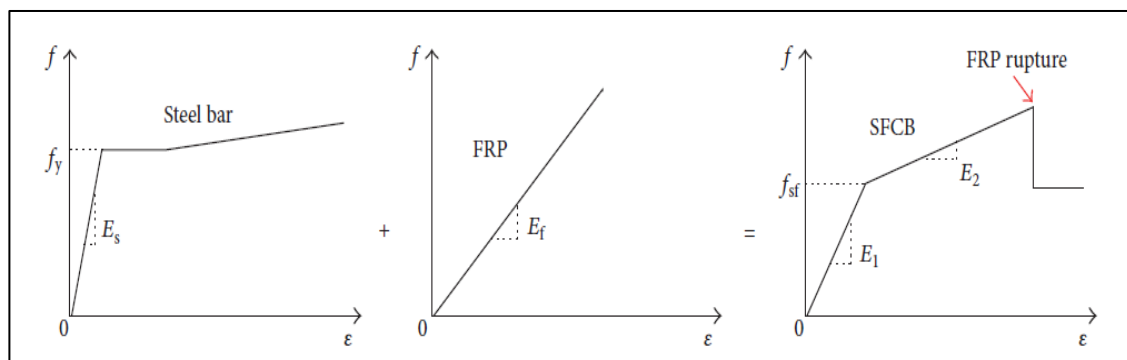


Fig. 1. Stress-Strain Relationship of steel, FRP and SFCB Sun et al. (2017)

## 2. OBJECTIVES OF STUDY

In this paper, the mechanical properties of SFCB were tested using standard tests. The main investigated properties were the tensile strength, modulus of elasticity, and bonding behaviour, which is essential to the overall durability of SFCB-reinforced concrete structures.

## 3. EXPERIMENTAL PROGRAM

The experimental work included testing the conventional steel and SFCB under the same conditions to investigate their mechanical properties, the standard tests were conducted to achieve the desired goal. The requirements of tensile strength and bonding tests were followed.

### 3.1. Production of SFCB

A handmade SFCB was used in this paper. The description of the manual manufacturing steps of the hybridization process as follow: Firstly, the exterior surfaces of the CFRP sheet and steel bar must be thoroughly cleaned from the dust and rust to ensure proper adhesion of the epoxy, CFRP sheet and steel, after that the outer layer of SFCB with two distinct lengths of 300 mm, 1000 mm must be cut along the fiber's longitudinal direction. Then the bars must be coated with an epoxy solution, and the sheets to be submerged in resin (an "epoxy bath"), to guarantee a strong bonding between the steel bars and CFRP sheets, the next step is to tightly wrap the steel bar with CFRP sheets, in this step the steel bar surface to be coated with epoxy first, then CFRP sheet to be wrapped around the steel bar, in such a way that braids of the CFRP sheet are along the length of the used steel bar. In order to provide SFCB with fairly deformed outer surface to ensure a bonding between hybrid rebar and concrete, epoxy must also be applied during the wrapping process. Finally, the two ends of the SFCB must be secured with plastic holders to prevent any potential slipping during the curing process, which should last for around seven days.

### 3.2. Material Properties

#### 3.2.1. Steel Bar

All of the steel utilized in this study was of the Iraqi brand (FF), with a diameter of 10 mm. Sika Wrap R-300C CFRP sheets (mid-range strengths) and Sikadur R-330 adhesive material, were utilized in the SFCB production process.

#### 3.2.2. Concrete of Bonding Test Components

Normal Concrete (NC) mixture has been utilized to produce the specimens of bonding test, these specimens were prepared, cast, and tested based on the [ACI guide 440.3R-12 \(2012\)](#). The proportion of this mixture is listed in the [Table 1](#), the following ingredients were used to make this mixture; fine and coarse aggregate [IQS, No.45, 1984 \(1984\)](#), according to the guide the used coarse aggregate was with a size of a maximum of 25 mm, Iraqi-brand cement [IQS, No. 5 \(1984\)](#), and superplasticizer (SikaViscocrete-5930 (SP) meets the [ASTM standards C494/C494M \(2015\)](#). The mixture was produced using pure water (potable water), the molds shouldn't be taken out of the sample before 20 hours have passed since casting. Extreme caution must be exercised to avoid bumping into or otherwise disrupting the FRP bars. The specimens should be cured until the time of testing just after the molds were removed. The compressive strength of this mixture at age of 28 days was 33 MPa which is within the required range that the ACI mentioned guide.



**Fig. 2. The Steps of SFCB production process.**

(1-Cleaning steel bars, 2-Cutting CFRP sheets, 3-Coating with epoxy, 4-Tightly wrapping the steel bar with CFRP sheets, 5-Fixing the SFCB two ends)

**Table 1. Mix Proportions for the Normal Concrete Mixture of Bonding Test.**

<b>The Trial Mixes proportions of Normal Concrete</b>			
<b>Materials</b>	<b>Weight (kg/m<sup>3</sup>)</b>		
<b>Mix</b>	<b>Trial 1</b>	<b>Trial 2</b>	<b>Trial (3) Chosen</b>
Cement	500	500	500
Fine Aggregate	650	730	730
Coarse Aggregate	940	940	940
Water	212	225	200
SP	0	0	2
Compressive Strength	38	36	33

### **3.3. Testing Procedure**

#### **3.3.1 Tensile Strength**

Tensile tests of normal steel and SFCB specimens were carried out at laboratories of the Engineering Consulting Bureau of Kufa University, using a static hydraulic testing machine with a maximum capacity of 600kN, which has a control system helps to ensure precise positioning of sample into the jaws, the machine regulates the elongation precisely using an internal piston-mounted position sensor with a 1 mm resolution, the machine are connected to the computer and the result of the test shown automatically on the screen after the specimen failure, Three samples of each type of reinforcement were tested according to [ASTM A370 specifications \(2015\)](#), in the [Table 2](#) the test results were listed. [Figs. 3 and 4](#) illustrate the tested samples of Normal steel and SFCB respectively.



**Fig. 3. Testing Machine and Tested Normal Steel Bar.**



**Fig. 4. Testing Machine and Tested SFCB.**

### 3.3.2 Bond Strength

In this test, six 200 mm concrete cubes with vertically embedded reinforcing bars were used to test both types of reinforcements (three for SFCBs and three for normal steel). The testing molds were made of plywood plates with a thickness of 16 mm, each one had four sides and a base, the base had a small hole in the middle where the SFCB/ steel bar was located to ensure that the bars were centred after the concrete had been poured in. This hole should have been sealed with oil or another similar material.

Additionally, before casting, the inside surfaces of the test molds should be treated with oil or a similar substance. Four identically thick layers of concrete were utilized to completely fill each test cube, and each layer was compacted 25 times using a rod with a 16 mm diameter (tamping bar). The NC mixture used had a compressive strength of 33 MPa at age of 28 days, [Table 1](#).

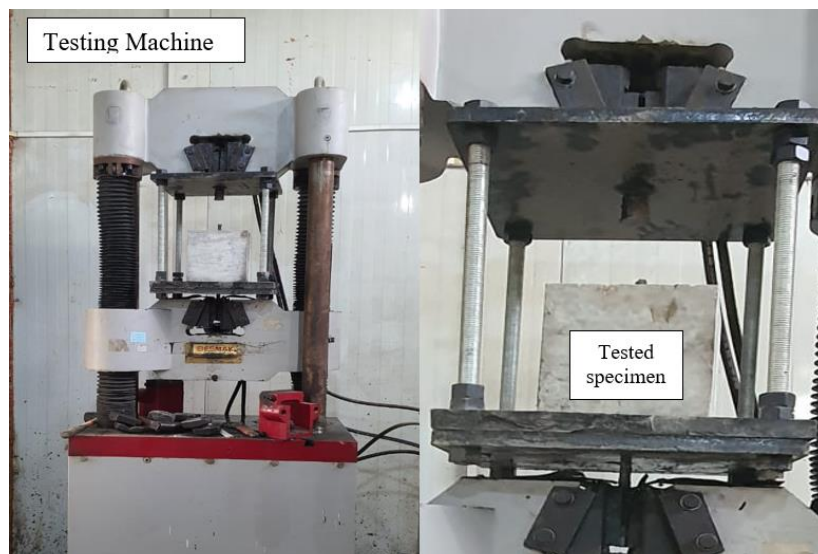
A part of the embedded bar with a specific length which should be five times more than the diameter of the steel bar according to [ACI 440.3R-12 \(2012\)](#) (item B.3.5.1.2) should be covered in polyvinyl chloride (PVC) to prohibit bonding of this length of the bar. In the test, the bars were 32 mm outside the concrete blocks from the bottom.



**Fig. 5. Bonding test models and Their Details.**

The specimens underwent a 28-day process of wet curing after the wood models were removed. The bonding tests were conducted in the Engineering Consulting Bureau of Kufa University using a Static Hydraulic Universal Test Machine (BESMAK Brand), controlled by a computer, and the result of the test shown automatically on the screen after the specimen failure, the machine has a maximum load capacity of 600 kN. A steel frame, with two 40 cm square steel plates and a height of 40 cm between them, Fig. 5, was mounted between the loading and stationary heads of the testing machine. The cube samples were put on this frame which was specifically designed for the bonding test. It has been secured from the top by the hock of the testing machine's stationary head.

The samples were placed inside the frame, their steel bars were threaded through the hole at the base of the frame, and the force was applied and sustained until the specimens failed. In addition, the slips of the free ends were measured by noting the location of the steel bar and watching the displacements before and after the test. The load and elongation measurements were obtained from digital computer readings that were displayed on the computer screen.



**Fig. 6. Testing Machine of Bonding Test.**

#### 4. EXPERIMENTAL RESULTS AND DISCUSSIONS

Experimental results of the tensile strength, and bonding strength tests are listed in [Tables 2, 3, and 4](#) respectively. The Modulus of Elasticity of SFCB and Normal Steel are represented graphically in [Fig. 8](#) and [Fig. 9](#).

The tensile testing failure mode of SFCBs, [Fig. 7](#) showed a thread-like fracture, it demonstrated that the outer CFRP and the inner steel bar functioned effectively together on the other hand, the resin with the CFRP, are showing superior coupling performance. This shows that the pultrusion procedure used in this research may produce a solid CFRP-steel interface and ensure collaborative working between the CFRP and the steel bar.

**Table 2. The Values of Tensile Strength of Normal Steel and SFCB.**

	Normal steel bar	SFCB
<b>Yielding Tensile Strength (Mpa)</b>	576	553
<b>Ultimate Tensile Strength (MPa)</b>	683	656



**Fig. 7. Failure modes of Normal Steel bar and SFCB Respectively.**

The test results of the tensile testing, [Table 2](#), show that SFCB has less yielding and ultimate tensile strength than the conventional steel bar with a negligible percentage of 4% for both values. This can be considered as a result of the phenomenon of shear lag that causes the non-uniform

distribution of the normal stresses and appearing of deformation in the cross-section of the rebar, the influence of this phenomenon showed because the elastic modulus value of CFRP is similar to normal steel. (5)

However, the inescapable nonuniformity of the outer fibre during the SFCB pultrusion process, which would cause an initial bending of the outer fibre, maybe the cause of this slight loss in strength as the inner steel and CFRP worked together to carry the load at the initial stage. After the inner steel yielded, the outer fibre mainly carried the load because the inner core steel bar had already yielded. When the fibre cracked in the middle of the specimen because of the load increases, then only the inner steel bar started to carry the load at that point, and the tensile strength of SFCB reached the ultimate, this load carrying mechanism could be the reason behind the minor reduction in strength compared to conventional steel. Also, the effect of the CFRP sheet will appear by increasing the surrounding layers of the outer CFRP sheet.

**Table 3. Practical and Theoretical Values of Modulus of Elasticity of Normal steel bar and SFCB.**

	Normal steel bar	SFCB
<b>Modulus of Elasticity (E) (MPa)</b>		
<b>Practical*</b>	200,000	E1=172,000, E2=20,000
<b>Theoretical**</b>	200,000	E1=142,000 E2=27,000

Table 2 has the experimental and theoretical values of the modulus of Elasticity of steel bar and SFCB, \* the experimental values were found based on the values of the stress-strain relationship, which were extracted from the computer linked to the test machine, then the E values were calculated using Young's modulus equation  $E = \frac{\Delta \text{Strees}}{\Delta \text{Strain}}$ , Fig. 9 shows the test result.

\*\* the theoretical calculation of SFCB was found according to the classical mixture rule by Wu et al.:

$$E1 = \frac{(E_s * A_s) + (E_f * A_f)}{A_t}$$

$$E2 = \frac{(E_f * A_f)}{A_t}$$

Where:

Es: modulus of elasticity of inner steel bar,

$A_s$ : cross-section area of inner steel bar,

$E_f$ : the elastic modulus of the outer continuous fibre cover,

$A_f$ : cross-section area of the outer continuous fibre cover,

$$A = A_s + A_f + A_r$$

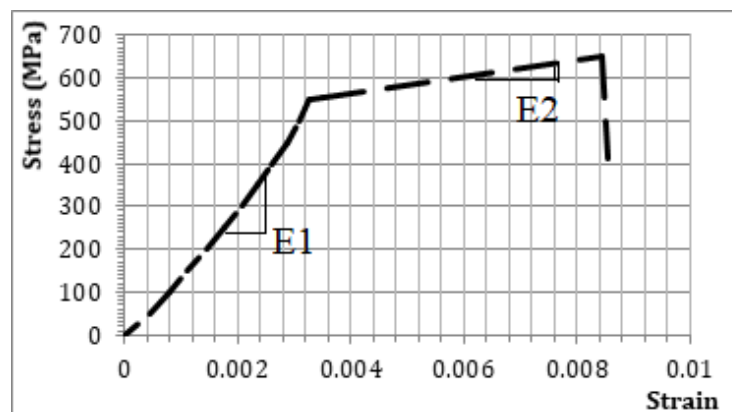
$A$ : the total area of the cross-section of the SFCB.

$A_r$ : the cross-section area of the resin in the composite bar.

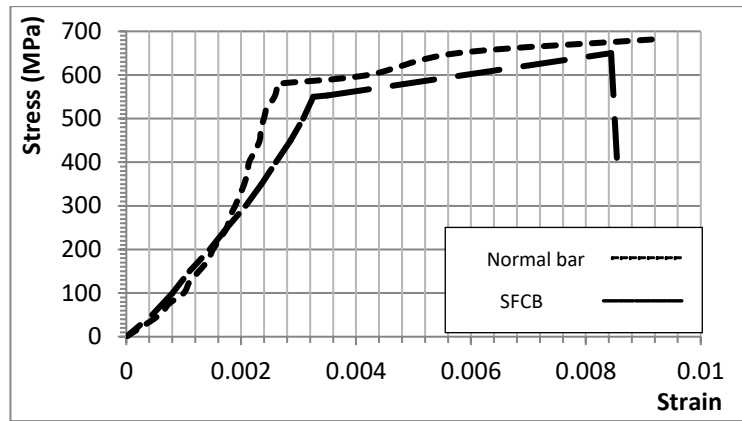
Strikingly from the values of modulus of Elasticity in Table 3, the value initial stiffness of SFCBs  $E_{I1}$  from the experimental test is bigger than the theoretical value with a percentage of 21%, while the post-yield stiffness value  $E_{II}$ , is nearly 26% lower than the theoretical value, this indicated that SFCB behaviour is relatively closer to the mixture law presumptions in the initial stage and departs gradually from them with the increasing of the loading.

$E_{I1}$  from the experimental test is bigger than the theoretical value with a percentage of 21%, as the theoretical calculation assumed that the outer CFRP be completely straight and the steel bar had no initial bending, but in the experimental test the surface of the used SFCB was deformed because of using inner steel bar with a ribbed surface, therefore the SFCB had a partially curved surface, as a result, the strain of CFRP was slightly behind the strain of the core steel bar.

On the other hand, the experimental value of  $E_{II}$  was less than the theoretical value because the theoretical assumption assumed that the inner steel bar works with the outer FRP as one unit with perfect bonding until the end, but during the experimental test, a relative slip occurred at the steel and FRP interface after the inner steel yielding.



**Fig. 8. Stress-Strain Relationship of SFCB.**



**Fig. 9. Stress-Strain Curves of Normal Steel and SFCB.**

As shown in Fig. 8, both materials of SFCB, which are the outer CFRP, and inner steel bar worked together to carry the applied load. On the other hand, after the yielding of the inner steel bar, SFCB shows stable secondary stiffness  $E_2$  which is called (post-yield stiffness), because it had fewer, steadily increasing stress increments with the same strain increasing after the specimen reached its maximum loading capacity, the fracture of the outer fibre happened.

When comparing the stress-strain curves of the normal steel and SFCB Fig. 9, notably observed that there is a slight difference between the curves of both, as the outer layer of SFCB did not bring a significant effect because it receives large strain before failure. SFCB has two values of modulus of elasticity in different stages, the initial  $E_1$  has less value than the  $E$  of the steel bar, but it has steadily increased behaviour.

SFCB yielding strength is slightly less than the yielding of steel bar, but SFCB showed another value of stiffness  $E_2$  after inner steel yielding, providing another stage of stiffness after the steel yielding stage, which creates a controllable damage building that affects positively the building reparability process.

**Table 4. Bonding Test Results of Normal Steel and SFCB.**

	Normal steel bar	SFCB
<b>Pull-out strength (MPa)</b>	17.66	15.11
<b>Slip (mm)</b>	17	15.33

Fig. 10 shows the bonding failure mode of pullout specimens, which is called splitting failure, it refers to a type of failure in which, at peak load, the concrete cube split into pieces along its diagonal axes, and visible cracks were seen on the cube faces and the resin surface of the SFCB specimens was scraped during the pulled-out process.



**Fig. 10. Failure Mode of The Normal Concrete Specimens of Bonding Test.**

Furthermore, throughout the pullout testing, no CFRP layer peeling, relative slide, or debonding were seen, which means that the inner steel bar and outer CFRP were working together effectively, and the pullout test data mostly represents the SFCB-concrete interface behaviours.

According to the above-mentioned test results, SFCB specimens demonstrated a lower bonding strength than conventional steel specimens, with a loss in bonding strength of roughly 14%. The

bonding strength of SFCB to bonding strength of steel bar (SFCB/Steel) ratio is 0.86. This decrease came because of the less interlocking between the shallow ribs of SFCB and concrete matrix, and the less interface friction than the conventional steel. On the other hand, the reported slide in the conventional steel was 10% higher than the slip in the SFCB specimens.

## 5. CONCLUSION

The conducted tests to figure out the mechanical properties and the bonding performances of handmade produces SFCB, showed the following main conclusions:

1. The Stress-Strain curve of SFCB was different than that of conventional steel and FRP bars, it performed bilinear behaviours before the outer layer of fibre fracture and had a stable post-yield stiffness after the inner steel yielding.
2. The theoretical calculation using mixture law to find the elasticity modulus was in agreement with the experimental test findings.
3. The final findings indicated that SFCB had 4% lower values of yielding and ultimate tensile strengths than a conventional steel bar.
4. The SFCBs had less bond strength than conventional steel with a percentage of 14% as the ratio of the bond strength of SFCB to the bond strength of steel bar (SFCB/Steel) was about 0.86 and compared to standard steel, SFCB slip resistance was 10% greater.
5. The effect of the outer layer of SFCB is not significant on the behaviour of the stress-strain curve of the inner steel core because the CFRP outer layer receives a large strain before failure.

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