



New thermoplastic CFRP bendable rebars for reinforcing structural concrete elements

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ABSTRACT

This paper presents test results for new thermoplastic carbon fiber-reinforced polymer (CFRP) bendable rebars to be used as reinforcement for concrete structures. The new CFRP rebar is made of carbon fibers bonded together with thermoplastic resin which allows bending of the rebar – by heating – several times after the complete solidification of the resin. A microscopic study was performed to optimize the magnitude of the pressure and heat required to manufacture and bend the CFRP rebar. Once the manufacturing parameters were determined, three tests were conducted to evaluate the rebars' mechanical characteristics, namely: tensile strength test, pullout test, and bent bars and stirrups test. Based on the test results and modes of failure of the tested specimens, several possible modifications are proposed to improve the structure, and consequently the mechanical characteristics of the new thermoplastic CFRP rebars.

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1. Introduction

The past few decades have witnessed the deterioration of a large number of reinforced concrete structures that deemed them in need for rehabilitation or upgrade. In 2006, the cost of maintenance and renewal of the deteriorated infrastructures in Canada was estimated to be 125 billion Canadian dollars to bring the existing structures to an acceptable level [1]. This raised the need of investing in new structures that can better resist the environmental conditions, need less maintenance budget and have longer life time. This can be achieved by using fiber-reinforced polymer (FRP) composite materials as reinforcement for new structures. The FRP are non-corrodible materials, have high strength to weight ratio and are magnetic neutral.

Although FRP rebars offer several advantages with respect to corrosion resistance, they still have some limitations. One of the practical problems is the limitation of bending the currently available FRP rebars that are made of thermoset resin such as polyester. The thermoset rebars can be bent only right after the pultrusion process in the factory. In case of steel rebars, rebars are manufactured as straight bars with a certain length which can be cut and bent at the construction site or at a local supplier to the desired dimensions. Most of the available FRP rebars in the market are made of thermoset resins such as polyester. The rebars have to

be produced with the exact required lengths and bent in the factory during the manufacturing process before the resin solidifies. The thermoset rebars cannot be bent once the resin sets due to the crosslinking nature and brittleness of the material. Moreover, there are some extra limitations to the number of bends per rebar as well as the maximum spacing between any two successive bends. Accordingly, lap splices are required to overcome such problems which consume more material and time leading to more cost and less productivity. Also, excessive splicing of rebars in a concrete structural element could lead to congested reinforcement and complicated detailing with less clear space between rebars which affects casting of concrete. This raises the need of developing bendable rebars that can be used as shear stirrups, or bent to develop the sufficient end anchorage for flexural reinforcement. However, a limited number of thermoplastic FRP rebars with such characteristic are available.

FRP materials gained the attention in the civil engineering applications as reinforcing bars in new structures, as a strengthening and repair materials for the old structures, and for improving the seismic performance of concrete elements in seismic zones [2]. Pultruded FRP laminates are used to strengthen concrete elements due to their better quality control compared to wet lay-up systems and due to the high fiber volume fraction. In such system, the failure is either in the adhesive layer due to the high stresses at the end plate regions that leads to debonding of the laminate [3–7] or the rip-off of the concrete cover [8]. The long term behavior of concrete beams strengthened with pultruded FRP was studied by Ascione et al. [9].

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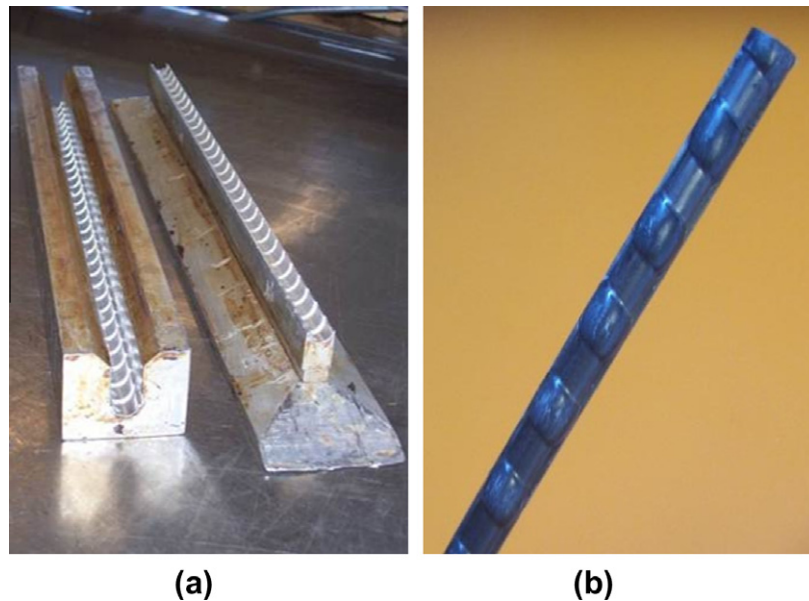


Fig. 1. (a) One of the molds used in manufacturing the rebar and (b) the new thermoplastic CFRP rebar.

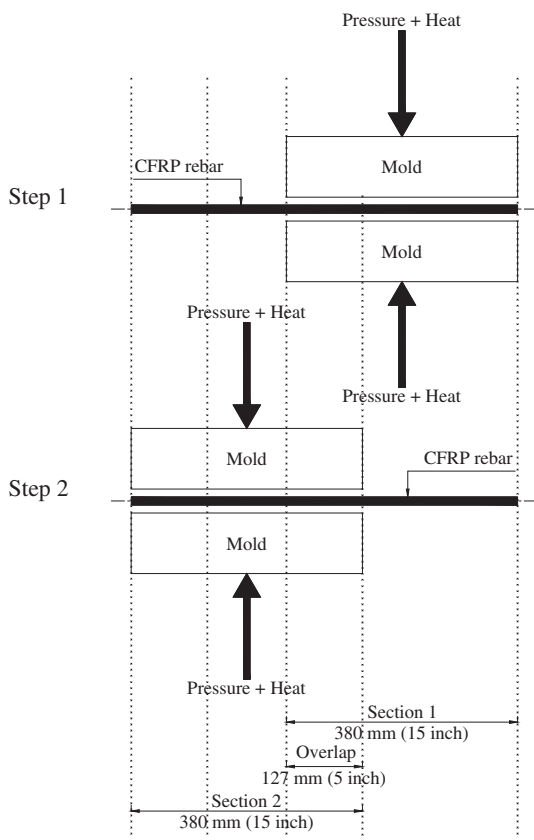


Fig. 2. Schematic drawing showing manufacturing steps of a CFRP rebar longer than 380 mm (15 in.).

A new thermoplastic FRP rebar was examined by Currier et al. [10]. Two different bars were examined: Aramid/Nylon and Carbon/Nylon where the fiber volume fraction was 50%. Both had a rectangular cross section with dimensions of 2.4 mm $\times$ 7.1 mm. The FRP stirrups were bent to dimensions of 560 mm $\times$ 75 mm using a heat gun. The bend strength of the thermoplastic FRP

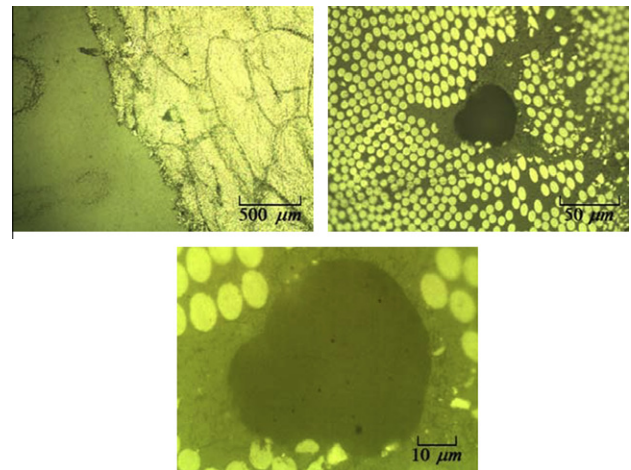


Fig. 3. Microscopic cross-section of a CFRP rebar showing void caused by air bubble.

stirrups was evaluated by putting the stirrup in two concrete blocks and applying a relative displacement between them. This test method is similar to the test method for strength of FRP bent bars and stirrups at bent location named as B.5 standard test method in the ACI 440 [11]. The strength of the bent rebar was 23% of the straight rebar. The reported mode of failure was due to the stress concentration of the bent stirrup.

GFRP thermoplastic rebars were tested by Mehrabi et al. [12]. Different mechanical, geometrical and surface treatments were examined. Tensile strength tests and bond to concrete tests were conducted to evaluate their properties. Different bond lengths were tested in order to obtain the bond strength. The tensile strength, modulus of elasticity and bond strength of the new thermoplastic GFRP rebars were 827–1034 MPa, 37.9–51.7 GPa, and 8.3–15.2 MPa, respectively.

Researchers of Concordia Center for Composites (CONCOM) at Concordia University developed a new thermoplastic CFRP rebar. This rebar could be bent – by heating – several times after the complete solidification of the thermoplastic resin. The new CFRP rebar was designed to have integral ellipsoidal ribs and made of carbon fibers bonded together with thermoplastic resin.

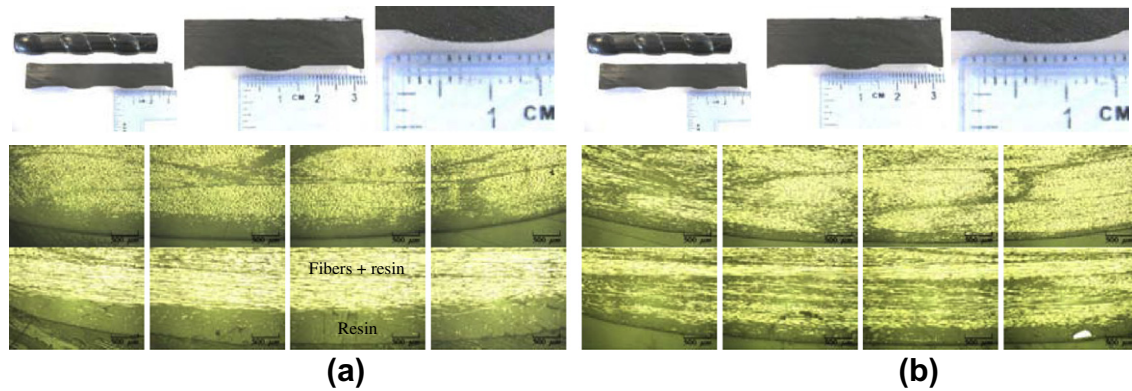


Fig. 4. Microscopic longitudinal section showing samples of: (a) improper consolidation in rib area of rebar, and (b) improved consolidation in rib area of rebar.

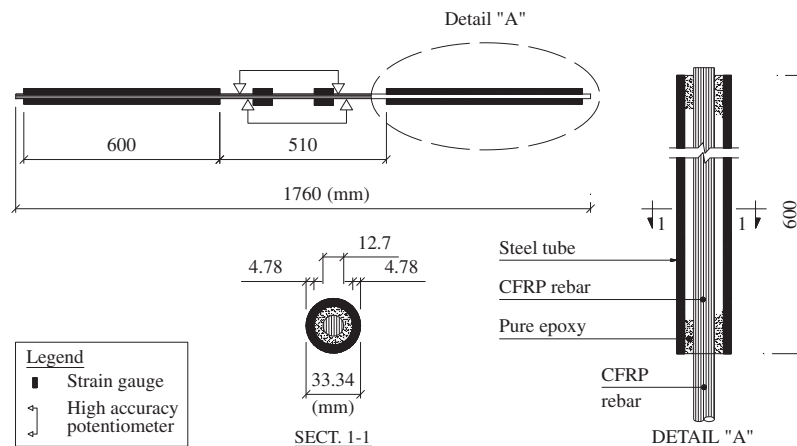


Fig. 5. Specimen details and instrumentation of the tension test.

A microscopic study was performed to identify the most suitable manufacturing parameters (temperature and pressure). Once the manufacturing parameters were optimized, the mechanical characteristics of the developed rebars were determined. Three sets of tests were conducted on the developed CFRP rebar in order to evaluate its performance and the effectiveness of using it in reinforcing new concrete structures.

2. Design, manufacturing and microscopic study of the new thermoplastic bendable CFRP rebars

The new thermoplastic CFRP rebar was manufactured with a diameter of 12.7 mm (1/2"). Each rebar consists of 150 yarns where each yarn has 12,000 fibers. The diameter of each fiber ranges from 7 to 10 μm . The new CFRP rebar was made using carbon fibers and thermoplastic resin. The newly developed thermoplastic rebar can be bent – by heating – several times after the complete solidification of the thermoplastic resin.

Unlike most of the ribbed rebars where the fibers are wound to the rebar or grooved to form the ribs which improves the bond properties of the rebar, the new CFRP rebar is designed to have integral ellipsoidal ribs. The ellipsoidal ribs were formed by the longitudinal fibers of the rebar which are expected to provide mechanical interlock between the concrete and the rebar and to eliminate the failure of the ribs due to debonding (shearing off).

The new CFRP rebars were made by compression molding technique. Fig. 1a shows the mold used in manufacturing the rebars, while Fig. 1b shows a finished rebar. For a rebar longer than 380 mm (15"), the yarns were cut and prepared to the desired length of the rebar, then the rebar was manufactured in sections

each of which is 380 mm (15"). To ensure the straightness of the rebar, each section consists of 127 mm (5") of the old solidified section and 255 mm (10") of the new section (loose yarns). This procedure was followed to insure the straightness of the rebar. Fig. 2 shows a schematic drawing illustrating the steps of manufacturing a rebar longer than 380 mm (15 in.) in sections using the compression molding technique.

The Wabash press used is equipped with heating platens and 25 tons of compression capacity. The compression molding was done with 4 tons of loading at a uniform temperature of 220 °C. After the heating and pressing operation the bar was cooled by air.

In order to bend the thermoplastic composite rebar into the required shape, it was necessary to heat the composite to a temperature that yields sufficient ductility while maintaining sufficient pressure to guarantee adequate consolidation of the fiber and matrix. This propagates many resin-rich areas where voids may also be created, thereby lowering the mechanical properties. A heat blanket was used to maintain overall temperature to at least 220 °C. A similar procedure could be done in a workshop or at the construction site to bend the thermoplastic composite rebar. A heat source (such as heat blanket) that can bring the temperature of the material up to 220 °C should be used. Allow 15 min for soaking and then a bending fixture similar to the copper pipe bender tool can be used to bend the rod.

A microscopic study was performed to detect any imperfection of the rebar after manufacturing. Short samples that have lengths less than 380 mm (15") were used to carry out this step in the study. Air bubbles were found in some specimens as shown in Fig. 3. Air bubbles were eliminated in subsequent specimens by applying enough pressure to drain the entrainment air out of the rebar cross section.

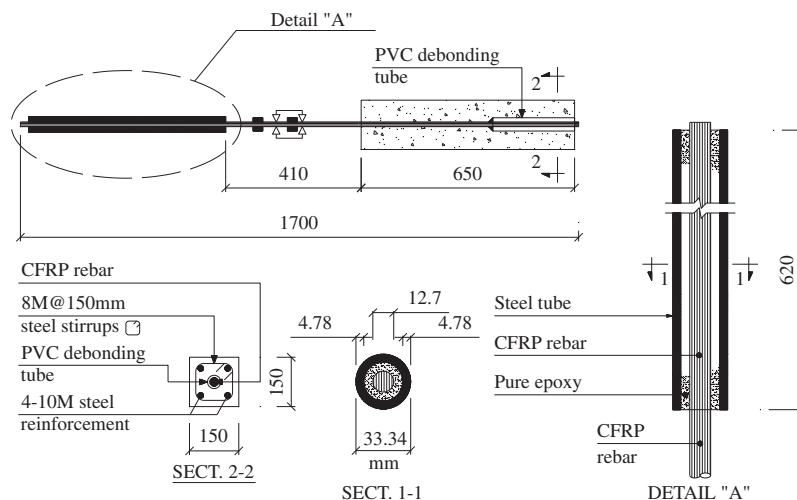


Fig. 6. Concrete dimensions, reinforcement details, and instrumentation of the pullout test.

The longitudinal cross section of the rebar was checked under the microscope to examine the inhabitation of the fibers in the ellipsoidal ribs. Fig. 4a shows improper consolidation in a rebar rib with excessive resin in the ribs. By applying gradual pressure during the heating cycle, this problem was eliminated as shown in Fig. 4b.

3. Experimental program

3.1. Mechanical properties test

The objective of this set of tests is to obtain the tensile strength, modulus of elasticity and the ultimate strain of the new CFRP bendable rebars. In order to obtain the mechanical characteristics of the new CFRP rebars, three rebars were tested according to the CSA-S806 [13]. As stated in the standard tension test in CSA-S806, two anchoring grips were prepared for each CFRP rebar at both ends. The anchor grip length is 620 mm and it was filled with pure high strength epoxy. The free distance between the two anchors is 510 mm ($40d_b$, where d_b is the rebar diameter) as recommended by Manav [14] and Castro and Carino [15]. The total length of each specimen is 1760 mm.

Each specimen was instrumented with four strain gauges and two high accuracy displacement transducers (potentiometers). The strain gauges have a gauge length of 5 mm, and a maximum measurable strain of 15,000 microstrains. The high accuracy potentiometers have a gauge length of 160 mm, maximum stroke of 25 mm and an accuracy of 0.05 mm.

A manually controlled universal testing machine was used for testing the new CFRP in tension. The machine was instrumented with a pressure transducer that was connected to the data acquisition system to monitor and record the load readings. The load was applied with a constant rate up to failure. The load, deformation and strain values were monitored during the test, while the data was recorded using a data acquisition system. Fig. 5 shows the specimen details and instrumentation of mechanical properties test. Specimens were designated with letters and numbers to reflect the test name and specimen number. Specimen MP-1 was the first CFRP rebar tested in mechanical properties test.

3.2. Pullout test

Pullout tests were conducted to determine the minimum development length required to transfer the force of the new CFRP rebars to the concrete. Nine specimens were prepared and tested up to failure. Each specimen consisted of 1700 mm CFRP rebar

which was embedded from one side to a concrete block with dimensions of 650 mm $\times$ 150 mm $\times$ 150 mm while from the other side the rebar was anchored using steel tube anchoring sleeve. The concrete block was reinforced longitudinally and laterally with steel rebars to prevent the concrete splitting failure mode.

The variables of the tested specimens were the embedment length which varied from 15 to $35d_b$. For the embedment lengths 15, 20, 25 and $30d_b$ two specimens were tested for each, while one specimen was tested for the embedment length of $35d_b$. The debonded part of the embedded CFRP rebar was created and secured using plastic PVC pipes, high strength silicon and duct tape. Concrete with a compressive strength of 31 MPa at age of 28 days and maximum aggregate size of 12 mm was used.

Two sizes of steel rebars were used; 10M deformed rebars as a longitudinal reinforcement, and 8 mm undeformed rebars as stirrups. The yield strength of the 10M rebars was 460 MPa.

The specimens were instrumented using two strain gauges and two high accuracy displacement transducers (potentiometers). The strain gauges have a gauge length of 5 mm and a maximum measurable strain of 15,000 microstrains. The high accuracy potentiometers have a gauge length of 160 mm, maximum stroke of 25 mm and an accuracy of 0.05 mm. Both the strain gauges and potentiometers were installed on the CFRP rebar on the free part between the concrete block and the steel gripping anchor in order to measure the ultimate strains of the CFRP rebar.

A universal testing machine was used for testing the new CFRP. The load was applied with a constant rate up to failure. The load, deformation and strain values were monitored on the computer during the test, while the data was recorded for further analysis. Fig. 6 shows the concrete dimensions, reinforcement details and instrumentation of pullout test. Specimens were designated with letters and numbers to reflect the test name, embedment length and specimen number of the same embedment length. For example specimen PL-25-2 is a CFRP rebar tested in pullout and bond strength test, have an embedment length of $25d_b$ and it is specimen number 2 of the same embedment length.

3.3. Bent bars and stirrups test

In order to evaluate the performance and the strength capacity of the CFRP bent rebars used as stirrups, four specimens were tested according to the CSA-S806 [13] specifications. The CFRP stirrup was embedded in two concrete blocks and tested by pushing the two blocks away from each other by applying a relative dis-

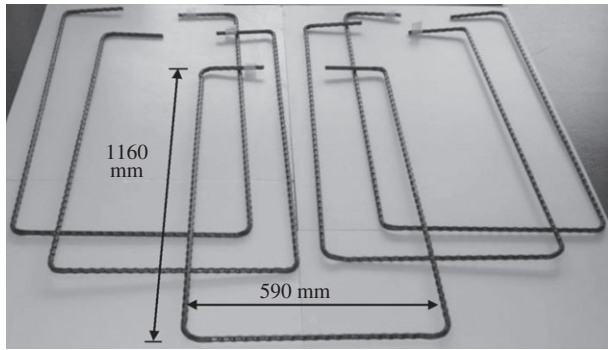


Fig. 7. The new CFRP stirrups used in this study.

placement between the two blocks using a hydraulic jack. The test variable was the tail length after the bent part of the rebar, while the bent radius was kept constant at a value of four times the rebar diameter ($4d_b$). Four specimens having tail lengths of $3d_b$, $6d_b$, $9d_b$ and $12d_b$ with a standard hook end anchorage type were tested up to failure to evaluate the effect of the tail length on the capacity of the bent bar. The debonded part of the CFRP stirrup was created and secured using plastic PVC pipes, silicone and duct tape.

Each specimen consisted of one 12.7 mm diameter CFRP rebar with a total length of 3200 mm which was bent at four locations to form a stirrup as shown in Fig. 7. The CFRP stirrup was embedded in two concrete blocks each with dimensions $450 \text{ mm} \times 750 \text{ mm} \times 400 \text{ mm}$. The concrete blocks were reinforced longitudinally and laterally to prevent any failure of the concrete by crushing or splitting.

Concrete with a compressive strength of 31 MPa at age of 28 days and maximum aggregate size of 12 mm was used. Steel rebars of 10M diameter and a yield strength of 460 MPa were used to reinforce the concrete blocks.

Since the exposed parts of the CFRP stirrups were very sensitive and their strength can be affected due to the handling or moving of the two-block concrete specimen prior to the test, the base of each wooden form was strengthened with two longitudinal and two transverse square timbers $4'' \times 4''$ in order to prevent any relative torsion or movement of the wooden form during the handling or moving of the specimens.

A hydraulic jack with a capacity of 1500 kN was used to apply a differential displacement between the two concrete blocks. Steel plates and plaster bags were used between the jack and the concrete surfaces in order to distribute the load. A load cell was placed between the jack and the steel plate to measure the applied load. Each specimen was instrumented with six strain gauges to measure the strains in the CFRP stirrup, two high accuracy potentiometers to measure the elongation in the CFRP stirrup and four linear measuring devices (potentiometers) to measure the relative displacement between the two concrete blocks. The loading was applied gradually with a constant rate up to failure. Fig. 8 shows the test setup and instrumentation of the bent bars and stirrups test.

Specimens were designated with letters and numbers to reflect the test name and tail length. For example specimen STR-9 is a CFRP stirrup tested in bent bars and stirrup test, and has a tail length of $9d_b$.

4. Results and discussion

4.1. Mechanical properties test

As expected, the stress–strain relationship of the new CFRP rebars exhibited a linear behavior up to failure. The modulus of

elasticity was obtained using the stress and the corresponding strain at 50% of the ultimate load, and the stress and the corresponding strain at 25% (CSA-S806-02, 2002). Table 1 summarizes the tensile properties of the tested rebars, while Fig. 9 shows the stress–strain relationships of the tested specimens. The test results show that the modulus of elasticity of the new CFRP rebars is about $91 \pm 2.6 \text{ GPa}$, the maximum tensile strength is 825 MPa and the corresponding maximum ultimate strain is 9000 microstrains.

A rupture with splitting between the two sides of the rebar was the typical mode of failure for specimens MP-1 and MP-3, while a rupture normal to the fibers orientation occurred for specimen MP-2. The rupture of specimens MP-1 and MP-3 occurred in three planes: perpendicular to the fibers direction at one half of the rebar, parallel to the fibers between the two halves of the rebar for a length of two to three bar diameters, and perpendicular to the fibers orientation in the other half of the rebar as shown in Fig. 10a.

The geometry of the rebar was designed such that at each section of the rebar a rib exists which allows the transfer of bond stresses to concrete. Accordingly, at any section of the rebar the ribs are not symmetrical around the center line of the rebar, which in turn created an extra force to the rebar. Consequently, a splitting force was created in the rebar leading to the typical splitting failure. The drawing in Fig. 10b shows the unsymmetrical ribs along the rebar and a longitudinal cross section showing the splitting forces that lead to the typical failure mode of the rebars.

Due to the splitting forces, a variation of 115 MPa in the tensile strength of the rebars was observed, while the variation in the modulus of elasticity was less than 5%. The authors believe that if the rebar had a symmetrical cross section, the rebar would have reached its desired strength (1500 MPa).

4.2. Pullout test

The nine specimens consist of two different batches, each batch was manufactured separately. The pullout test was conducted to determine the minimum development length required to transfer the force of the new CFRP rebars to the concrete. This test failed to provide the minimum development length due to the premature failure of the specimens. The results instead were used to examine the tensile properties and explore the different modes of failure. Moreover, the maximum reached bond stress was recorded.

The steel rebar of the control specimen PLS-30-1 failed in tension and no sign of debonding was observed. The stress strain curve of the control specimen was a typical stress–strain relationship of a steel rebar: linear up to yielding stress of 485 MPa, yielding plateau until the strains reached 27,100 microstrain, strain hardening up to ultimate stress of 582 kN and corresponding strain of 115,700 microstrain, then necking and failure occurred at a stress of 475 MPa. The two potentiometers were removed at stress of 580 MPa in order not to damage them during the rupture of the steel rebars.

For specimens PL-15-1, PL-15-2, PL-20-1, PL-20-2, PL-25-1, PL-25-2, PL-30-1, PL-30-2 and PL-35-1; the stress–strain relationship of the CFRP rebars exhibited a linear behavior up to failure. The modulus of elasticity was obtained using the load and the corresponding strain at 50% of the ultimate load, and the load and the corresponding strain at 25% (CSA-S806, 2002). Table 2 summarizes the tensile properties and the maximum recorded bond stress of the tested rebars, while Fig. 11 shows the stress–strain relationship of the nine tested specimens. The results show that the average modulus of elasticity of the new CFRP rebars is $118.5 \pm 2.0 \text{ GPa}$ and $90.3 \pm 5 \text{ GPa}$ for batches 1 and 2, respectively. The maximum tensile strength was 693 MPa and the maximum observed bond strength was 9 MPa.

Three modes of failure were observed: (S) rupture with a splitting between the two sides of the rebar; (S-W) splitting failure

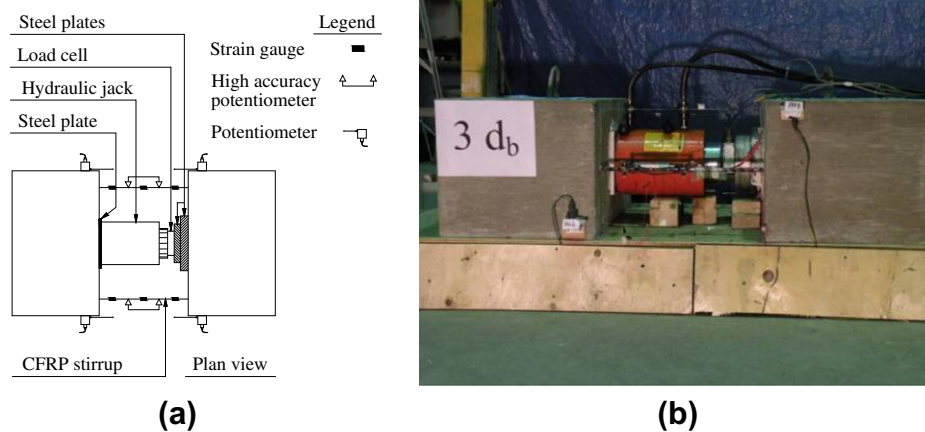


Fig. 8. Test setup and instrumentation of bent bars and stirrups test: (a) schematic plan view and (b) elevation.

Table 1
Mechanical properties of the tested CFRP rebars.

Specimen number	Nominal diameter (mm)	Load at failure (kN)	Tensile strength (MPa)	Ultimate strain (microstrain)	Modulus of elasticity (GPa)	Mode of failure
MP-1	12.7	104.5	825	9000	89.9	S
MP-2	12.7	101.4	800	8500	92.2	R
MP-3	12.7	90.0	710	8050	90.8	S

S: splitting failure; R: rupture normal to the fibers orientations.

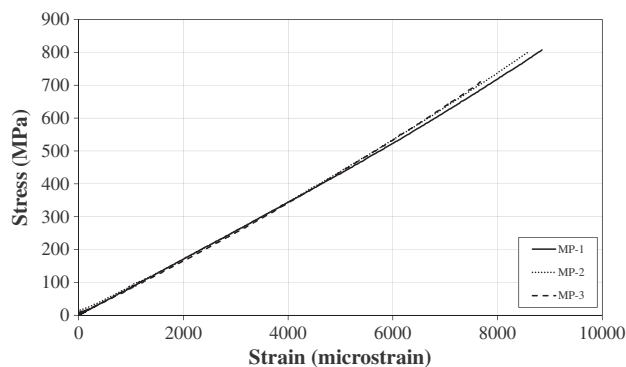


Fig. 9. Stress–strain relationship of specimens tested in tension.

with wavy fibers at the location of the failure; and (R) rupture. The splitting mode of failure (S) occurred in three planes: perpendicular to the fibers direction in one half of the rebar, parallel to the fibers between the two halves of the rebar for a length of two to three bar diameters and perpendicular to the fibers orientation in the other half of the rebar. The rupture mode of failure (R) had a plane of failure normal to the fibers orientation and located at the intersection of the rib and the smooth part of the CFRP rebar.

Specimen PL-20-2 failed with (S) mode of failure; specimens PL-15-1, PL-20-1, PL-25-1, PL-30-1, PL-30-2 and PL-35-1 failed with (S-W) mode of failure; while specimens PL-15-2 and PL-25-2 had (R) mode of failure. Figs. 12–14 show failed specimens with S-W, R, S modes of failure, respectively. The splitting mode of failure is due to the same reasons explained earlier in the mechanical properties test section.

Due to the splitting forces, a variation of 377 MPa in the tensile strength of the rebars was observed whereas the variation in the modulus of elasticity was less than $\pm 5\%$ for group1 and $\pm 2\%$ for

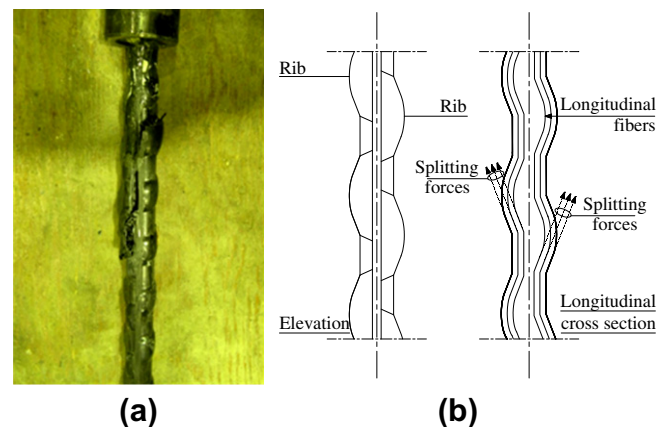


Fig. 10. (a) Typical failure mode of tested CFRP rebars. (b) A schematic drawing showing the inclined splitting force that cause the failure.

group 2. The authors believe that if the rebar had a symmetrical cross section, the rebar would have reached its desired strength (1500 MPa).

Although the rebar was designed with smooth ellipsoidal ribs, the specimen PL-20-2 indicates that there is stress concentration at the intersection of the ribs and the smooth part of the rebar.

4.3. Stirrups and bent bars test

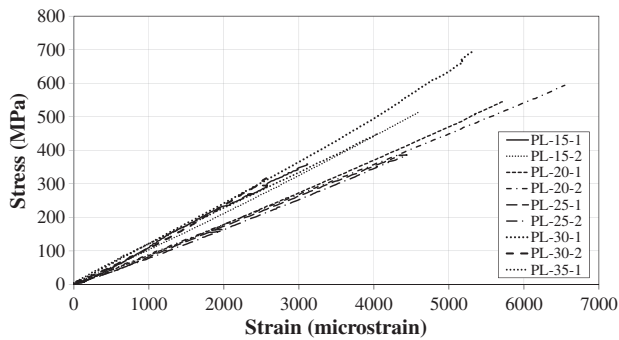
The results of the tested specimens are summarized in Table 3. All the tested specimens exhibited a linear stress–strain relationship up to failure as shown in Fig. 15. Specimens STR-3, STR-6, STR-9 and STR-12 failed at stress of 219, 204, 306 and 199 MPa; while the corresponding strains were 2265, 2425, 3120, and 3260 microstrains, respectively. The average modulus of elasticity was 91.1 ± 5 GPa. The readings of the potentiometers indicated

Table 2

Test results of the CFRP rebar tested in the pullout and bond strength test.

Specimen number	Embedment length (mm)	Ultimate load (kN)	Tensile strength (MPa)	Modulus of elasticity (GPa)	Ultimate bond strength (MPa)	Mode of failure
<i>Steel</i>						
PLS-30-1	339 (30d _b)	58.2	582	212	4	R
<i>Batch #1</i>						
PL-15-1	191 (15d _b)	45.4	359	120.1	6	S-W
PL-15-2	191 (15d _b)	65.1	514	112.4	9	R
PL-20-1	254 (20d _b)	68.5	544	125.5	7	S-W
<i>Batch #2</i>						
PL-20-2	254 (20d _b)	75.6	597	91.8	7	S
PL-25-1	318 (25d _b)	47.7	377	91.2	4	S-W
PL-25-2	318 (25d _b)	49.0	387	88.0	4	R
<i>Batch #1</i>						
PL-30-1	381 (30d _b)	87.7	693	115.9	6	S-W
PL-30-2	381 (30d _b)	40.0	316	123.3	3	S-W
PL-35-1	445 (35d _b)	56.7	448	113.9	3	S-W

R: rupture; S: splitting; S-W: splitting with wavy fibers.

**Fig. 11.** Stress–strain relationship of specimens tested in development length test.

that two concrete blocks were moved parallel without significant rotation.

The stirrups of specimens STR-3, STR-6 and STR-9 failed at the bent location, while specimen STR-12 failed in premature splitting tension failure as shown in Fig. 16.

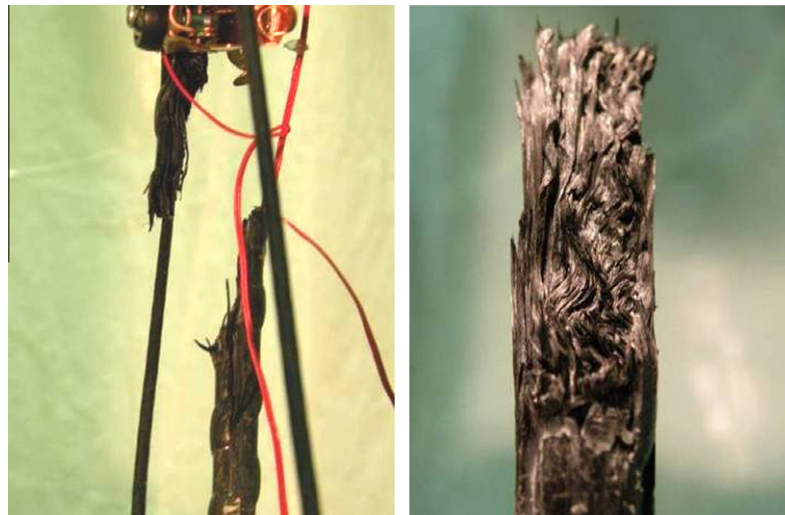
The properties of the bent rebars are evaluated with the ratio of the strength of the bent rebars to the strength of the straight rebars (F_{ub}/F_{us}). The capacity of the bent stirrups was 27%, 24%, 37% and

24% of the capacity of the straight rebars for specimens with tail length of $3d_b$, $6d_b$, $9d_b$ and $12d_b$, respectively.

5. Recommendations for improving the mechanical properties of the new bendable CFRP rebars

The typical modes of failure of the tested straight rebars were: (1) splitting failure and (2) splitting failure with wavy fibers which shows the need of some modifications to the manufacturing structure of the fibers in the rebar in order to improve its mechanical properties and to prevent such premature modes of failure. In order to prevent the premature failure with wavy fibers, the yarns should be under tension during the molding process. This can be achieved by applying small tension force to the yarns to ensure the straightness of the fibers. Moreover, the geometry of the rebars should be modified in order to prevent the splitting mode of failure. The existing rebars geometry with the ellipsoidal ribs lead to inclined forces causing the rebar to split in two halves and rupture prematurely. Accordingly, the rebar should have a symmetric cross section with straight fibers.

Proposed designs can be used in manufacturing the new thermoplastic CFRP rebars by means of the pultrusion technique. In this geometric design the rebar will be first pultruded in a circular

**Fig. 12.** Typical failure with splitting and wavy fibers.

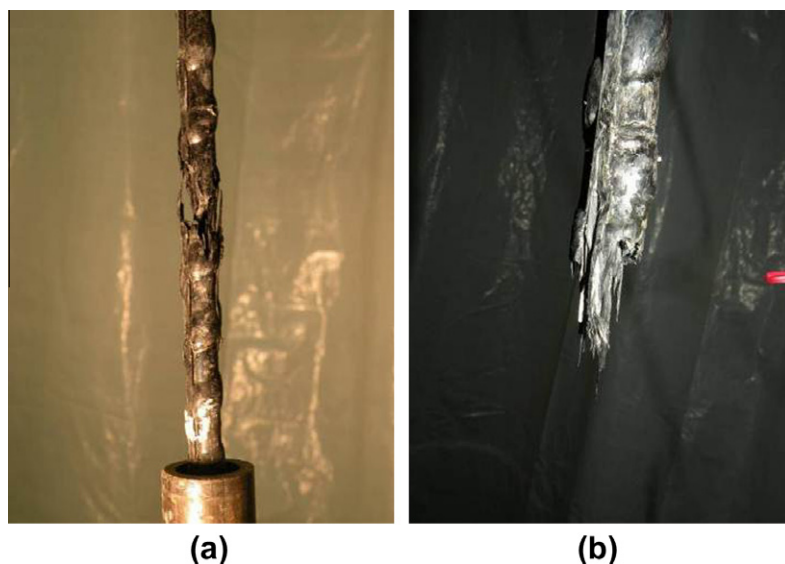


Fig. 13. Typical failure with rupture normal to the fibers orientation mode of failure.

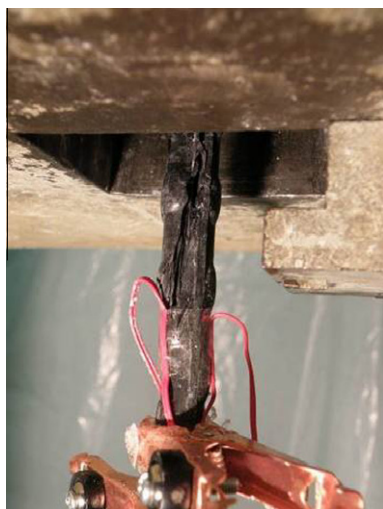


Fig. 14. Failure with splitting failure of specimen PL-20-2.

cross section. Then either sand coating or winding circumferential fibers with filament winding technique to increase the bond strength of the rebar. The sand coated rebar is expected to be the cheapest alternative, while the pultruded rebar with wounded fibers is expected to perform well at bent locations.

6. Summary and conclusions

An experimental study was carried out to evaluate the performance of the straight and bent new thermoplastic CFRP rebars to

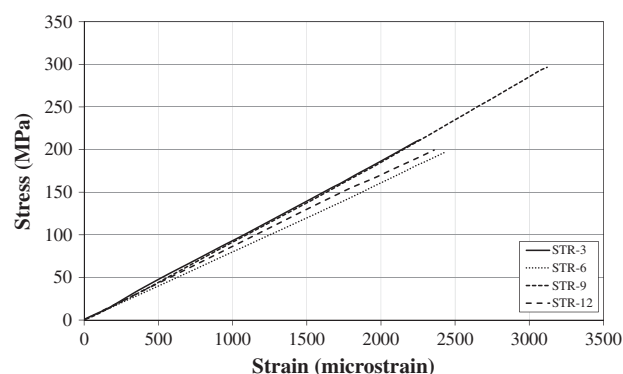


Fig. 15. Stress–strain relationship of the CFRP rebars tested in the stirrups and bent bars test.

be used as internal reinforcement for structural concrete elements. This study consisted of three sets of standard test: mechanical properties test, pullout test, and bent bars and stirrups test. Based on the results of this study, the following conclusions can be drawn:

- The new CFRP rebars exhibited a linear behavior up to failure when subjected to tension. The tensile strength of the tested rebars reached 825 MPa and the modulus of elasticity was 91 MPa.
- The maximum bond stress was 9 MPa, but no debonding failure was reached because of the premature failure of the tested rebars.
- The ratio of the strength of the bent rebars to the strength of the straight rebars was found to be 0.37.

Table 3

Test results of the CFRP rebar tested in the stirrups and bent bars test.

Specimen number	Tail length (mm)	Ultimate load (kN)	Ultimate strength (MPa)	Ultimate strain (microstrain)	Modulus of elasticity (GPa)	Mode of failure
STR-3	38 ($3d_b$)	27.7	219	2265	94.5	R
STR-6	76 ($6d_b$)	25.8	204	2425	85.1	R
STR-9	114 ($9d_b$)	38.8	306	3120	96.4	R
STR-12	154 ($12d_b$)	25.2	199	3260	88.4	S

R: rupture at the bent part; S: splitting failure.

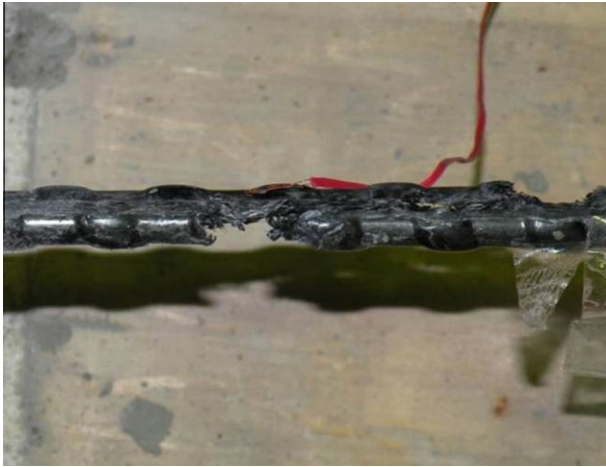


Fig. 16. Splitting failure of specimen STR-12.

- Although some of the rebars had a premature failure, the results of the three conducted tests are promising compared to the other rebars available in the market and literature
- With some improvements of the geometric design of the new CFRP, the behavior of the straight and bent rebars is expected to be higher. It should be noted that such mechanical characteristics could be then adjusted to meet the requirements of the various codes to be economically feasible.

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