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Tensile Property of FRP Composites and Metallic Material through Tensile Coupon Test

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ABSTRACT

FRP and metallic materials have diverse tensile properties, requiring detailed material specifications and sample fabrication for accurate description. This study uses experimental methods to compare the tensile properties of GFRP, CFRP, Hybrid FRP, AFRP, BFRP, and MS. Mechanical testing was performed with a 50 kN UTM and flat coupon grip fixture according to EN ISO 527/ASTM D638. Results show that the average tensile strength of T-MS was highest, with 485.20 MPa, followed by T-HB (314.22 MPa). Mono FRP plate materials have shown that T-AF was the strongest among all 4 FRP plates, followed by T-CF, T-BF, and T-GF (279.43 MPa, 199.89 MPa, 198.25 MPa, and 169.51 MPa). All FRP material samples exhibit sudden fracture at different maximum strains, with GFRP providing the largest strain before fracture, while MS samples exhibit strain softening due to necking before fracture. Based on the stress-strain curves, all FRP materials behave like brittle materials, and metallic materials behave like ductile materials, which exhibit large strain before fracture. GFRP, generally, failed through breakage and fibers pulled out of resins, while CFRP failed with angled cracks, and fibers mostly remained within matrix resins. Hybrid FRP composed of GFRP and CFRP has provided failure by an inclined crack with fiber breakage and a sign of fibers pulling out of resin. AFRP material exhibits scattered cracking failure with fibers remaining within the matrix resins, while BFRP fails with shear fibers breakages with remaining matrix resin. The metallic material represented by the mild steel sample has fractured with necking, indicating clear signs of ductile failure. Mechanical testing on all FRP composites and metallic material samples has provided at least 6 mechanical property results that can be used for further study in this area.

INTRODUCTION

Concrete structure strengthening has been through a lot of investigations and studies. According to Elwakkad et al. [1], metals and Fiber Reinforced Polymer (FRP) composites have been widely used to enhance concrete structural performance. The strengthening methods varied roots from either internal or external reinforcement. Internal strengthening approaches have introduced various configurations and arrangements of metals as well as FRP applications. Steel and FRP bars, rods, wires, strands, or meshes have been employed as internal reinforcement in concrete material to compensate for the fragility of concrete by integrating ductile and stiffer materials into the concrete system [2]. According to Namaan [3], the internal reinforcement materials were either in continuous phase, discontinuous phase, or mixed of both.

Steel application, however, was prone to corrosion that weakens the concrete structure, and thus, the applications of FRP in concrete reinforcement have gained focus among researchers. FRP's advantages as info or cement material are corrosion resistance, high sure strength-to-weight, and facial strengthening through wrapping and jacketing of concrete substructures. Besides jacketing, near-surface mounting (NSM) has also been introduced as an external reinforcement method for concrete structures with FRP and metallic materials [6,7]. A review by Parvin and Raad [5] has reported that other than FRP and steel, corrosion-free shape memory alloys have also been employed in strengthening concrete structures. According to Raza et al. [7], researchers have studied the external strengthening of concrete structures for the past three decades, especially in strengthening reinforced concrete (RC) columns.

Compared to the internal mean, external reinforcement has provided efficient crack repair on-site capability without damaging the core concrete structure, less labor work, and an occupant-friendly nature [8,9]. In addition, external strengthening has also provided strength enhancement on concrete structures with openings due to passage for ducting or piping, as well as joint strengthening, shear strengthening, flexural strengthening, seismic retrofit, and hoop strain constraint on concrete column structures [10]. Restraining hoop stress during compressive load on a concrete column with FRP materials has been applied with glass fiber reinforced polymer (GFRP), carbon fiber reinforced polymer (CFRP), basalt fiber reinforced polymer (BFRP), aramid fiber reinforced polymer (AFRP), and through a hybrid approach by combining more than one type of FRP materials [11].

Baasankhuu et al. [12] have stated that glass (GF), carbon (CF), and Aramid fiber have been used for a long time as FRP materials in concrete structure strengthening. In contrast, basalt fiber is relatively new in strengthening concrete structures. Besides, some other previous studies have also reported on strengthening through concrete structure confinement using aramid fiber [13], basalt fiber [14-16], and steel tubes [17,18]. The confinement methods varied with full or partial wrapping, and according to Rahamad Ali et al. [19], both variations have effectively enhanced the strength of a concrete column.

The tensile property of confinement materials is the main parameter restraining the hoop strain of a concrete column during compressive loading. An experimental study comparing the tensile strength of FRP and steel as confinement material by Yu et al. [20] concluded that both materials have approximately similar tensile strengths. However, the study needs to provide more information on the specifications of test samples as both FRP and steels have a wide variety of specifications, especially regarding the composition of the materials. Therefore, this study aims to compare the required sample specifications in the tensile properties of FRP and steel through experimental methods. The fabrication of every test sample was presented at each stage, from flat coupon preparation up to the standard shape of tensile test sample based on EN ISO 527 [21] and ASTM D638 [22].

EXPERIMENTAL

In this study, the materials used as fibers for FRP reinforcement are glass fibers (GF) unidirectional (UD)-700 gsm, carbon fibers (CF) unidirectional (UD)-400 gsm, basalt fibers (BF) unidirectional (UD)-300 gsm, and aramid fibers (AF) unidirectional (UD)-200 gsm. The material used as binders for the FRP matrix was epoxy Sikadur-330-part A and B (4:1) from SIKA. ASTM 106 MS mild steel (MS) pipe has been employed for metallic material. The mild steel pipe was machined to a thickness of 1 mm and extracted to produce a tensile coupon test sample. Figure 1 shows test samples, and Table 1 describes the sample variations.

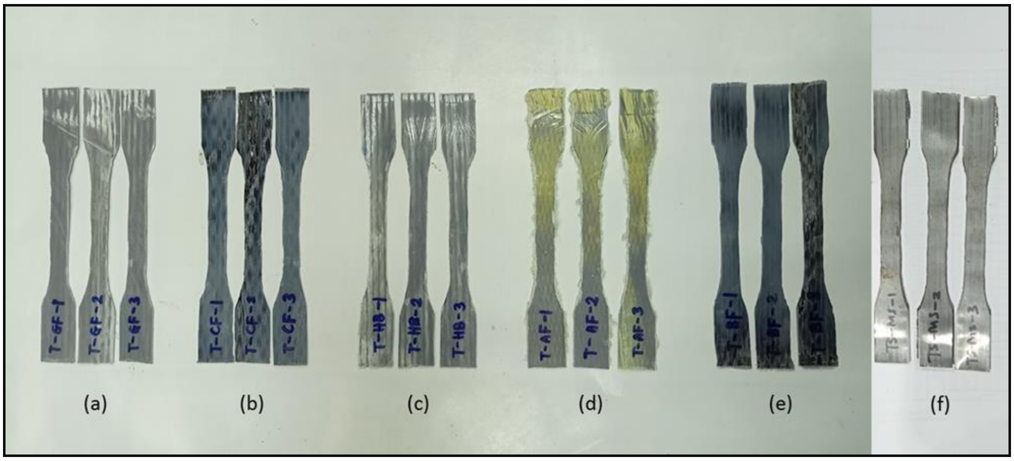

Figure 1. All test samples are ready for the tensile test.

Table 1: Specifications and variations of all test samples.

Test Samples	Thickness, t (mm)	Gauge Width, b_1 (mm)	Gauge Length, L_0 (mm)	Grips Distance, L (mm)	Gauge Cross Section, A_0 (mm^2)
T-GF-1	1.65	11	50	115	18.15
T-GF-2	1.75	10	50	115	17.50
T-GF-3	1.84	11	50	115	20.24
T-CF-1	0.84	10.5	50	115	8.82
T-CF-2	0.74	9.5	50	115	7.03
T-CF-3	0.77	9	50	115	6.93
T-HB-1	1.45	10.5	50	115	15.23
T-HB-2	1.47	11	50	115	16.17
T-HB-3	1.4	11	50	115	15.40
T-AF-1	0.96	11	50	115	10.56
T-AF-2	0.95	11	50	115	10.45
T-AF-3	0.7	9	50	115	6.30
T-BF-1	0.9	10	50	115	9.00
T-BF-2	0.81	11	50	115	8.91
T-BF-3	0.58	10.5	50	115	6.09
T-MS-1	1.12	12	50	115	13.44
T-MS-2	1.07	11.5	50	115	12.31
T-MS-3	1.09	12	50	115	13.08

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Mechanical testing was performed using a 50 kN universal testing machine and a flat coupon grip fixture on the upper and bottom sides of the test samples. The tensile testing specification, including test samples, loading rate, and machine setup, has been referred to EN ISO 527 and ASTM D638 standard test methods for the tensile properties of plastics. In addition, previous experimental studies by Pham et al. [23] and Young & Wu [24] have also been referred to in this test setup regarding test procedures and interpretation of the test results. Most of the test samples were FRP materials, but the tensile strength of mild steel plates was also measured using the same standard test (EN ISO 527/ ASTM D638) for data consistency. The test loading was based on strain rate at 5 mm/ min of crosshead speed.

RESULTS AND DISCUSSION

Mechanical Test Results

Table 2 summarizes the mechanical test results for all test specimens, including the average data to represent each test sample. T-GF1, T-GF2, and T-GF3 have shown reliable patterns on maximum load (2.97 kN, 2.93 kN, 3.59 kN), maximum displacement (3.725 mm, 4.232 mm, 5.448 mm), maximum strength (163.78 MPa, 167.28 MPa, 177.47 MPa), and maximum strain (0.0324, 0.0368, 0.0474). However, yield strength and modulus Young have shown that T-GF3 exhibits the lowest with 145.64 MPa and 3.97 GPa compared to yield strength and modulus Young of T-GF1 and T-GF2 (137.01 MPa, 5.54 GPa and 166.09 MPa, 4.37 GPa). These conditions occur probably due to errors in mounting the specimens on the testing machine grip or inadequate wetting of resins during specimen fabrication.

The average value for maximum load, maximum displacement, maximum strength, maximum strain, yield strength, and modulus Young for the T-GF sample was 3.16 kN, 4.47 mm, 169.51 MPa, 0.0389, 149.58 MPa, and 4.63 GPa. For CFRP sample, T-CF1, T-CF2 and T-CF3 have shown persistent results on all specimens with maximum load (1.83 kN, 1.37 kN, 1.36 kN), maximum displacement (3.021 mm, 3.082 mm, 2.891 mm), maximum strength (207.54 MPa, 195.23 MPa, 196.91 MPa), maximum strain (0.0263, 0.0268, 0.0251), yield strength (206.03 MPa, 195.18 MPa, 181.22) and modulus Young (7.17 GPa, 6.57 GPa, 8.82 GPa). The average value for maximum load, maximum displacement, maximum strength, maximum strain, yield strength, and modulus Young for the T-CF sample was 1.52 kN, 3.00 mm, 199.89 MPa, 0.0261, 194.14 MPa, and 7.52 GPa. Then, specimens T-HB1, T-HB2 and T-HB3 have shown closed pattern on maximum load (2.97 kN, 2.93 kN, 3.59 kN), maximum displacement (3.725 mm, 4.232 mm, 5.448 mm), maximum strength (163.78 MPa, 167.28 MPa, 177.47 MPa), maximum strain (0.0324, 0.0368, 0.0474) and modulus Young (7.87 GPa, 7.16 GPa, 7.13 GPa). However, the yield strength of T-HB2 has shown that T-HB2 exhibits the lowest with 258.79 MPa compared to T-HB1 and T-HB3 (303.39 MPa and 300.43 MPa). This condition may be due to either specimens or test procedures. The resin may not penetrate the fibers well enough during specimen fabrication, and the test specimen may not align well during the placement of the testing machine's upper and lower grip fixtures.

The average value for maximum load, maximum displacement, maximum strength, maximum strain, yield strength, and modulus Young for the T-HB sample was 4.90 kN, 5.16 mm, 314.22 MPa, 0.0449, 287.54 MPa, and 7.39 GPa. Mechanical test results for AFRP, represented by T-AF samples, have shown scattered data, making it less reliable. The test data measurement of mechanical properties for T-AF1, T-AF2 and T-AF3 were 3.56 kN, 2.81 kN, 1.46 kN (maximum load), 4.539 mm, 3.824 mm, 2.834 mm (maximum displacement), 337.26 MPa, 269.06 MPa, 231.99 MPa (maximum strength), 0.0395, 0.0332, 0.0246 (maximum strain), 223.44 MPa, 220.42 MPa, 215.43 MPa (yield strength) and 7.97 GPa, 7.52 GPa, 9.48 GPa (modulus Young). These conditions occur probably due to errors in test specimens because the AFRP plate took much work to cut and trim in the specimen fabrication process, resulting in non-uniform specimen size, especially on narrow sections.

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The average value for maximum load, maximum displacement, maximum strength, maximum strain, yield strength, and modulus Young for the T-AF sample was 2.61 kN, 3.73 mm, 279.43 MPa, 0.0325, 219.76 MPa, and 8.32 GPa. Then, for the BFRP sample, T-BF1 and T-BF2 have shown reliable patterns on maximum load (1.82 kN, 1.88 kN), maximum displacement (3.241 mm, 3.610 mm), maximum strength (202.65 MPa, 210.53 MPa), and maximum strain (0.0282, 0.0314). However, yield strength has shown that T-BF2 exhibits the lowest with 150.53 MPa compared to the yield strength of T-BF1 and T-BF3 (197.95 MPa and 157.35 MPa). In contrast, modulus Young has shown that T-BF3 exhibits the highest with 9.75 GPa compared to T-BF1 and T-BF2 (6.76 GPa and 7.20 GPa). These conditions occur probably due to specimen defects due to inadequate wetting by resins during sample fabrication.

The average value for maximum load, maximum displacement, maximum strength, maximum strain, yield strength, and modulus Young for the T-BF sample was 1.60 kN, 3.05 mm, 198.25 MPa, 0.0265, 168.61 MPa, and 7.90 GPa. Even though there was some inconsistency in the mechanical test measurement of FRP materials, the final test sample, which is metallic material represented by specimens T-MS1, T-MS2, and T-MS3 have shown reliable and persistent pattern on all specimens with maximum load (6.29 kN, 6.11 kN, 6.43 kN), maximum displacement (7.086 mm, 8.578 mm, 10.058 mm), maximum strength (468.24 MPa, 495.94 MPa, 491.40 MPa), maximum strain (0.0616, 0.0746, 0.0875), yield strength (315.63 MPa, 342.20 MPa, 344.21) and modulus Young (30.80 GPa, 26.12 GPa, 19.37 GPa). The average value for maximum load, maximum displacement, maximum strength, maximum strain, yield strength, and modulus Young for the T-MS sample was 6.28 kN, 8.57 mm, 485.20 MPa, 0.0746, 334.01 MPa, and 25.43 GPa.

Table 2. Summary of mechanical test results.

Samples	**Max. Load (kN)**	**Max. Disp. (mm)**	**Max. Strength (MPa)**	**Max. Strain**	**Yield Strength (MPa)**	**Modulus Young (GPa)**
T-GF1	*2.97*	*3.725*	*163.78*	*0.0324*	*137.01*	*5.54*
T-GF2	*2.93*	*4.232*	*167.28*	*0.0368*	*166.09*	*4.37*
T-GF3	*3.59*	*5.448*	*177.47*	*0.0474*	*145.64*	*3.97*
Average	3.16	4.47	169.51	0.0389	149.58	4.63
T-CF1	*1.83*	*3.021*	*207.54*	*0.0263*	*206.03*	*7.17*
T-CF2	*1.37*	*3.082*	*195.23*	*0.0268*	*195.18*	*6.57*
T-CF3	*1.36*	*2.891*	*196.91*	*0.0251*	*181.22*	*8.82*
Average	1.52	3.00	199.89	0.0261	194.14	7.52
T-HB1	*4.95*	*5.141*	*324.94*	*0.0447*	*303.39*	*7.87*
T-HB2	*5.06*	*5.386*	*312.62*	*0.0468*	*258.79*	*7.16*
T-HB3	*4.70*	*4.955*	*305.10*	*0.0431*	*300.43*	*7.13*
Average	4.90	5.16	314.22	0.0449	287.54	7.39
T-AF1	*3.56*	*4.539*	*337.26*	*0.0395*	*223.44*	*7.97*
T-AF2	*2.81*	*3.824*	*269.06*	*0.0332*	*220.42*	*7.52*
T-AF3	*1.46*	*2.834*	*231.99*	*0.0246*	*215.43*	*9.48*
Average	2.61	3.73	279.43	0.0325	219.76	8.32
T-BF1	*1.82*	*3.241*	*202.65*	*0.0282*	*197.95*	*6.76*
T-BF2	*1.88*	*3.610*	*210.53*	*0.0314*	*150.53*	*7.20*
T-BF3	*1.11*	*2.293*	*181.56*	*0.0199*	*157.35*	*9.75*
Average	1.60	3.05	198.25	0.0265	168.61	7.90
T-MS-1	*6.29*	*7.086*	*468.24*	*0.0616*	*315.63*	*30.80*
T-MS-2	*6.11*	*8.578*	*495.94*	*0.0746*	*342.2*	*26.12*
T-MS-3	*6.43*	*10.058*	*491.40*	*0.0875*	*344.21*	*19.37*
Average	6.28	8.57	485.20	0.0746	334.01	25.43

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Comparison on Average Mechanical Properties

Figure 2 compares average mechanical properties among all 6 variants of test samples (T-GF, T-CF, T-HB, T-AF, T-BF and T-MS) under tensile loading. The average test results for tensile strength, tensile strain, yield strength, and modulus Young for each sample were graphically presented using bar charts to observe the difference in their magnitudes. Figure 3(a) shows that the average tensile strength of T-MS was the highest among all samples, with 485.20 MPa. The second highest was T-HB (314.22 MPa), comprising GFRP and CFRP materials. A comparison of mono FRP plate materials has shown that T-AF was the strongest among all 4 FRP plates, followed by T-CF, T-BF, and T-GF (279.43 MPa, 199.89 MPa, 198.25 MPa, and 169.51MPa). Tensile strength is an important parameter in structural design that provides an allowable limit for a material in design analysis. The findings indicate that AFRP was the strongest mono FRP material represented by T-AF and hybrid FRP of GFRP and CFRP represented by T-HB.

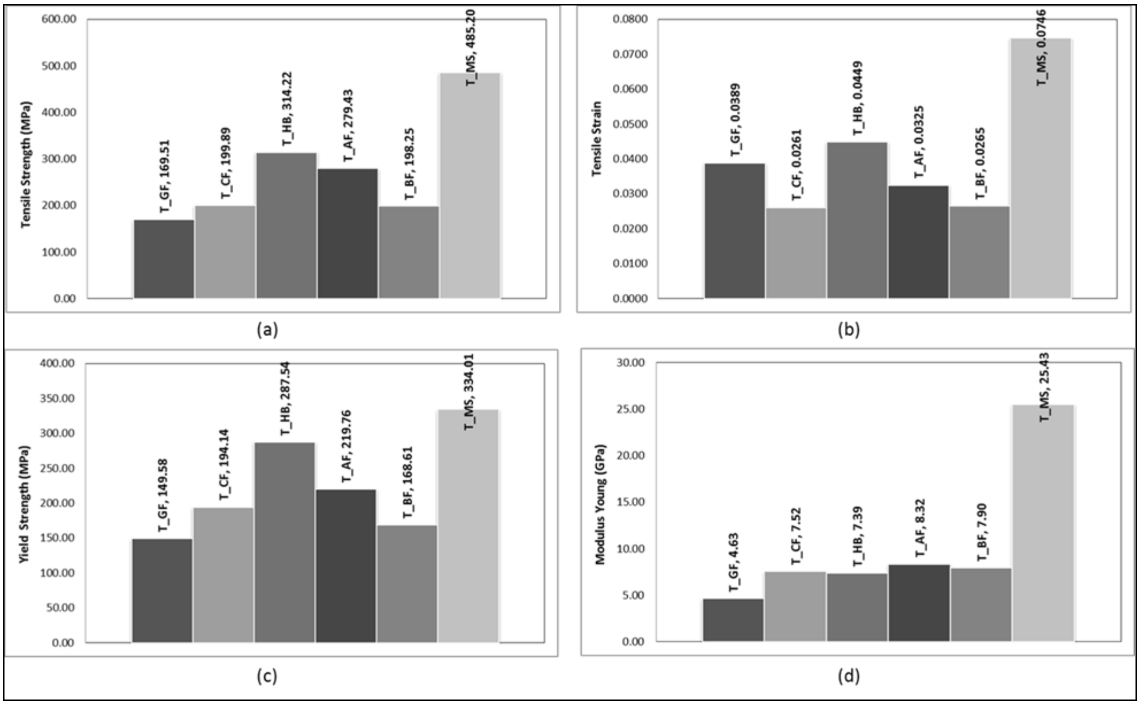

Figure 2. Comparison of average mechanical properties. (a) Tensile strength, (b) Tensile strain, (c) Yield strength, and (d) Modulus Young.

Another parameter that has been compared among all test samples was tensile strain. Tensile strain describes the deformation level of a material under applied tensile loads. The equivalent strain value at maximum strength was accounted for in the tensile strain comparison among all test samples. Figure 2(b) shows that T-MS samples have the highest strain with 0.0746. The second highest strain was T-HB, with 0.0449. Unlike strength comparison, the tensile strain value for mono FRP plate materials shows that T-GF has the highest strain (0.0389), followed by T-AF (0.0325). T-CF and T-BF have the lowest strain values, and both have almost the same values, with 0.0261 and 0.0265. The experimental result on tensile strain shows that metals, specifically mild steel (T-MS), can provide larger deformation up to maximum strength. However, for mono-FRP materials, GFRP (T-GF) has the highest degree of deformation.

In design analysis, other than ultimate strength, some designers used yield strength to represent the allowable limit of a material. The reason is that yield strength indicates the material's elastic limit, which means that permanent deformation is likely to occur if the material is subjected to an external load that causes higher stress than yield strength. Between all test samples, T-MS (334.01 MPa) has the highest yield strength, followed by T-HB (287.54 MPa), T-AF (219.76 MPa), T-CF (194.14 MPa), T-BF (168.61 MPa) and T-GF (149.58 MPa) with the lowest yield strength measurement. These results reflected that GFRP has the lowest range of elastic response towards external loads. Other than that, experimental results have also shown that in the combination of GFRP and CFRP through hybrid FRP materials (T-HB), the yield strength of both materials has enhanced from 149.58 MPa and 194.14 MPa to 287.54 MPa. Figure 2(c) shows the yield strength for each test sample.

The last parameter that has been compared among all variants of test samples is modulus Young. This parameter describes tensile strength and tensile strain simultaneously through a single value representing the linear relationship between strength and strain up to their elastic limit. The modulus Young values indicate the stretchable level of a material relative to other materials. In this study, T-MS has the highest modulus Young value with 25.43 GPa. However, all FRP materials, mono and hybrid compositions, have shown significant differences with metals by providing consistently low modulus Young value. The modulus Young for T-GF, T-CF, T-HB, T-AF, and T-BF from the experimental was 4.63 GPa, 7.52 GPa, 7.39 GPa, 8.32 GPa, and 7.90 GPa. These findings indicate that, in general, FRP materials are hard to stretch compared to metallic materials. Figure 2(d) shows the modulus Young comparison among test samples.

Stress versus Strain Curves

Stress versus strain curves describe test samples' behavior under gradually increasing tensile loads up to fracture. The reason for gradually increasing the load was to produce a static loading approximation as in the actual application. In this experiment, the loading rate was represented by a 5 mm/ min strain rate according to ISO EN 527/ ASTM D638. The tensile test sample then responds to the test loads by deformation, and the deformation patterns reflect the behavior of the materials. However, the reflection on the loading and deformation relationship does not quantify the magnitude of a material relative to other materials because it depends on sample size, where the large sample produces less deformation compared to the smaller sample, even if both samples are of the same material. Therefore, the stress versus strain curve overcomes the issue by applying loads per unit area to represent material strength placed on the y-axis. Then, on the x-axis, the deformation ratio occurred with the original size representing the strain applied. Both stress and strain can describe the behavior and magnitude of the test materials. Figure 3 shows that there are all 18 curves of stress versus strain representing 3 specimens for each sample of 6 variants, T-GF, T-CF, T-HB, T-BF, T-AF, and T-MS. To facilitate the observation, the curve is colored with specific colors and different line thicknesses, with specimen 1 being the smallest and specimen 3 being the largest. The curves of all test samples indicate that tensile samples are grouped well according to their variants, which can be observed based on specific colors.

Overall curves indicate that mild steel, represented by T-MS curves, has the highest tensile strength, yield strength, tensile strain, and modulus Young. This condition has been marked by a straight horizontal line on the top section of the curves, as in Figure 3. The second largest group of stress versus strain curves, which are laid in the middle section, shows that AFRP (T-AF) and Hybrid FRP (T-HB) have dominated the area. This condition indicates that both samples have the second-highest tensile and yield strength. For tensile strain, another material from the bottom section, GFRP (T-GF), also provides high strain values such as T-AF and T-HB. In contrast, all FRP material variations except GFRP for modulus Young have shown almost similar values. Finally, samples grouped as bottom sections in the stress versus strain curve (Figure 3) are T-CF, T-BF, and T-GF, which pose relatively lower tensile strength and strain among other samples.

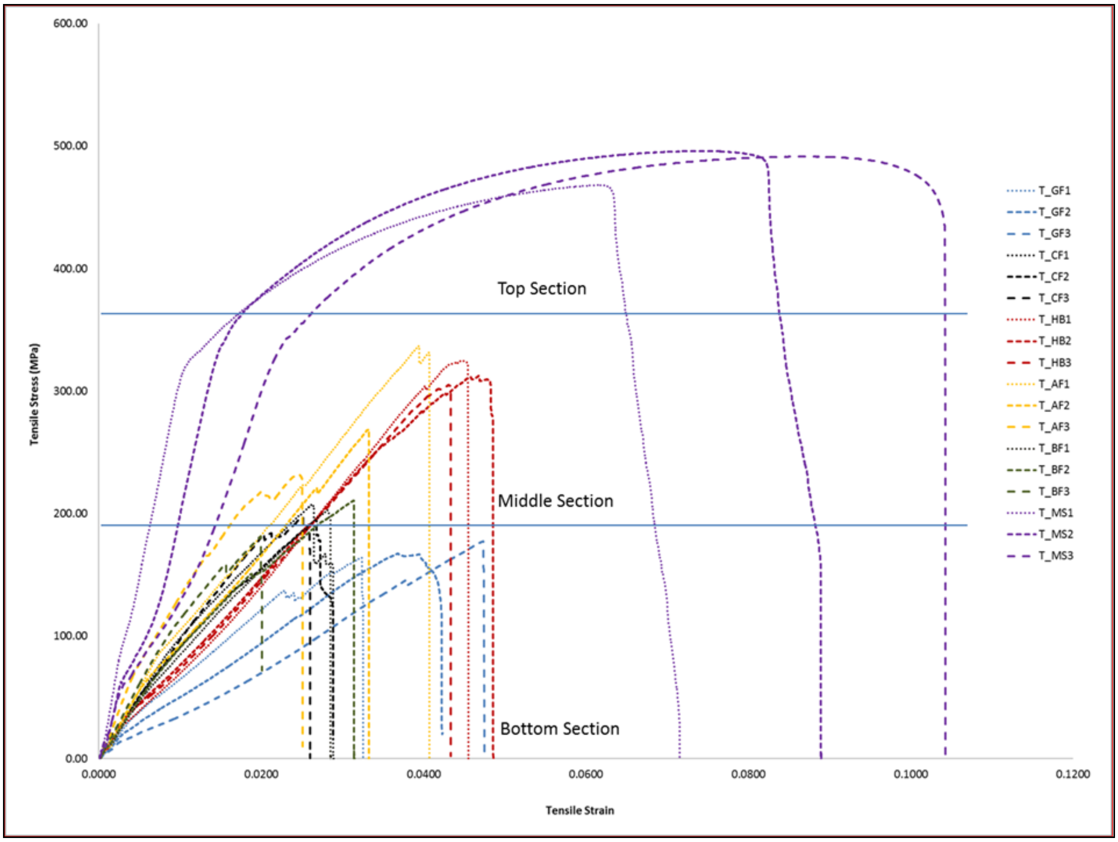

Figure 3. Tensile strength versus tensile strain curves for all test samples.

Failure Modes

Each specimen was subjected to uniaxial tensile loads up to fracture in the experiment. Failure modes describe the failure pattern on the fractured area of the test specimens. Figure 4 shows the failure modes of all test specimens for every sample (T-GF, T-CF, T-HB, T-AF, T-BF, and T-MS). Figure 4(a) describes that T-GF1 and T-GF3 specimens have failed with fibers pulled out of resin, and an inclined scattered breakage has occurred in the middle of the test specimen. T-GF2 has shown splitting of the test specimen at the top section, which includes the upper grip area. The failure at the grip area may be considered a test error because the fracture was caused mostly by the grip of the upper area of the test specimen.

Figure 4 shows that T-CF1 and T-CF2 specimens have failed with an angled crack near the top of the specimen's narrow area. Fibers seem to remain in good bond with resins, indicating that wetting of fibers during sample fabrication was perfectly done. T-CF2 has shown long vertical splitting of the sample from the middle section of the test specimen up to the near lower grip area. Figure 4(c) describes that T-HB2 and T-HB3 have failed with the long vertical splitting of the test specimen at the top section of the specimen's narrow area. T-HB1, on the other hand, indicates an inclined crack with fiber breakage and a little sign of fiber pull out of resin. The location of this failure is on the top section of the test specimen.

For AFRP, Figure 4(d) shows that T-AF1 exhibits scattered cracks near the middle section from the top of the test specimen, while T-AF2 also shows scattered cracks near the top section of the test

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specimen. T-AF3, however, experienced splitting of the test specimen at the bottom section of the test specimen up to the lower grip area. Figure 4(e) describes the failure pattern of the BFRP sample, where T-BF1 shows shear breakage and fibers pull out from resin at the top section of the test specimen. T-BF2 also shows shear breakage and fibers pulled out of resin, but the range of shear breakage occurs throughout the specimen's gauge length area. Then, specimen T-BF3 exhibits splitting of the test specimen at the top section up to the upper grip area. The last sample was metallic material represented by a mild steel tensile test sample (T-MS), which provides the most persistent failure modes as the material system is not as complex as the FRP material system. Figure 4(f) indicates that T-MS1 exhibits ductile failure with a clean transverse cut and a sign of necking before fracture at the middle section of the test specimen. T-MS2 also has shown ductile failure but with necking and a small angular cut at the middle section of the test specimen. The failure mode of the T-MS3 specimen has exhibited necking before fracture, representing ductile failure with a clear shear cut at the middle section of the test specimen.

Overall, each FRP and metallic material has provided a failure pattern that differentiates them from other materials. GFRP generally failed through breakage and fibers pulled out of resins, while CFRP failed with angled cracks, and fibers mostly remained within matrix resins. Hybrid FRP composed of GFRP and CFRP has provided failure by an inclined crack with fiber breakage and a sign of fibers pulling out of resin. AFRP material exhibits scattered cracking failure with fibers remaining within the matrix resin, while BFRP failed with shear fiber breakages with fibers remaining with matrix resin. Through a mild steel sample, the metallic material was fractured with necking, indicating clear signs of ductile failure.

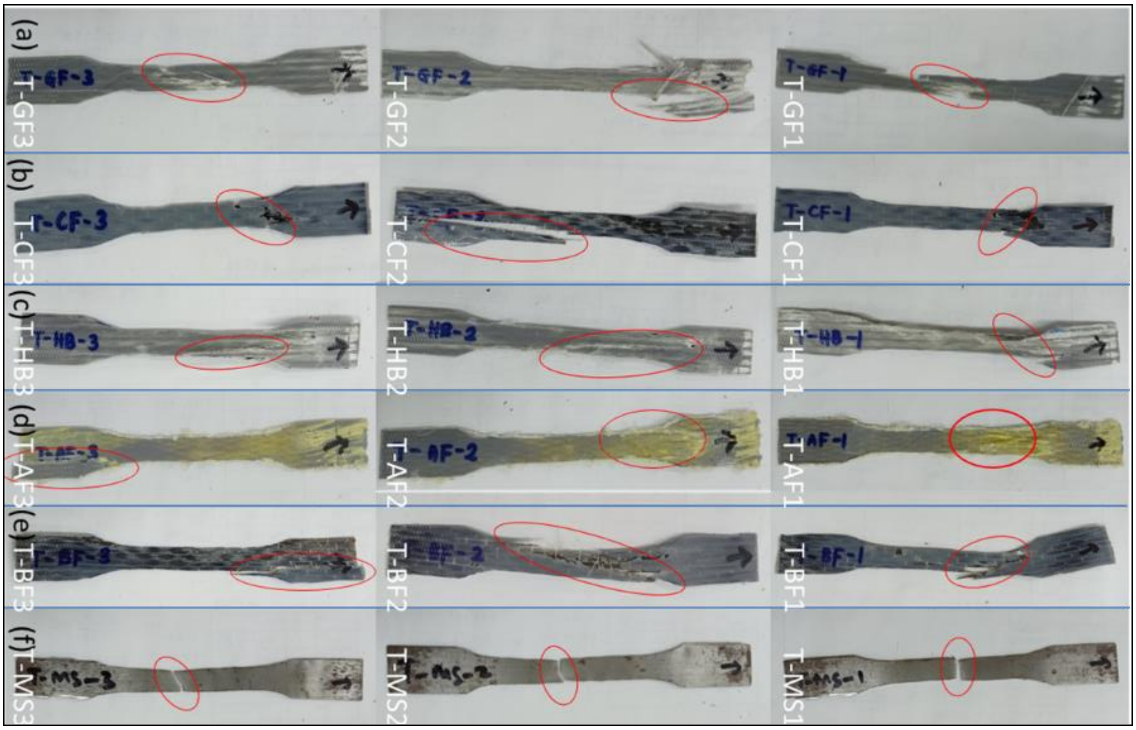

Figure 4. Failure modes of all test samples. (a) Failure modes of GFRP samples, (b) Failure modes of CFRP samples, (c) Failure modes of Hybrid FRP samples, (d) Failure modes of AFRP samples, (e) Failure modes of BFRP samples, (f) Failure modes of Mild steel samples.

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CONCLUSION

This experimental study compared the tensile properties of FRPs and metallic materials commonly used in the external strengthening of concrete structures. T-MS had the highest tensile strength (485.20 MPa), followed by T-HB (314.22 MPa), a hybrid of GFRP and CFRP. Among mono-FRP plates, T-AF was the strongest (279.43 MPa), followed by T-CF, T-BF, and T-GF. Yield strength was lowest in T-GF (137.01 MPa) and highest in T-MS (315.63 MPa). T-MS also had the highest Young's modulus (30.80 GPa), while T-GF had the lowest (5.54 GPa). Maximum strain varied, with T-MS showing the highest (0.0616). FRP samples exhibited sudden fractures, while the metallic material showed strain softening before necking. The failure patterns were distinct for each material: GFRP showed fiber pull-out, CFRP cracked at an angle, and the hybrid of GFRP and CFRP displayed fiber breakage. AFRP and BFRP showed different cracking behaviors, while the metallic material indicated ductile failure. These findings provide insights into the mechanical properties of FRP composites for further study.

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CONFLICT OF INTEREST STATEMENT

The authors agree that this research was conducted without any self-benefits or commercial or financial conflicts and declare the absence of conflicting interests with the funders.

AUTHORS' CONTRIBUTIONS

Muhamad Soffi and Nor Shaufina conducted the research and wrote and revised the article. Shukur conceptualized the central research idea and provided the theoretical framework. Mohd Ruzaimi and Muhamad Soffi designed and supervised the research progress; Muhamad Ruzaimi anchored the review and revisions and approved the article submission.

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