Exploring Strength of Straight and Bent GFRP Bars: Refinements to CSA S807:19 Annex E

Ahmed Mohsen Khalil, Rami Hawileh and Mousa Attom

July 15, 2023

SP-XXX—1

Exploring strength of straight and bent GFRP bars: Refinements to CSA S807:19 Annex E

Ahmed Khalil, Rami A. Hawileh, and Mousa Attom

Synopsis: This study explores technological advancements enabling the utilization of GFRP bars in concrete structures, particularly in coastal areas. However, their application is hindered by the limited availability and reduced performance of curved GFRP bars. The bent strength of GFRP bars is crucial for quality assurance, yet existing testing methods stated in ASTM D7914M-21 and ACI 440.3R-15 have limitations when applied to different GFRP bent shapes. Furthermore, those methods require special precautions to ensure symmetry and avoid eccentricities in specimens. To address these challenges, CSA S807:19 introduced a simpler standardized testing procedure that involves embedding an L-shaped GFRP stirrup in a concrete block. However, the large block size specified in CSA S807:19 Annex E may present difficulties for on-site quality control. Hence, this study aims to thoroughly investigate the user-friendliness and efficiency enhancements to method proposed by CSA S807:19 Annex E, including reducing the block size and eliminating block confinement provided by the steel stirrups. This study explores refinements to CSA S807:19 Annex E by reducing the width of the block, which will result in a significant reduction in the net weight of the concrete block. Particularly for bars less than 16mm in diameter, smaller blocks are recommended. Furthermore, strain gauges are employed in this study with a focus on assessing their impact on debonding and test results. The study suggests incorporating additional tail length to mitigate the debonding effects. By exploring these modifications, the study seeks to enhance the effectiveness of the testing procedure and expand its practical application for on-site quality assurance. The findings hold implications for the reliable testing of GFRP bars' strength, advancing their use as reinforcement in concrete structures.

Keywords: Durability, CSA, ACI, ASTM, Bent, FRP, Strength.

ACI student member **Ahmed Khalil** is a PhD. Candidate in Material Sciences and Engineering (MSE) at American University of Sharjah, Sharjah, the United Arab Emirates (UAE).

ACI member **Rami Hawileh** is a Professor in the Department of Civil Engineering at American University of Sharjah, Sharjah, the UAE. He is a member of ACI Committees 440 (Fiber-Reinforced Polymer Reinforcement) and voting member of 440-0D (Research Development and Applications). His research interests encompass strengthening of reinforced concrete structures, computational modeling, fire resistance, and in the analysis and design of sustainable concrete structures. He is a licensed Professional Engineer in Virginia.

Mousa Attom is a Professor in the Department of Civil Engineering at American University of Sharjah, Sharjah, the UAE.

INTRODUCTION

Fiber-reinforced polymer (FRP) bars have emerged as a promising alternative to traditional steel reinforcement in concrete structures due to their high strength, lightweight nature, and corrosion resistance. However, the effectiveness of FRP materials is typically compromised when subjected to a combination of stresses, as opposed to pure axial tension. Previous studies have revealed that curved FRP reinforcements in RC structures are susceptible to premature failures at the bent corner due to a reduction in tensile strength when exposed to a combination of tensile and shear stresses [1]–[14]. Although there are various types of FRP bars available, carbon (CFRP) and glass (GFRP) seem to be the most widely used in actual RC applications and research [15]. CFRP has superior properties, and GFRP is significantly more affordable than other composites [16]–[18]. Nevertheless, it is important to note that FRP bars experience gradual degradation of mechanical properties over time due to environmental factors and sustained loading. This degradation phenomenon is particularly evident in the case of bent FRP bars, where localized stress concentrations at the bend portion can cause microcracking and fiber breakage, leading to strength reduction. Previous studies have demonstrated that when composite bars are bent, their tensile strength can significantly decrease. Shehata et al. [9], [13], [19] found that the strength of bent composite bars could be as low as 40% of the maximum tensile strength that can be achieved in a straight bar. [20] reported even lower values, stating that bent FRP bars can have as low as 25% of the maximum tensile strength of a straight bar. The results of these experiments indicate that bending composite bars can significantly impact their strength, a factor which designers should be mindful of when utilizing these materials.

Specifically, research on the strength degradation of bent FRP products [1], [21]–[24] has been limited in recent years, with only a few studies focusing on bent GFRP bars [25]–[27]. This limited research is in contrast to the larger body of literature available on the strength of GFRP bars (i.e., [28]–[31]). Figure 1 illustrates the publication trends over the past five years regarding the bending and straight strength of GFRP bars. Notably, there has been a significant scarcity of research on bent GFRP bars during this period. This dearth of studies emphasizes the necessity for a thorough review of existing methodologies and the current knowledge regarding the strength deterioration of bent GFRP bars. The primary objective of this study is to comprehensively examine the enhancements made to the method proposed in CSA S807:19 Annex E [32], focusing on improving user-friendliness and efficiency. These enhancements encompass the reduction of block size and the elimination of block confinement achieved through steel stirrups. The investigation in this study revolves around refining CSA S807:19 Annex E [32] by reducing the width of the blocks. Consequently, this reduction in width will significantly decrease the overall weight of the concrete blocks. Moreover, this study aims to provide an updated overview of the investigated methods and approaches up to the present time. It includes an evaluation of the methods explored so far, based on provincial North American standards such as the American Concrete Institute (ACI) [33], American Society for Testing and Materials (ASTM) [34], and Canadian Standards Association (CSA)[32].

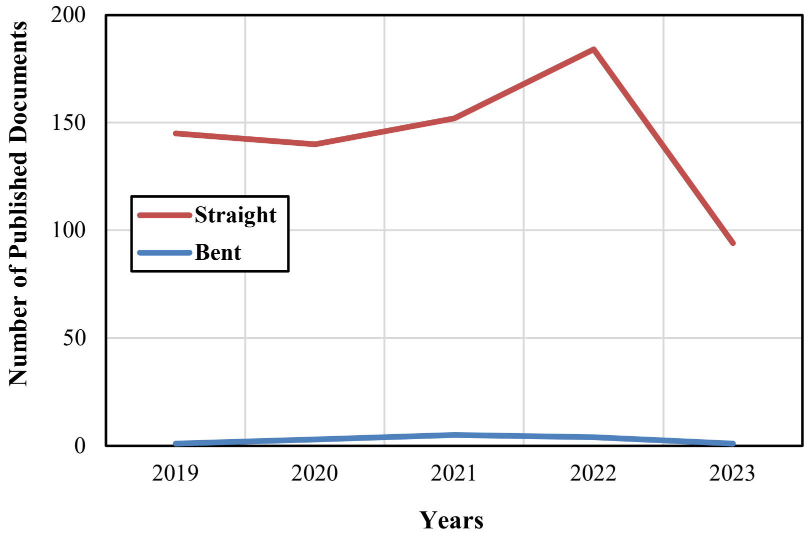


Fig.1—Number of publications on straight and bent strength over time (Access date 4/12/2023)

BACKGROUND AND LITERATURE REVIEW

The phenomenon of a decline in bent strength of FRP is impacted by various parameters. One of the key parameter that have been identified to influence strength degradation in bent GFRP bars is the curvature ratio [1], [35], which is defined as the ratio between the bending radius and the bar diameter (*r/d*). Higher curvature ratios lead to greater stress concentrations and, consequently, more significant strength degradation in bent GFRP bars [1], [35]. Another factor affecting the strength degradation of bent GFRP bars is exposure to harsh environmental conditions, such as temperature and humidity. In bent portion of GFRP bar, elevated temperatures and humidity levels can accelerate the rate of degradation, as these conditions can result in thermal expansion and moisture absorption, which can lead to microcracking and fiber breakage. Even though, to the best of the author's knowledge, no study has been conducted on the durability of GFRP bent bars. Moreover, the degree of degradation in bent GFRP bars can be influenced by the material quality (i.e., surface treatment of the GFRP bars [36]). In the bend regions of higher quality GFRP bars, strength is more resistant to degradation as a result of superior manufacturing processes and fiber alignment than in lower quality GFRP bars. Overall, the strength degradation of bent GFRP bars is a complex phenomenon that is influenced by factors such as the curvature ratio, environmental exposure, and the quality of the FRP material. In addition to the aforementioned parameters, this section underscores various factors that may influence the bent strength of GFRP bars in the context of a literature review. These factors include but are not limited to the length of the tail, size of the bar, loading rate, shape of rebar, and type of concrete and strength.

Mohamed et al. [26] recently conducted a study aimed at standardizing a new method for testing the tensile strength of bent GFRP bars. Mohamed et al. sought to develop a more practical approach than the current ASTM D7914M-21 [34], which requires special precautions to ensure symmetry and avoid eccentricities in specimens. The study involved testing the strength of 25 bent GFRP bars from five different manufacturers using the proposed method and compared to that of 25 samples tested using the ASTM D7914M-21[34] standard. The findings revealed a 4%-20% difference for L-shaped testing. The proposed method entails embedding L-shaped bent GFRP bars in concrete blocks and subjecting them to tensile pullout forces. Although this approach has been examined in previous studies (i.e., Miyata et al. [35] Imigai et al. [2]), its application towards the standardization of a test protocol for ensuring the quality of bent GFRP products is a novel contribution. It is worth noting that the testing protocol developed in this study has been adapted and included in the new edition of Canada's specification for FRP [32]. Additionally, Mohamed et al. [26] were the first to use steel reinforcement to prevent concrete cube collapse prior to FRP rupture. Furthermore, the study examined various parameters, such as bar size, concrete compressive strength, tail length, dimensions of the concrete block and cover, and loading rate, to optimize the setup. Mohamed et al. [26] suggested using a 300 x 300 x 600-mm concrete block without reinforcement, an anchor length of 12 times the bar diameter, fast-setting concrete capable of attaining compressive strength of 48 MPa, and a loading rate to induce failure within 1-10 min to make the setup suitable for any shape of GFRP bar up to No. 6 (20 mm).

EXPERIMENTAL PROGRAM

Testing setup by the ACI and the ASTM for B.5 and B.12 methods:

ACI 440.3R proposes the B.5 method (bent bar capacity) and the B.12 method (corner radius), which are illustrated in Figure 2a,b. According to the B.5 method, the FRP's ultimate capacity is determined by tension testing the straight piece of a C-shaped stirrup in which the bent ends are embedded in two concrete blocks (Figure 2a). A strength reduction factor resulting from bend effects is calculated by measuring the bend capacity of bent FRP bars and comparing it with their ultimate tensile strength. Using the testing apparatus outlined schematically in Figure 2b, the B.12 method assesses the impact of corner radius on the tensile strength of FRP bars. Tension is applied to the U-shaped FRP, which in turn reacts against the bent portion. Bent strength can be calculated as follows:

$$f_{bent\ (B.5\ or\ B.12)} = \frac{F_{Ult}}{2A} \tag{1}$$

where $f_{bent\ (B.5\ or\ B.12)}$ is the bent strength measured by the B.5 or B.12 testing (MPa); F_{Ult} is the failure load (N); and A is the GFRP cross-sectional area.

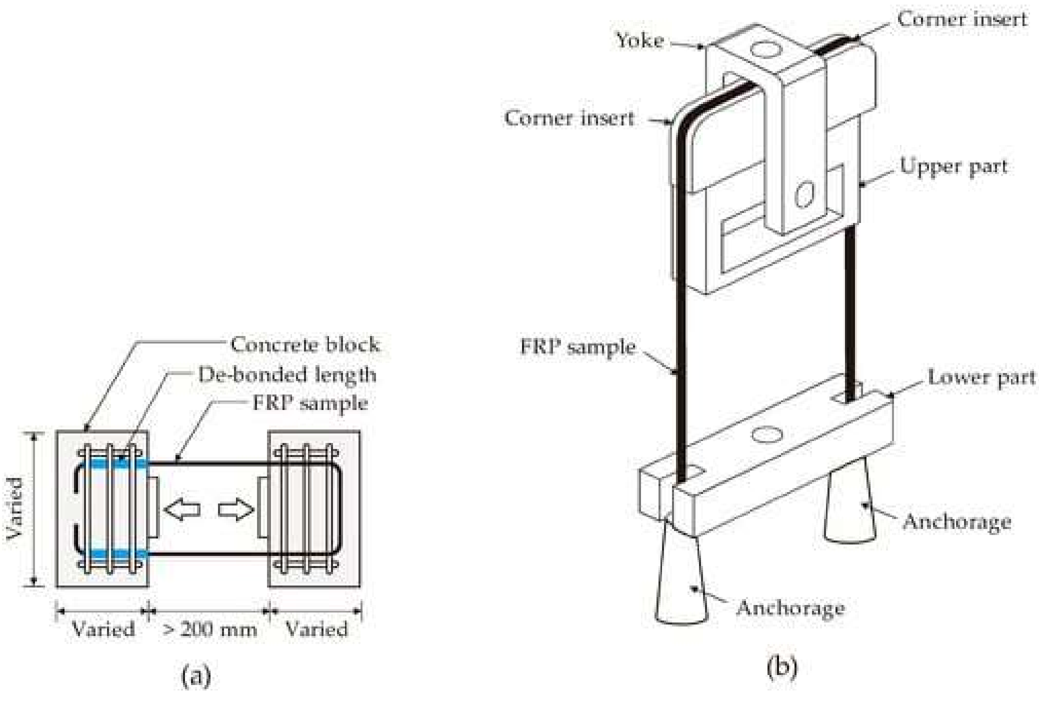


Fig.2—(a) B.5 and (b) B.12 according to ACI 440.3R.

Summary of test setup by The CSA code:

CSA S807:19 Annex E [32] proposes a simpler testing procedure involves embedding an L-shaped GFRP stirrup in a concrete block as shown in Figure.3(a). According to CSA S807:19 Annex E [32], it is recommended to prepare L-shaped specimens for testing in a certain way; first, the smaller (horizontal) leg of the specimen, also called the tail length, should be set at 6d, where d is the diameter of the bar. Additionally, the longer (vertical) leg of the specimen, known as the head length, should be cut to provide adequate length for installing steel anchors and achieving the required embedment length in the concrete. More details about the steel anchors is provided later in this section. This will ensure that the specimen is securely embedded in the concrete while also providing a free length between the concrete surface and the anchors.

To prevent force transmission through the bond, it is essential to attach debonding tubes to the GFRP bars, starting at the bent portion (Figure 3). This step is necessary and analogous to the testing method outlined in ASTM D7914M-21[34]. The GFRP bent bars are fixed in the middle of the concrete blocks with a 50 mm clearance gap to the nearest concrete surface. The GFRP bars needs to be leveled carefully in the vertical position to prevent any out-of-plane force components. The dimensions of the concrete block should be as stated in CSA to prevent splitting before attaining the full strength of the bars, without using transverse steel reinforcement. The testing procedure using one GFRP bent bar reduces the stress on the concrete blocks by half compared to specimens prepared according to the ASTM D7914M-21[34] testing method. Therefore, the recommended concrete strength in CSA (30 MPa) should be adequate to carry the applied loads. The specimens should be loaded using a hollow hydraulic tension jack or universal testing machine (UTM). The bent strength can be calculated as follows:

$$f_{bent\ (L-shape\ setup)} = \frac{F_{Ult}}{A} \tag{1}$$

where $f_{bent\ (L-shape\ setup)}$ is the bent strength measured by the B.5 or B.12 testing standards (MPa); F_{Ult} is the failure load (N); and A is the GFRP cross-sectional area (mm^2).

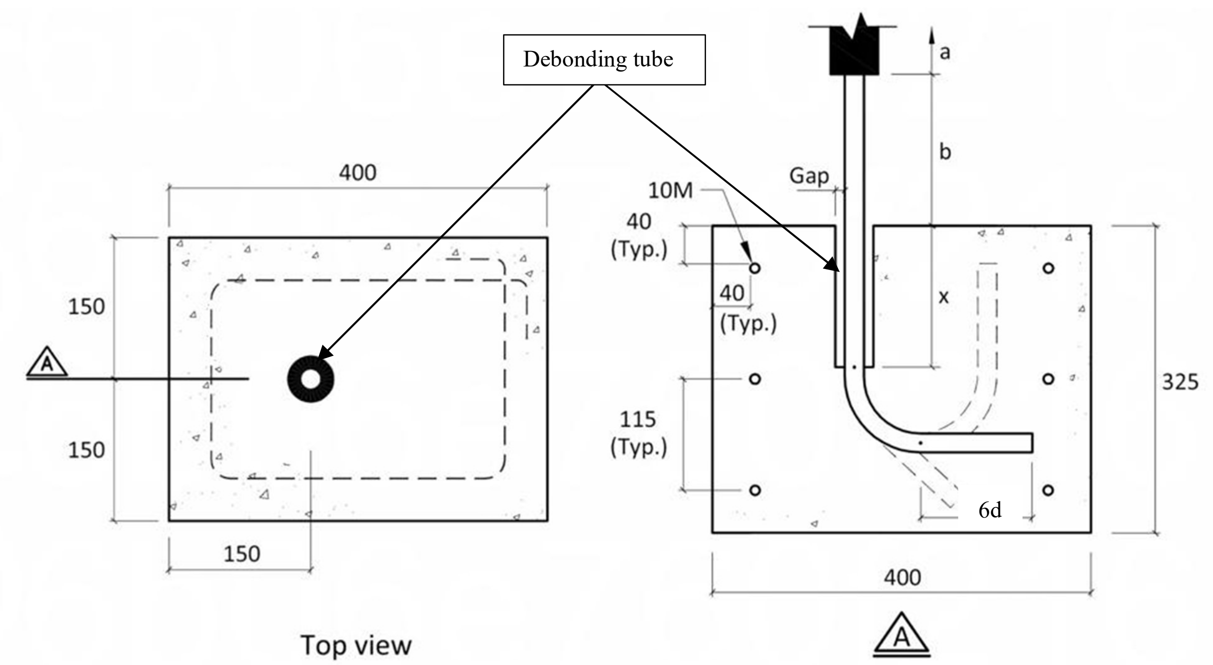


Fig. 3—Test setup according to CSA S807:19 Annex E [32]

Pilot Study: Test setup details:

The L-shaped GFRP bar was subjected to testing in accordance with the CSA S806:21 [37] standards. To secure the steel tube onto the GFRP bar, an expandable cement grout was mixed and utilized (Figure 4a). The longer leg of the tested L-shaped GFRP bar is anchored using the aforementioned grout (Figure 4b). Additionally, a framework is employed to embed the shorter leg of the tested L-shaped GFRP bar and facilitate the casting of concrete (Figure 4c). To maintain the integrity of the GFRP bars and prevent any influence from surface indentations on their bending strength (Ahmed et al. [5]), it was necessary to embed them within concrete blocks. The dimensions of the concrete blocks are chosen to prevent concrete splitting before bar e rupture, while avoiding the use of transverse steel reinforcement. According to Mohamed et al. [26], it is important to note that this suggested testing scheme, utilizing a single FRP bent bar, effectively reduces the stress imposed on the concrete blocks by half compared to the B.5 testing. In this study the concrete strength suggested in CSA S807:19 Annex E [32] is utilized.

(a)

(b)

(c)

Fig. 4—(a) expandable cement grout used for anchoring steel tubes to GFRP bars; (b) Anchor setup used to cast the grout; (c) embedding the L-shaped GFRP bars after casting the concrete cubes.

The initial step in the experimental program involved conducting tensile tests to establish a benchmark for the full strength of straight GFRP bars. This benchmark was later used for comparison with the strength of the GFRP bar in its bent configuration. The installation of anchors followed the guidelines outlined in CSA S806:21 [37] standards. Following the installation of anchors, Figure 5a illustrates the attachment of the sample to a Universal Testing Machine (UTM) that has a capacity of 2000kN. In addition to the previous setup, the UTM is utilized to perform the tensile strength tests on the bent GFRP bars. However, in this case, the concrete block was securely fixed within the UTM using a fabricated steel cage shown in Figure 5a. The steel cage is securely attached to the bottom grip of the UTM to serve as a stable anchor within the experimental setup, ensuring no movement occurs during testing, as depicted in Figure 5a and c. This arrangement ensured the stability and proper alignment of the concrete block during testing. Moreover, the upper grip of the UTM was connected to the GFRP bar, which was encased with the steel pipe. The GFRP bar is bonded to the steel pipe with expandable grout in a similar way as with straight GFRP samples shown in Figure 4a, b. This connection ensured a reliable transfer of forces during tensile tests and maintained the integrity of the tested specimen.

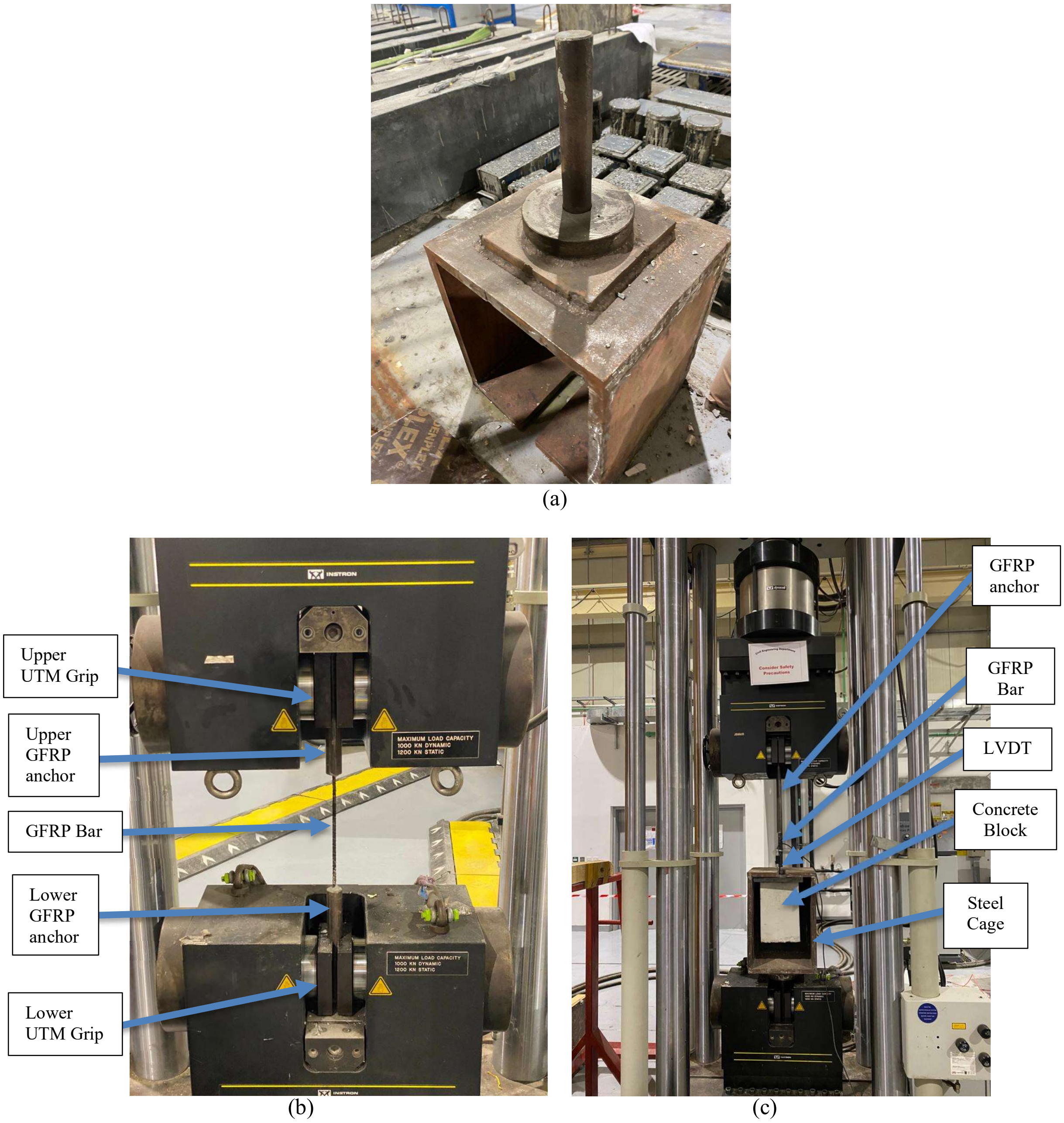


Fig. 5—(a) Steel cage (b) straight bar setup attached to the UTM (c) Bent GFRP bar setup with concrete block attached to the UTM.

RESULTS AND DISCUSSION

Table 1 presents the average ultimate loads for both straight and bent configurations of GFRP bars obtained from four different manufacturers. The determination of ultimate tensile load followed the specified procedure outlined in CSA CSA S806:21 [37] standards, and the values closely aligned with those reported by Mohamed et al. [26] for various manufacturers. However, for the bent GFRP bars, the ultimate load was assessed using CSA S807:19 Annex E [32]. Notably, all the data exhibited a reduction in ultimate load capacity in the bent portion when compared to the strength of straight GFRP bars. The reduction observed in this study was consistent with the findings reported by Mohamed et al. [26], as demonstrated in Table 1.

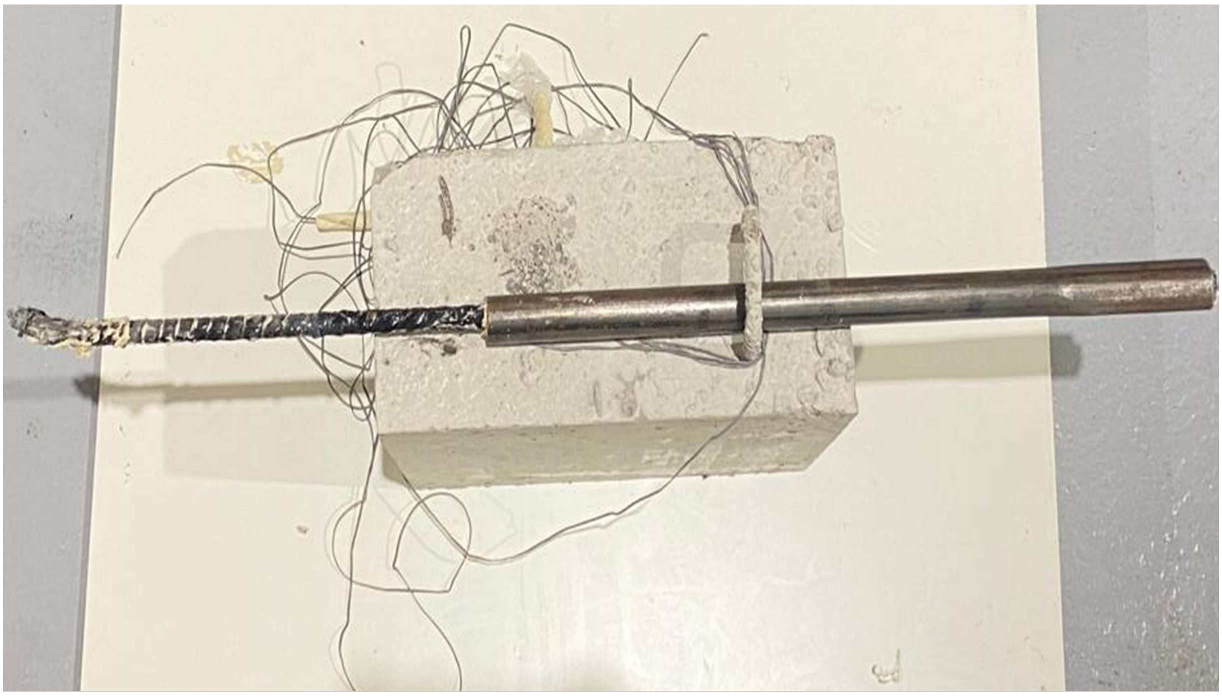
Table 1— The test results for T16 GFRP bars, tested with a concrete block of approximately 32 MPa strength.

	This study	Previous study (Mohamed et al. [26])		
	Manufacturer X	Manufacturer C	Manufacturer D	Manufacturer E
Actual cross-sectional area (mm^2)	200.60	270.87	227.30	297.51
Straight Ultimate Load (kN)	169.00	338.59	307.16	334.28
Bent Ultimate Load (kN)	53.98	132.00	125.00	134.00
Reduction (%)	68.06	61.01	59.30	59.91

The observed reduction in the ultimate load can be attributed to the fact that the fibers in the corner positions of the bent GFRP bar are subjected to shearing forces, which increases their vulnerability to breakage. This is in contrast to the straight GFRP bar, which was loaded following CSA S806:21 [37] standards, where the loading direction was parallel to the fibers and did not induce shearing forces.

Figure 6 provides a visual representation of the failure mode observed in the GFRP bent bar that underwent testing using the recommended testing procedure outlined in CSA S807:19 Annex E [32], standard. The failure of the bent GFRP specimens can be attributed to fiber rupture, specifically occurring at the bent location. This failure mode aligns with previous observations and findings documented in studies conducted by Jeremic and Sheikh [25], Mohamed et al. [26], Ahmed et al. [5] and Shehata et al. [13].

(a)



(b)

Fig. 6—Failure mode of (a) bent GFRP bar (b) bent GFRP with the concrete block.

SUMMARY AND CONCLUDING REMARKS

This study examined the strength characteristics of both straight and bent GFRP bars. The primary objective was to thoroughly explore user-friendliness and efficiency enhancements to the method proposed by CSA S807:19 Annex E. This involved reducing the block size and eliminating block confinement provided by steel stirrups. The study focused on refining CSA S807:19 Annex E [32] by reducing the width of the concrete block, which resulted in a significant reduction in the net weight of the block. L-shape FRP bars are embedded in concrete blocks cast using the concrete strength specified in CSA S807:19 Annex E [32], which achieved a compressive strength of 32 MPa after 7 days of casting. Subsequently, the specimens underwent testing to determine the tensile strength of the bent bars using a Universal Testing Machine (UTM). The bottom grip of the UTM gripped the concrete blocks with a fabricated steel cage, while the specimen was held securely using a specific steel anchor attached to the upper grip of the UTM, following the guidelines specified in ASTM7205M-16 [38]. The obtained tensile strengths of the bent bars were found to be 68.06% less than the tensile strength obtained for straight bars, followed the CSA S806:21 [37]. Additionally, the tensile strength of the straight GFRP bars closely matched the strength provided by the manufacturer. Moreover, the results of this study are compared to the findings reported by in a previous study for T16 bars, which followed CSA S807:19 Annex E [32] precisely, including the block dimensions specified in the annex. The bent strength obtained in this study closely aligned with the bent strength reported in previous studies, highlighting the effectiveness of the suggested concrete block dimensions for determining the strength of FRP bent bars in on-site applications for quality assurance and control. Future research can further investigate the application of the proposed refinement across different bar sizes and concrete strengths to enhance their applicability and reliability.

ACKNOWLEDGMENTS

The authors acknowledge financial support from the American University of Sharjah.

REFERENCES

[1] T. Maruyama, M. Honma, and H. Okamura, "Experimental study on tensile strength of bent portion of FRP rods," *Special publication*, vol. 138, pp. 163–176, 1993.

[2] T. Imjai, M. Guadagnini, and K. Pilakoutas, "Bend Strength of FRP Bars: Experimental Investigation and Bond Modeling," *Journal of Materials in Civil Engineering*, vol. 29, no. 7, p. 04017024, Mar. 2017, doi: 10.1061/(ASCE)MT.1943-5533.0001855.

[3] T. Imjai, M. Guadagnini, and K. Pilakoutas, "Curved FRP as concrete reinforcement," *https://doi.org/10.1680/eacm.2009.162.3.171*, vol. 162, no. 3, pp. 171–178, May 2015, doi: 10.1680/EACM.2009.162.3.171.

[4] L. Vint and S. Sheikh, "Investigation of bond properties of alternate anchorage schemes for glass fiber-reinforced polymer bars," *Structural Journal*, vol. 112, no. 1, pp. 59–68, 2015.

[5] E. Ahmed, *Shear behaviour of concrete beams reinforced with fibre-reinforced polymer (FRP) stirrups= Étude du comportement à l'effort tranchant de poutres en béton armé avec des étriers en polymère renforcé de fibres (PRF).* Library and Archives Canada= Bibliothèque et Archives Canada, Ottawa, 2010.

[6] S. Spadea, J. Orr, and K. Ivanova, "Bend-strength of novel filament wound shear reinforcement," *Compos Struct*, vol. 176, pp. 244–253, 2017.

[7] L. Ascione, A. G. Razaqpur, and S. Spadea, "Effectiveness of FRP stirrups in concrete beams subject to shear," in *7th International Conference on FRP Composites in Civil Engineering, CICE 2014*, International Institute for FRP in Construction, 2014.

[8] E. A. Ahmed, A. K. El-Sayed, E. El-Salakawy, and B. Benmokrane, "Bend strength of FRP stirrups: Comparison and evaluation of testing methods," *Journal of composites for construction*, vol. 14, no. 1, pp. 3–10, 2010.

[9] H. Nakamura and T. Higai, "Evaluation of shear strength of concrete beams reinforced with FRP," *Doboku Gakkai Ronbunshu*, vol. 1995, no. 508, pp. 89–100, 1995.

[10] R. Morphy, E. Shehata, and S. Rizkalla, "Bent effect on strength of CFRP stirrups," in *Proceedings of the Third International Symposium on Non-Metallic (FRP) Reinforcement for Concrete Structures*, 1997, pp. 19–26.

[11] T. Nagasaka, H. Fukuyama, and M. Tanigaki, "Shear performance of concrete beams reinforced with FRP stirrups," *Special publication*, vol. 138, pp. 789–812, 1993.

[12] C. Lee, M. Ko, and Y. Lee, "Bend strength of complete closed-type carbon fiber-reinforced polymer stirrups with rectangular section," *Journal of Composites for Construction*, vol. 18, no. 1, p. 04013022, 2014.

[13] E. Shehata, R. Morphy, and S. Rizkalla, "Fibre reinforced polymer shear reinforcement for concrete members: behaviour and design guidelines," *Canadian Journal of Civil Engineering*, vol. 27, no. 5, pp. 859–872, 2000.

[14] M. R. Ehsani, H. Saadatmanesh, and S. Tao, "Bond of hooked glass fiber reinforced plastic (GFRP) reinforcing bars to concrete," *ACI Mater J*, vol. 92, no. 4, pp. 391–400, 1995.

[15] M. L. Porter and K. Harries, "Future directions for research in FRP composites in concrete construction," *Journal of Composites for Construction*, vol. 11, no. 3, pp. 252–257, 2007.

[16] F. Elgabbas, E. Ahmed, and B. Benmokrane, "Basalt FRP reinforcing bars for concrete structures," in *Proceedings of the 4th Asia-Pacific Conference on FRP in Structures, APFIS*, 2013, pp. 11–13.

[17] H.-C. Wu and C. D. Eamon, "Strengthening of concrete structures using fiber reinforced polymers (FRP): design,

construction and practical applications," 2017.
[18] L. Van Den Einde, L. Zhao, and F. Seible, "Use of FRP composites in civil structural applications," *Constr Build Mater*, vol. 17, no. 6–7, pp. 389–403, 2003.
[19] J. Currier, C. Fogstad, D. Walrath, and C. Dolan, "Bond development of thermoplastic FRP shear reinforcement stirrups," in *Infrastructure: New Materials and Methods of Repair*, ASCE, 1994, pp. 592–597.
[20] T. Imjai, R. Garcia, M. Guadagnini, and K. Pilakoutas, "Strength degradation in curved Fiber-reinforced Polymer (FRP) bars used as concrete reinforcement," *Polymers (Basel)*, vol. 12, no. 8, p. 1653, 2020.
[21] T. Imjai, M. Guadagnini, and K. Pilakoutas, "Bend Strength of FRP Bars: Experimental Investigation and Bond Modeling," 2017, doi: 10.1061/(ASCE).
[22] C. Lee, M. Ko, and Y. Lee, "Bend Strength of Complete Closed-Type Carbon Fiber-Reinforced Polymer Stirrups with Rectangular Section," *Journal of Composites for Construction*, vol. 18, no. 1, Feb. 2014, doi: 10.1061/(asce)cc.1943-5614.0000428.
[23] E. A. Ahmed, A. K. El-Sayed, ; Ehab El-Salakawy, and B. Benmokrane, "Bend Strength of FRP Stirrups: Comparison and Evaluation of Testing Methods", doi: 10.1061/ASCECC.1943-5614.0000050.
[24] T. Imjai, M. Guadagnini, and K. Pilakoutas, "Curved FRP as concrete reinforcement," *Proceedings of the Institution of Civil Engineers-Engineering and Computational Mechanics*, vol. 162, no. 3, pp. 171–178, 2009.
[25] N. Jeremic and S. A. Sheikh, "Performance of glass fiber-reinforced polymer bent bars," *ACI Struct J*, vol. 118, no. 2, pp. 273–285, Mar. 2021, doi: 10.14359/51729349.
[26] K. Mohamed, B. Benmokrane, C. Nazair, and M.-A. Loranger, "Development and Validation of a Testing Procedure for Determining Tensile Strength of Bent GFRP Reinforcing Bars," *Journal of Composites for Construction*, vol. 25, no. 2, Apr. 2021, doi: 10.1061/(asce)cc.1943-5614.0001102.
[27] B. Benmokrane, K. Mohamed, and P. Cousin, "Performance and durability of in-plant partially cured GFRP bent bars in steam-cured precast concrete elements," *Journal of Composites for Construction*, vol. 24, no. 4, p. 04020020, 2020.
[28] Y. A. Al-Salloum, S. El-Gamal, T. H. Almusallam, S. H. Alsayed, and M. Aqel, "Effect of harsh environmental conditions on the tensile properties of GFRP bars," *Compos B Eng*, vol. 45, no. 1, pp. 835–844, 2013.
[29] F. Yan, Z. Lin, and M. Yang, "Bond mechanism and bond strength of GFRP bars to concrete: A review," *Compos B Eng*, vol. 98, pp. 56–69, 2016.
[30] M. Iqbal, D. Zhang, F. E. Jalal, and M. F. Javed, "Computational AI prediction models for residual tensile strength of GFRP bars aged in the alkaline concrete environment," *Ocean Engineering*, vol. 232, p. 109134, 2021.
[31] S. Liu, C. Bai, J. Zhang, K. Zhao, Q. Li, and G. Jin, "Experimental study on bonding performance of GFRP bars-recycled aggregate concrete under sulfate attack environment," *Constr Build Mater*, vol. 379, p. 131231, 2023.
[32] CSA S807:19 Annex E, "Specification for fibre-reinforced polymers ," Toronto, ON, Canada, 2019.
[33] A. C. Institute, "Guide Test Methods for Fiber-Reinforced Polymers (FRP) Composites for Reinforcing Or Strengthening Concrete and Masonry Structures," American Concrete Institute, 2012.
[34] ASTM D7914/D7914M, "Standard specification for strength of fiber reinforced polymer (FRP) bent bars in bend locations.," West Conshohocken, PA, 2021.
[35] S. Miyata, "Experimental study on tensile strength of FRP bent bar," *Proc. of JCI*, vol. 11, no. 1, pp. 789–794, 1989.
[36] T. Imjai, R. Garcia, M. Guadagnini, and K. Pilakoutas, "Strength degradation in curved Fiber-reinforced Polymer (FRP) bars used as concrete reinforcement," *Polymers (Basel)*, vol. 12, no. 8, p. 1653, 2020.
[37] C. S. Association, "Design and construction of building structures with fibre-reinforced polymers: CAN/CSA S806-12," *Rexdale, ON, Canada*, 2012.
[38] A. Standard, "D7205/D7205M-06,"," *Standard Test Method for Tensile Properties of Fiber Reinforced Polymer Matrix Composite Bars", ASTM International, West Conshohocken, PA*, 2016.