Journal of Engineering Science 13(1), 2022, 31 - 39
DOI: https://doi.org/10.3329/jes.v13i1.60560

JES
an international Journal

INVESTIGATION OF THE COMPRESSIVE STRENGTH OF CFRP WRAPPED NYLON FIBER REINFORCED CONCRETE CYLINDERS

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Received: 22 February 2022 Accepted: 20 May 2022

ABSTRACT

Nylon fibers are found to increase the mechanical properties of structural concrete like compressive and tensile strength when introduced into the concrete matrix by partially replacing fine aggregates. Since Nylon fibers are cheap waste materials, properly controlling their percentage into the matrix results in higher strength as well as cost control. This study discusses the compressive strength of nylon fiber induced concrete cylinders by wrapping them with 200gsm carbon fiber sheets as well as records the failure pattern, which is done by comparing the compressive strength of control specimens with sets of cylinders which are induced with nylon fiber and wrapped around with zero, one and three layers of CFRP laminates. Alongside the compressive test results, this study also reflects on several tensile tests carried out on CFRP strips which can be used as a measure to check hardener bond strengths in field. For that purpose, five coupons were prepared for flat tensile test and another five for overlap splice tensile test, stress-strain data were recorded; and the tests followed the guidelines stated in ACI code. The recorded tensile test data was found satisfactory with the recommended values for ACI 440.3R-04 and better compression capacity for cylinders were found with increasing CFRP layers.

Keywords: *Bond strength, CFRP, Flat tensile test, laminates, overlap splice test.*

1. INTRODUCTION

Retrofitting materials are used for strengthening an existing structural member, or repairing a member which has already lost its service capacity. Jacketing and plate bonding techniques, NSM FRP bars or strips, textile reinforcing using glass, aramid, polyethylene and carbon fiber fabrics etc are famous retrofitting measures available for concrete members. Among these, Carbon Fiber Reinforced Polymer (CFRP) sheets are extensively used for their relatively cheaper expense and easy application. CFRP sheets can be attached to any concrete surface with minimal priming, and lesser amount of maintenance or supervision is required. The bond strength and mixing of saturants play a vital role in this process as well as the curing period for both priming and hardening are relatively short. If the compressive force that can be sustained by substrate concrete members when subjected to carbon fiber laminates can be predicted beforehand, then the structures can be overloaded beyond the actual concrete compressive strength (Mostofinejad & Moshiri, 2015). Also if the members are subjected to tensile forces; measuring the fiber bond strength under tensile loading similar predictions can be made.

American Concrete Institute (ACI 440.3R) has explicit guidelines for FRPs intended for retrofitting and strengthening of concrete members. Subsection L.2 and L.3 are dedicated directly for the test methods of flat tensile test and overlap splice tensile test specimens. Test specifications, coupon size, preparation guideline of wet layup materials etc are clearly indicated there. (Hou and Ruiz 2000) tested strength properties of woven CFRP T300/914 under different strain rate. Their results indicated linear elastic properties in both zero and ninety degree directions. Under tension, the specimens remained virtually linear elastic up to failure, and Plastic deformation occurred before total failure in compression tests. Tensile tests on [±45] specimens gave non-linear stress strain curves. Studies were also conducted with tensile and lap splice properties of CFRP sheets under varying temperature range (Cree et al. 2015), and CFRP bars as well (Aly et al. 2006). Tab materials for tensile testing of CFRP laminates were also determined using combination of digital image correlation and acoustic emission techniques (Tabrizi et al. 2019). On the other hand, FRP confinement of concrete cylinders were undertaken and compressive strengths were determined by various researchers, and idealization for design

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ISSN 2075-4914 (print); ISSN 2706-6835 (online)

oriented stress strain curve were also conducted (Lam and Teng 2003), (Benzaid et al. 2010), (Ozbakkaloglu et al. 2013).

Various other properties of members-either cylindrical or rectangular in shape was investigated by researchers. In a study, isogrid cylindrical shells were fabricated and wrapped with CFRP and their static compression test was checked against the numerical ones using FEM approach (Sakata and Ben 2012). Again, both static and dynamic properties of CFRP epoxy laminates were investigated to check the effects against blast loading and other high impact loads (Zhang et al. 2016). They investigated the application of a CFRP wrapped unidirectionally over a wide range of strain set. Confinement of brick masonry columns with CFRP laminates also suggested strong increase of substrate ultimate load, stiffness and ductility (Corradi et al. 2007). They utilized monodirectionally wrapped CFRP sheets on 24 clay solid brick columns to determine the effects of FRP reinforcement systems where two widely diffused types of masonry columns having differing square cross-sections were tested for compression. But there are lesser studies on cost effective field testing of supplied CFRP laminates and plates where they can be used without overstressing the substrate concrete. Since the effectiveness of any bonded FRP system is dependent on the soundness and tensile strength of both the substrate and the FRP system, as well as there are fewer investigations to prescribe tensile and compressive strength of FRP sheets numerically, a prior assessment of the tensile and compressive strength of the supplied FRP system beforehand of application is required to avoid unwanted cases of overloading in site. Discrete fibers such as Nylon (polyamide 6.6), are found to increasing durability of the concrete in deleterious environment with the presence of supplementary cementitious materials (Samrose and Mutsuddy 2019). Introducing nylon fibers in concrete matrix at certain ratio increases compressive, split tensile and flexural strength (Ali et al. 2003). (Brugo et al. 2017) tried to interleave fibers into CFRP laminates and could efficiently control rate of delamination and crack propagation. Based on these previous studies on CFRP properties, this research has made an attempt to monitor the strength response of Nylon fiber induced concrete while subjected to CFRP lamination as well as measuring the bond strength of CFRP fabric laminates.

2. SPECIMEN PREPARATION

The impregnated epoxy or hardener (locally known as saturant), which is an important latex for retrofitting the yielded frames with CFRP, needs to be tested for bond strength before field application. Two types of tests were chosen for monitoring the supplied resins bond strength- flat tension test and overlap splice tensile test. Five coupons were prepared for flat tensile test and five others were prepared for overlap splice test. The supplied CFRP material has the following specifications besides the technical advantage of high strength, flexibility, non-corrosiveness, high alkalinity and lightweight. Properties of the supplied CFRP materials are cited in Table 1.

Table 1: Properties of the supplied CFRP material (Source: Fidstrong-Luckfid Industry Co. Ltd; Shanghai, China. Web: www.fidstrong.com).

Color	Black
Woven	Unidirectional
Areal weight	$200 g/m^2$
Fiber content	100%
Dry fiber tensile strength	5800 MPa
Composite Tensile Strength	4000 MPa
E Modulus	240 GPa
Thickness	0.111mm
Elongation at break	1.60%
Density	$1.8 g/cm^3$
Length/ roll	100m
Width Package	60cm

For flat tensile test's laboratory preparation of wet layup materials, guidelines prescribed in ACI 440.3R section L.2 was rigorously followed. It consisted of a plastic sheet placed on a smooth, flat horizontal surface and resin was coated onto the film. The FRP fabric or sheet material was placed into the resin and additional resin was overcoated. This process was repeated for multiple plies with the help of a grooved roller used to work out trapped air. A second plastic sheet was placed over the assembly. Using the flat edge of a small paddle, excess resin was forcibly pushed out of the laminate with a screeding action in the fiber direction. The laminate was cured without removing the plastic. The sample size was 25mm wide and 12 inches long with three consecutive FRP straps with splayed resin. After a sample sandwich of FRP prepared, it underwent for trial run in a universal testing machine. The ultimate load and stress was recorded in the dial gauge. Also, for overlap splice tension test, ACI 440.3R's section L3 guidelines was used. The sample preparation process is same as of flat tensile test, except an overlap splice of 25mm was made between consecutive samples. The sample preparation and testing procedure is shown in Figure 1. The displacement data recorded is the sample displacement, occurring predominantly due to debonding or side splitting. Probable failure modes found in research are (source: ACI 440.3R)-

• Delamination/debond—The failure is a generally clean separation at the overlap interface.

• Tension failure—Specimen fails outside of overlap splice at representative single laminate strength and not within or adjacent to either of the grips.

• Splitting—Specimen fails along entire length, leaving portions of overlap bond intact.

• Tab failure—A significant proportion of failures within one specimen width of the tab should be cause to re-examine the tab material and configuration, gripping method and adhesive, and to make necessary adjustments to promote failure within gage length of specimen.

(a) (b)

Figure 1: (a) Preparation and (b) Testing of Flat tensile and overlap splice coupons.

The test followed the testing procedure described on ASTM C39/C39M-20 (C09 Committee n.d.) guidelines for testing of cylinder compressive strength. For the purpose of monitoring the post yield and pre-yield behavior of 28 day old concrete cylinders; testing was done by wrapping the cylinders with CFRP. Four sets of cylinders were present: one set contains no presence nylon fiber in concrete matrix, one set with nylon fiber present and no layer of CFRP wrapping, one set having nylon fiber present and one layer of wrapping and the final set has three layers of CFRP laminates. After monitoring the conditions of NFRC cylinders after they reached their capacity, need for impregnating them with resin and mono layer fiber was assessed to observe if their post-yield behavior could be modified. The w/c ratio was kept 0.42. The unit weight of local sand used was kept 43.3 kg/cft and stone chips used was 44.64kg/cft. Measured slump was found to be 4.5 inches (true slump). Mold shapes used for cylinders were 4″ x 8″, and the mix ratio was maintained 1:1.5:3 for cement, local sand and stone chips. The mix design is detailed with corresponding material weight in Table 2. Nylon fibers were induced in the concrete matrix to prevent early age micro cracking (Khan and Ali 2016) and develop fatigue resistance (Lee et al. 2005); i.e. durability. These nylon fibers were slightly lighter than water (specific gravity 1.14) and the fiber content chosen was 0.1%. To ensure proper workability, conplast SP-337 superplasticisers were used according to recommended dosage. After 28day curing, the cylinders were taken out of water bath and surface dried. Nodules, protrusions, etc if found, was cleared. Fabric was cut with heavy duty scissors having splits of 13 inches width and 8 inches height. The usage of dull or worn cutting implements was avoided to prevent fiber weakening or fraying. Prior to placing the fabric, concrete cylinders were primed with FSE302 (Primer Epoxy) by spraying, brushing or rolling and waited until the resin is slightly tacky.

The package of CFRP contained two primer mixes (A & B-designated FSE302) and two impregnated epoxy mixes (FSE 322). Both were mixed with a ratio of 2:1 for three minutes until the color is even. Then when the primer has dried off, the impregnated epoxy was pasted over the primer. The drying period by primer is usually six hours, then the hardener was mixed and applied.

(a) (b)

Figure 2: (a) Wrapping the concrete cylinders with CFRP fabrics (b) Prepared CFRP induced cylinders.

After 28 days and a curing period for setting of the hardener, the cylinders were tested in UTM for compressive strength as per guidelines prescribed in ASTM C39. Cylinder sets were designated as following:
Concrete cylinders with no nylon fiber presence and no CFRP laminates = 0F0
Concrete cylinders with 0.1% nylon fiber and no CFRP laminates = 0F0.1
Concrete cylinders with 0.1% nylon fiber and one layer of CFRP laminates = 1F0.1
Concrete cylinders with 0.1% nylon fiber and three layer of CFRP laminates = 3F0.1

Table 2: Mix design of the cylinders intended for compression test.

Fiber content (%) and mix ratio	Material required	Volume (cm3)	Weight (gm)
0.1% of cement weight 1:1.5:3	Cement	299.38	3806.06
	Sand	449.07	6180.09
	Coarse Aggregate	898.13	12742.69
	Nylon fiber	1.65	16.91
	Water	-	1598.55

3. RESULTS AND DISCUSSIONS

The results of the tests performed were split into major two sections: tensile test coupons (flat tensile and overlap splice) and compressive test specimens (cylinders with/without CFRP). The first section consists of load-deflection scenario and failure criterion; while the later one contained compressive strength of cylinders followed by their corresponding failure pattern.

3.1 Results of Tensile Test Coupons

For five tensile test specimens, the corresponding recorded load vs deflection scenario is provided below in Table 3; and for five overlap splice tensile test specimens, the corresponding recorded load vs deflection data is provided below in Table 4.

Table 3: Load vs Deflection scenario of loaded flat tensile coupons.

Sample number	Maximum Load sustained (kN)	Maximum Deflection (mm)
01	32.2	15.36
02	31.98	15
03	33.29	15.36
04	29.42	14.62
05	27.27	17.06

Table 4: Load vs Deflection scenario of loaded Overlap Splice tensile coupons.

Sample number	Maximum Load sustained (kN)	Maximum Deflection (mm)
01	2.31	50.87
02	24.67	17.26
03	33.3	21.93
04	38.05	19.07
05	1.21	35.78

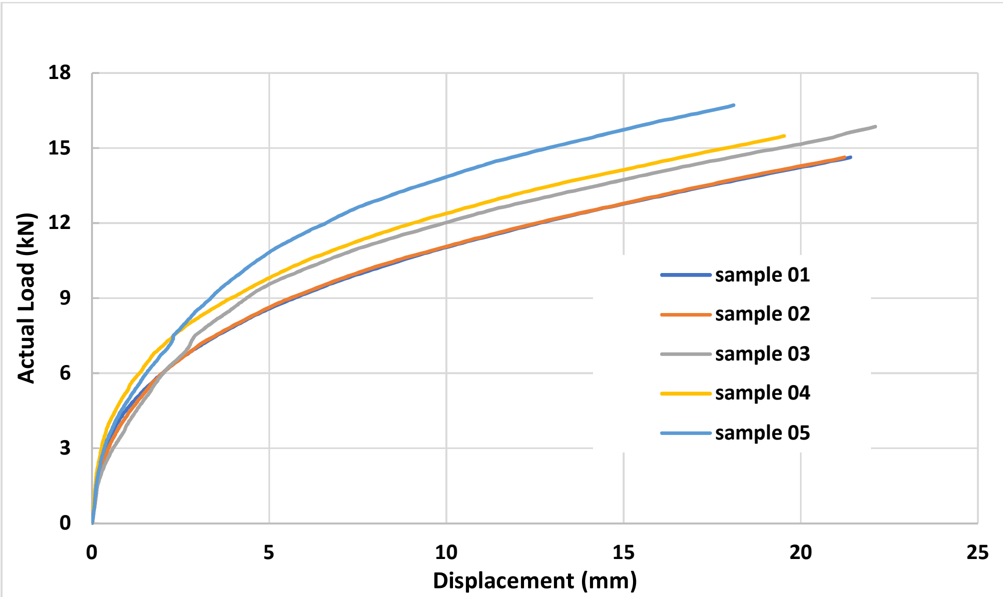

Figure 3: Combined load vs deflection curve for all flat tensile coupons.

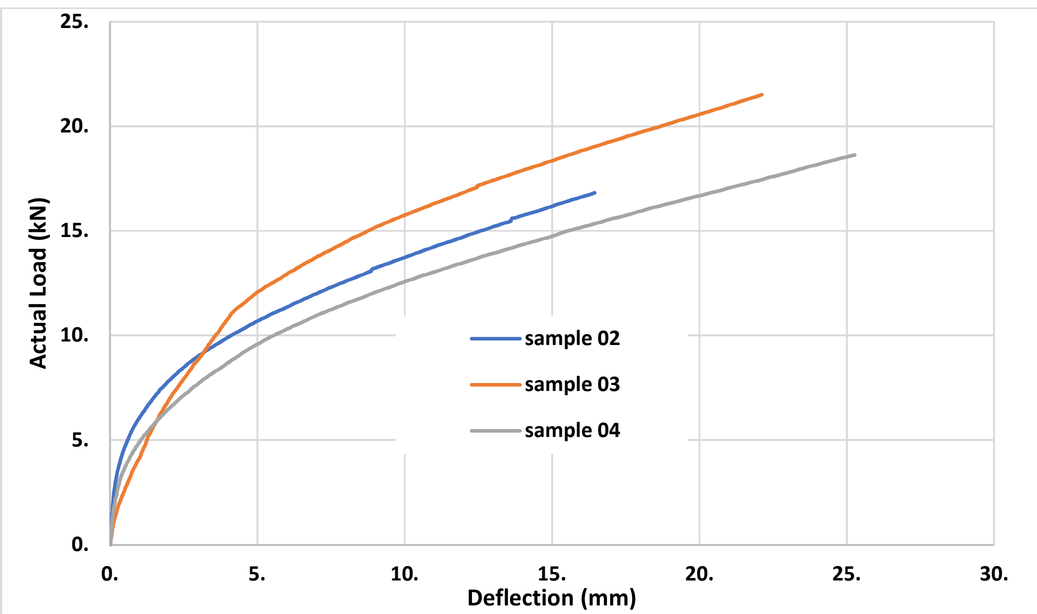

Figure 4: Combined load vs deflection curve for all overlap splice tensile coupons.

From the registered load deflection data in Figure 3 and Figure 4 it is evident that all of the samples showed nonlinear ductile characteristics under static increasing load. Sample 01 and 05 of overlap splice tensile coupons did a slip failure, so their load-deflection characteristics were not included in the graph. Loads were multiplied with correction factor for to obtain actual load-deflection statistics. Average ultimate load was found out to be 30.82 kN, and all specimens showed almost similar yielding characteristics. Code specified minimum bond strength 5.5 MPa, where for sample strength, (1inch width = 25.4mm, 2mm thick) becomes 606 MPa, so sample sustains in required strength. And for overlap splice coupons it was found that coupons failed due to debonding between laters, while splice region was unyielded. Also it can be seen that since average strength of overlap splice samples is 19.91 kN, and cross section area bearing the same as flat tensile coupons, the debonding stress is 391 MPa which is greater than code specified minimum code strength. Failure criterion of all samples is summarized below in Table 5.

Table 5: Failure criterion of Flat tensile and overlap splice coupons.

Flat tensile coupon 01:	Side splitting
Flat tensile coupon 02:	Side splitting
Flat tensile coupon 03:	Side splitting
Flat tensile coupon 04:	Side splitting
Flat tensile coupon 05:	Side splitting
Overlap splice coupon 01:	Plastic response after debonding starts, no splice failure, shear among layers and slip
Overlap splice coupon 02:	gradual crack development along plastic layer, tear of plastic and bursting of side
Overlap splice coupon 03:	tear of plastic, bursting of side with explosive sound, lap splice unharmed
Overlap splice coupon 04:	complete failure, splitting of plastic cover, debonding and total disintegration of layers
Overlap splice coupon 05:	cover splitting

Figure 5: Typical failure pattern of flat tensile and overlap splice coupons.

3.2 Results of Compression test of Cylinders (As per ASTM C39)

The normal concrete cylinders yielded after reaching estimated crushing strength. Wrapping the cylinders with CFRP layers had increased the yield strength to a high magnitude (almost 3/4 times). At first the 800kN capacity machine was used for testing the cylinders with FRP layers, but since increasing CFRP layers had induced large crushing strength within the cylinders, for those with multiple layers of CFRP was shifted to a 2000kN capacity machine. Attaching one layer of FRP initiates heavy confining stress which had increased the resistance against compression several times, while attaching three layers had shifted concrete behavior from brittle to large ductile attitude. The cylinders had started to sustain extremely high loads before coming down to collapse with high splitting sound. The corresponding capacities of different cylinders are stated in Table 6.

Table 6: Average Compressive Strengths sustained by Cylinder sets in accordance with presence of CFRP layers.

Cylinder labels	Sample number	Ultimate capacities (MPa)	Average Compressive strength (MPa)
	01	20.66	
0F0	02	19.47	20.13
	03	20.26	

Cylinder labels	Sample number	Ultimate capacities (MPa)	Average Compressive strength (MPa)
	01	22.22	
0F0.1	02	25.92	24.19
	03	24.44	
	01	61.72	
1F0.1	02	60.49	58.92
	03	54.56	
	01	98.38	
3F0.1	02	119.24	114.92
	03	127.14	

Observing the compressive strengths of different layers of wraps and presence of nylon fibers, it can be seen that when nylon fiber was introduced into the mix, the average compressive strength of cylinders rose from 20.13 MPa to 24.19 MPa, indicating a 1.20 times rise of average strength. This can be attributed to nylon fibres capacity to improve mechanical properties of concrete when introduced into them. After the nylon fiber induced cylinders were wrapped with CFRP, this rise was significantly visible. Wrapping cylinders with a single layer of FRP had yielded average strength of 58.92 MPa and cylinders with three layers of wrap is 114.92 MPa. So wrapping a cylinder with one layer of CFRP had increased the average strength of NFRC 2.44 times and with three layers the strength increment is almost 4.75 times. Cylinders had started to intake large amount of loads due before failure due to their heightened stress absorbing capacity due to heavy confining strength provided by FRP plastics. From the graph provided below, it can be seen that for two layers the average compressive strength became around 85 psi, which is 3.5 times enhancement of the strength provided by no CFRP layers, and 1.44 times increment from one layer CFRP. Adding another layer had yielded 1.35 times strength enhancement. So it can be seen that adding one single layer of CFRP enhances the concrete strength hugely, and for practical purposes, to retrofit a concrete member under compressive stress or to strengthen an already performing concrete member under service loading, one layer of CFRP with surface priming and added hardener is recommended.

By observing the failure patterns from Figures 6 and 7, it can be seen that with increasing layers of FRP wrapped around the cylinders, the failure pattern had shifted from splitting or shear/crushing failure to de-bonding of FRP layers by barreling effect then crushing. This type of failures that happen in those which are confined by CFRP layers, are mainly instigated by hoop tension stress that is caused by the wrapping CFRP layers in the negative direction by preventing the cylinders to collapse and assisting it to sustain a larger load. This hoops can be concentrated at the central zone of the cylinder specimens. The width of the hoop section determines the concrete section that remains attached with the inside face of delaminated CFRP. The failure patterns and compressive strength seem consistent with the results observed in the studies of (Benzaid et al., 2010).

(a1) (b2) (c3) (a2) (b2) (c2)

Figure 6: Sample control cylinders (consecutive failure types: (a1) shear (b1) side fracture at bottom (c1) Cone and Shear; Cylinders wrapped with one layer of CFRP (a2) (debonding of laminate) (b2) explosive (c2) crushing of concrete and fiber debonding.

Figure 7: Failure pattern of cylinders wrapped in three layers.

Table 7: Failure types of concrete cylinders induced with nylon fiber and wrapped with various CFRP layers.

Cylinder Designation	Failure Type
0F0.1 Sample 01	Shear failure
0F0.1 Sample 02	Side fracture at bottom
0F0.1 Sample 03	Cone and Shear
1F0.1 Sample 01	Debonding of laminate
1F0.1 Sample 02	Explosive or bursting of concrete
1F0.1 Sample 03	Crushing of concrete with delamination of fiber sheets from surface
3F0.1 Sample 01	Debonding from fiber sheets
3F0.1 Sample 02	Detachment of fiber laminates from primed concrete surface in the maximum hoop stress region
3F0.1 Sample 03	Detachment of fiber laminates from primed concrete surface in the maximum hoop stress region

4. CONCLUSIONS

The study results shows a constant rise in the capacity of nylon fiber cylinders after introducing layers of CFRP fabric wrappings around it, as well as tested epoxy bond capacity with FRP laminates by flat tensile and overlap splice coupons. Introducing one layer of CFRP showed a steep rise, and the rate of gain was slow with additional layers of laminates. It can be said that if a fourth layer was introduced, the rate would not vary much from the third one and failure would have been a complete debonding failure (separation from concrete surface). Finally, a guideline for field test of CFRP bond strength of hardeners was completed by performing tensile tests and overlap splice tensile tests. The specimens which satisfied the prescribed behavior in ACI codes were accepted and those which did not rejected. By performing these tests, users of CFRP can be ensured of their material quality before applying it on their structural members.

REFERENCES

Mostofinejad, D., & Moshiri, N. (2015). Compressive Strength of CFRP Composites Used for Strengthening of RC Columns: Comparative Evaluation of EBR and Grooving Methods. Journal of Composites for Construction, 19(5), 04014079. https://doi.org/10.1061/(ASCE)CC.1943-5614.0000545

ACI 440.3R-04 Guide Test Methods for Fiber-Reinforced Polymers (FRPs) for Reinforcing or Strengthening Concrete Structures. Page 30-36.

Ali, A., Aijaz, A., Arsalan, M. "a study on nylon fibre reinforced concrete by partial replacement of cement with metakaolin : a literature review." International Research Journal of Engineering and Technology (IRJET) Volume: 05 Issue: 03 Mar-2018 05(03), 3 ISSN: 2395-0072. DOI: https://doi.org/10.35337/ejasr.2020.v02i04.006

Aly, R., Benmokrane, B., and Ebead, U. (2006). "Tensile Lap Splicing of Bundled CFRP Reinforcing Bars in Concrete." Journal of Composites for Construction, American Society of Civil Engineers, 10(4), 287–294. DOI: https://doi.org/10.1061/(asce)1090-0268(2006)10:4(287)

Benzaid, R., Mesbah, H., and Chikh, N. E. (2010). "FRP-confined Concrete Cylinders: Axial Compression Experiments and Strength Model." Journal of Reinforced Plastics and Composites, SAGE Publications Ltd STM, 29(16), 2469–2488. DOI: https://doi.org/10.1177/0731684409355199

Brugo, T., Minak, G., Zucchelli, A., Yan, X. T., Belcari, J., Saghafi, H., and Palazzetti, R. (2017). "Study on Mode I fatigue behaviour of Nylon 6,6 nanoreinforced CFRP laminates." Composite Structures, 164, 51–57. DOI: https://doi.org/10.1016/j.compstruct.2016.12.070

C09 Committee. (n.d.). Test Method for Compressive Strength of Cylindrical Concrete Specimens. ASTM International. DOI: https://doi.org/10.1520/c0039_c0039m

Corradi, M., Grazini, A., and Borri, A. (2007). "Confinement of brick masonry columns with CFRP materials." Composites Science and Technology, 67(9), 1772–1783. DOI: https://doi.org/10.1016/j.compscitech.2006.11.002

Cree, D., Gamaniouk, T., Loong, M. L., and Green, M. F. (2015). "Tensile and Lap-Splice Shear Strength Properties of CFRP Composites at High Temperatures." Journal of Composites for Construction, American Society of Civil Engineers, 19(2), 04014043. DOI: https://doi.org/10.1061/(asce)cc.1943-5614.0000508

Hou, J. P., and Ruiz, C. (2000). "Measurement of the properties of woven CFRP T300/914 at different strain rates." Composites Science and Technology, 60(15), 2829–2834. DOI: https://doi.org/10.1016/s0266-3538(00)00151-2

Khan, M., and Ali, M. (2016). "Use of glass and nylon fibers in concrete for controlling early age micro cracking in bridge decks." Construction and Building Materials, 125, 800–808. DOI: https://doi.org/10.1016/j.conbuildmat.2016.08.111

Lam, L., and Teng, J. G. (2003). "Design-oriented stress–strain model for FRP-confined concrete." Construction and Building Materials, Fibre-reinforced polymer composites in construction, 17(6), 471–489. DOI: https://doi.org/10.1016/s0950-0618(03)00045-x

Lee, S. J., Rust, J. P., Hamouda, H., Kim, Y. R., and Borden, R. H. (2005). "Fatigue Cracking Resistance of Fiber-Reinforced Asphalt Concrete." Textile Research Journal, SAGE Publications Ltd STM, 75(2), 123–128. DOI: https://doi.org/10.1177/004051750507500206

Ozbakkaloglu, T., Lim, J. C., and Vincent, T. (2013). "FRP-confined concrete in circular sections: Review and assessment of stress–strain models." Engineering Structures, 49, 1068–1088. DOI: https://doi.org/10.1016/j.engstruct.2012.06.010

Sakata, K., and Ben, G. (2012). "Fabrication method and compressive properties of CFRP isogrid cylindrical shells." Advanced Composite Materials, Taylor & Francis, 21(5–6), 445–457. DOI: https://doi.org/10.1080/09243046.2012.743711

Samrose, S., and Mutsuddy, R. (2019). durability of nylon fiber reinforcement concrete. Conference: International Conference on Disaster Risk Management, March 2019

Tabrizi, I. E., Khan, R. M. A., Massarwa, E., Zanjani, J. S. M., Ali, H. Q., Demir, E., and Yildiz, M. (2019). "Determining tab material for tensile test of CFRP laminates with combined usage of digital image correlation and acoustic emission techniques." Composites Part A: Applied Science and Manufacturing, 127, 105623. DOI: https://doi.org/10.1016/j.compositesa.2019.105623

Zhang, X., Hao, H., Shi, Y., Cui, J., and Zhang, X. (2016). "Static and dynamic material properties of CFRP/epoxy laminates." Construction and Building Materials, 114, 638–649. DOI: https://doi.org/10.1016/j.conbuildmat.2016.04.003

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