A State of the Art Use of FRP in Prestressed Concrete Structures

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***Abstract*— The corrosion of steel reinforcement in concrete and the resulting deterioration of structures prompted research on fiber reinforced polymers (FRP) as potential reinforcement for concrete members, for use in new construction. Looking to the known appropriate properties of FRPs like their high tensile strength, noncorrosive, lightweight, and nonmagnetic nature, FRP composites are being used as reinforcement in concrete. In the developed countries, FRPs are used in many applications like repair and rehabilitation works, anchors for slope stabilization, MRI units of hospitals, road side barriers, and high-speed linear motor railway tracks, where as in developing countries, it's use is slowly started. Now a days, extensive research is going on worldwide for the use of FRPs in prestressed concrete structures. Hence a detailed survey is carried out limited to FRPs particularly used for prestressed concrete construction only. An attempt has been made in this paper to provide a comprehensive review of the FRPs technology developed so far, ongoing research in the related areas and future need.**

***Index Terms*--About four, alphabetical order, key words or phrases, separated by commas. *Abstract*--These instructions**

I. Introduction

THE term Fiber Reinforced Polymer (FRP) refers to the technology whose goal is to make structures noncorrosive, lightweight and nonmagnetic. Various shapes of the FRPs like strips, plates, rods and tendons or strands are used for different applications. This paper reviews the class of structural material which has been used since the 1930s but recently has won the attention of engineers to be used as a main structural component [1].

A. Requirement of FRPs

Over the past years corrosion of steel reinforcement has resulted in enormous maintenance costs especially in bridges. Engineers, researcher and authorities were looking for possible improvements to reduce or even eliminate corrosion of embedded reinforcement in concrete structures. Aggressive atmosphere and subsoil water increases the risk of corrosion of embedded reinforcement in concrete. The situation is more dangerous for prestressing tendons in thin elements. Deterioration of highway concrete bridges due to corrosion has a developing tendency which results in necessity of frequent structural diagnosis and high maintenance costs. Structural engineers dealing with durability of concrete are greatly concern about possibility of improving service life of embedded reinforcements. This realization obviously prompted the desire to use noncorrosive materials such as FRP, especially in environments where steel has been shown to be vulnerable [2].

Primary benefits of the FRPs are high strength-to-weight ratio, favorable fatigue strength, electro-magnetic transparency and low relaxation characteristics when compared with steel reinforcement, offering a structurally sound alternative in most applications. However, FRP reinforcement shows linear stress–strain characteristics up to failure, without any ductility [3].

B. History of FRPs

The earliest FRP materials used glass fiber embedded in polymeric resins that were made. The combination of high-strength, high-stiffness structural fiber with low-cost, lightweight, environmentally resistant polymers resulted in composite materials with mechanical properties and durability better than either of the constituents alone. Fiber materials with higher strength, higher stiffness, and lower density, such as boron, carbon, and aramid, were introduced for space exploration, air travel and sporting goods. On the other hand for the application of FRPs in concrete engineering, properties like creep, fatigue, and modulus of fracture have been observed. Efforts have been made to check the performance level of FRPs used as a reinforcing material in reinforced and prestressed concrete construction, strengthening and retrofitting works [1].

This paper makes the following contributions. Section II provides the details of composition, types and mechanical properties of FRPs. Section III provide the details of anchor devices for FRPs used in prestressed concrete structures. Section IV provides the details of various design and serviceability criteria of FRPs as reinforcing material. Section V gives the details of life cycle cost analysis of structures using FRPs. In section VI status FRPs in India is discussed. Section VII gives the details about further research needs. Finally, section VIII gives the concluding remarks of the survey work.

II. Fiber Reinforced Polymer Materials

As against short fiber of steel continuous long fiber are used as a replacement to improve the tensile strength and post cracking behavior of the brittle concrete matrix for reinforced and prestressed concrete construction. In continuous FRP composites extremely fine fiber are embedded in a matrix. The volume fraction of the fiber in commonly available FRPs ranges from about 50 to 65%. Properties of FRP composite products are related to the properties of the fiber used, the properties of the matrix used, and volume fraction of the fiber.

A. Constituent Fibers

Fibers made from carbon, aramid, glass, and polyvinyl alcohol are commonly used for the manufacture of FRP. It is observed that though all the fiber exhibit a higher tensile strength than steel, the elongation of the fiber is found very less before the material fails. Fig. 1 gives a diagrammatic representation of the stress-strain curves for some commonly used FRP composites. Range of tensile modulus of the fibers is 70 to 800 GPa and ultimate elongation is 0.3 to 5 %. Resin materials for FRP reinforcements are usually epoxy and polyster resins. Resins does not carry any tensile load directly, it acts as a filler material and holds the fiber together and also play a crucial role in transferring the load and protecting the fiber [1].

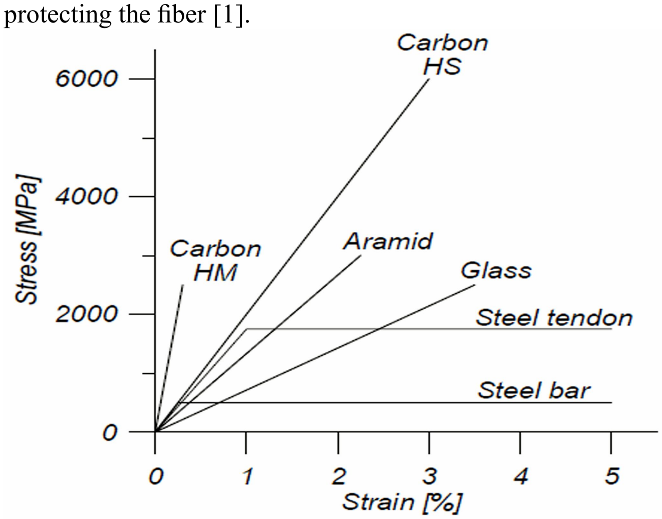

Fig.1 Stress vs. Strain diagram for fibers and steel.

B. Types of Fibers

Carbon: Carbon fibers do not absorb water, resistant to many chemical solutions, withstand fatigue excellently, does not stress corrode, do not show any creep, having less relaxation. Carbon fiber is electrically conductive and, therefore, might give galvanic corrosion in direct contact with steel.

Glass : Glass fibers are sensitive to stress corrosion at high stress levels and may have problems with relaxation. Glass fibers are sensitive to moisture, but with the correct choice of matrix the fibers can be effectively protected.

Aramid : Aramid has a high fracture energy and is therefore used for helmets and bullet proof garments. Aramid fibers are sensitive to elevated temperatures, moisture and ultra violet, hence proper matrix is required [6].

C. Properties of FRP reinforcement

Due to inhomogenenity of composite material FRP reinforcement have different mechanical properties than that of steel reinforcements. Fibers define longitudinal characteristics of FRP, however, characteristics in transverse direction are considerably influenced by the matrix as well.

Tensile strength and young's modulus : These properties are mainly depending on the type of fibers, the volumetric ratio of fibers, the angle between load carrying fibers an longitudinal axis of reinforcement, the shape of the cross section, diameter and the resin matrix. It has linear elastic behavior up to failure without any plasticity. Table 1 summarizes available data on tensile characteristics of CFRP tendon.

Relaxation: Nedri has tested a 7 mm diameter CFRP strand with the initial prestress of 48.58 kN at 20˚C for 1000 hours. Test result has shown that the final relaxation observed is 1.22% [7].

Creep: Creep strain increase of CFCC strands under a stress of $0.65f_{fu}$ for 1000 hours at 22˚C experimental results found to be a negligible strain increase can be observed as 0.0068%, where f_{fu} is the initial tensile strength of tendons.

Thermal characteristics: Thermal actions can influence both mechanical characteristics and bond behavior of FRPs. Coefficient of thermal expansion of different fibers, resins for FRPs and concrete can be referred as in [5].

Durability: FRPs needs to be resistant to alkaline environment and UV radiation in case of internal and external reinforcement respectively. Various tests are carried out using FRP rods to study the static fatigue fracture, alkali resistance, ultraviolet ray resistance, freeze-thawing resistance, high temperature and fire resistance. The comparative results can be referred in [5]-[8].

TABLE 1
TENSILE CHARACTERISTICS OF CFRP TENDONS

Brand Name	Nominal Diameter (mm)	Tensile Strength (MPa)	Young's Modulus (GPa)	Ultimate Strain (%)
Leadline	8	1876	147.0	1.28
	8	2911	163.3	1.78
CFCC	12.5	2280	137.0	1.66
	15.2	2140	137.0	1.56
	7.5	2255	134.0	1.68
Bri-Ten	5	2350	134.3	1.75
Nefmac	-	1800	92.3	1.95
Eurocrete	8	1200	90 to 110	-
Carbon	-	2400	160.0	1.50
Stress	-	3000	158.0	1.9
Carbopree	16	2300	115.0	2.0

III. ANCHOR DEVICES

Mainly two techniques are used for anchorage of the FRP tendon: Bonding and friction. Bonded anchors keep the tendon in place through plain adhesion between the adherent and adhesives, while the friction anchor is a mechanical anchor, which uses compression force and, through this, friction to grab the tendon.

A. Straight Sleeve Anchorage (SSA)

SSA is composed of an outer sleeve filled with the bonding agent and the inserted tendon [10]. The bond strength mainly depends on the properties of the bonding agent-cement grout, the geometry and surface conditions of the tendon, and the radial stiffness of the confining medium [22]. Harada has shown that expansive cement generates significant lateral pressure and increases the slipping resistance of the tendon. The internal radial pressure of 25 to 40 MPa is adequate for gripping FRP tendons [16].

Jose A. Pincheira and John P. Woyak [12] have done test on three different procedures for attaching the sleeves to the rods. Specimens with resin-filled, epoxy-bonded, or swaged sleeves are prepared. It is observed that the strength and failure mode of the resin filled and epoxy bonded sleeves varied widely and are sensitive to the preparation of the specimen. In contrast, specimens with swaged sleeves showed dependable strengths and consistent failure modes.

B. Contoured Sleeve Anchorage (CSA)

The principal difference between the two systems is the varied profile of the inner surface of the contoured sleeve, which may be linearly tapered or parabolically tapered. The load-transfer mechanism from the tendon to the sleeve is by interface shear stress, which is a function of bonding, and radial stress produced by the variation of the potting material profile. Kim and Meier developed a variable stiffness anchorage for FRP tendons [16]. Schmidt J.W. & Täljsten B. [10] have worked on this and concluded the need for further improvement of the system.

C. Clamp Anchorage (CA)

CA consist of two rectangular steel plates, a sleeve (mostly aluminum or copper) and clamping bolts. Each steel plate is manufactured with a circular longitudinal notch at one side and holes for the bolts. The aluminum sleeve is made thin with slits along the part clamped in the anchorage. A short section of the sleeve is left without slits to hold the parts together; this part is named the sleeve head and should be positioned on the outside of the plates when they are clamped [11].

D. Split-wedge anchorage (SWA)

Split-wedge anchorage generates a clamping force around the tendon by pushing or pulling wedges into a conical barrel. SWA are widely used in anchoring steel tendons but should be modified for use with FRP tendons by increasing their length to reduce transverse stress on the tendon and controlling roughness in the wedge to prevent notching the tendon. A small tapered wedge is of great importance to provide a smooth and uniformly distributed transverse stress. To improve the efficiency work has been done by Jacob W. Schmidt, Anders Bennitz, Björn Täljsten and Henning Pedersen [12],[18].

A. Al-Mayah, K. Soudki, and A. Plumtree [21] have done static load tests, the effect of presetting loads, usage history, and sleeve material are investigated. Cyclic load tests are conducted on anchors using aluminum sleeves with a presetting load. A finite element model, consisting of three contact surfaces, is applied to simulate the anchor components; the displacement of the rod compared well with experimental results.

Giovanni Pietro Terrasi, Christian Affolter, and Michel Barbezat [19] have achieved optimized design by means of FE analysis, in which parametric studies are complemented with extensive experimental work for validation. Analytical results demonstrated a reduction up to 25% for the relevant stress peaks in the tendons. The static rupture load under laboratory conditions increased by 25%, and pretensioning level on-site could be increased by 50%.

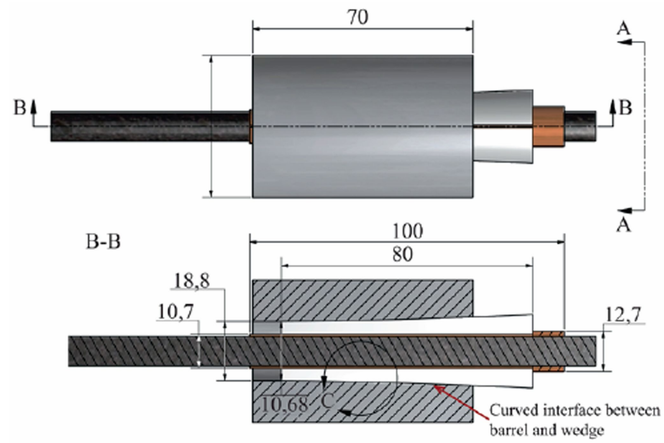

Fig. 2 Geometrical configuration of wedge anchorage with longitudinal curved wedge

Anders Bennitz and Jacob W. Schmidt, Prof. Björn Täljsten [20] have identified seven mode of failure in wedge anchorage: soft slip, power slip, cutting of fiber, crushing of rod, bending of fiber, frontal overload and intermediate rupture. The failures are documented with explanatory figures and their backgrounds are found in the theory.

IV. Design And Serviceability Criteria

A. Flexural Capacity

Comprehensive data for design and performance recommendations on the basis of research work done in Japan, Europe, Canada and US on flexural capacity is presented in [16].

The approach to determine the flexural strength of FRP prestressed beams is based on the concept of balanced ratio (ρ_b), under-reinforced section and over reinforced section. In the balanced ratio concept rupture of the tendons and crushing of the concrete happens simultaneously. Beams with a reinforcement ratio (ρ) less than ρ_b, fails by tendon rupture and are divided into two different conditions: very under-reinforced beams (reinforcement ratio < 0.5 ρ_b) and under-reinforced beams (0.5 ρ_b < reinforcement ratio < ρ_b). While concrete fails in over-reinforced beams, with a reinforcement ratio higher than ρ_b [16], [23]-[26].

Burke Chad R. and Dolan Charles W.[23] presented an unified approach for flexural design of beams with FRP tendons. Equations for flexural strength have presented, failure modes have been defined, calibrations with test data were presented, and strength reduction factors are presented in this study. Derivations found reliable and match with as given in [16].

Kim Yail J. [24] has analyzed the flexural capacity of concrete beams prestressed with AFRP tendons. Three-dimensional nonlinear finite element analysis and iterative sectional analysis are conducted to predict the behavior of AFRP-prestressed members, including experimental validation.

Grace Nabil F., Jensen Elin A. and Noamesi Delali K.[25] have done an experimental investigation including load and strain distribution tests and a flexural ultimate load test of bridge model. Test behavior agreed well with that predicted according to [16]. The longitudinal and transverse reinforcement remained intact during the test.

Grace Nabil F., Enomoto Tsuyoshi, Sayed George, Yagi Kensuke and Collavino Loris [26] have presented a study on flexural testing of double-tee (DT) beam, prestressed by bonded and unbonded strands. Testing focused on measurement of strain distributions along the length and depth of the beam, transfer length, camber/deflection, cracking load, forces in post-tensioning strands, ultimate load-carrying capacity, and mode of failure. Theoretical calculations are similar in value to the corresponding experimental results especially under the service load.

B. Deflection

Short-Term Deflection : Before cracking, the gross moment of inertia can be used to calculate the deflections from traditional mechanics of materials. If deflection calculation following crack formation is required, methods that take into account the softening effect that cracking has on concrete members need to be used [9],[16],[41].

Long-term deflection—For long-term deflections, camber and deflection are separated into individual components, adjusted by a multiplier [9],[16],[41] and then superimposed to obtain final deflections in a manner similar to that for conventional steel prestressed concrete members.

J. A. Rodriguez-Gutierrez and J. Dario Aristizabal-Ochoa [17] have proposed a model that calculates both short-term and long-term deflections. The effects of creep, shrinkage, and tension stiffening in the concrete and flexural rotational restraints at the beam extremes are included in the proposed model. Five examples are included that show the effectiveness and to predict the load–deflection behavior of reinforced and prestressed beams.

Abdelrahman Amr A. and Rizkalla Sami H.[27] have performed the serviceability of concrete beams prestressed by CFRP reinforcements. The measured deflection and crack width are compared to the predicted values based on different codes, using the properties of CFRP bars.

C. Crack width and spacing

Dolan et al. (2000) studied crack widths in flexural members prestressed with FRP. Both monotonic and cyclic loadings are studied. A linear growth in crack width with increasing load is observed after the initial precompression is overcome. The cracks are evenly spaced and occurred at the location of the stirrups, suggesting that major debonding of the carbon tendons did not occur during static or fatigue loading. Crack lengths and widths increased during flexural cycling. Final crack widths are approximately three times those in a comparable steel prestressed concrete beam [5], [9], [16].

D. Fatigue

Fatigue strength of CFRP is much higher than that of conventional steel prestressing materials. Various tests have been done to observe the fatigue strength of CFRP in comparison with steel. It observed that 2 to 3 million cycles of reversal of stresses CFRP can withstand. It is also observed that fatigue failure of CFRP is almost 3 times higher than steel at particular stress level.[5],[9],[16].

E. Shear Capacity

It is observed that less work has been done in this area. From the assessment of theoretical and experimental nominal shear capacities, a rational approach that conservatively modifies the ACI 318-02 expressions to account for the special characteristics of FRP stirrups is suggested [16]. Various issues needs to be addressed for using FRP as shear reinforcement are:

- FRP may have a relatively low modulus of elasticity;
- FRP has high tensile strength and no yield plateau;
- Tensile strength of the bent portion of an FRP bar is significantly lower than the straight portion;
- FRP has lower dowel resistance and tensile strength in any direction other than that of the fibers; and
- The bond characteristics of FRP stirrups may vary significantly from steel reinforcement.

Maruyama Kyuichi and Rizkalla Sami H. [35] have discussed the influence of slippage of the prestressing strands on beam behavior of pretensioned prestressed concrete tee beams with high tensile steel tendons, tested statically up to failure. Contribution of various shear reinforcement configuration, crack behavior, overall deformation, and mode of failure are presented.

Collins Michael P., Mitchell Denis, Adebar Perry, and Vecchio Frank J, [36] have presented a simple unified method for the shear design of both prestressed and nonprestressed concrete members. The method can treat members subjected to axial tension or compression and treats members with and without web reinforcement.

Morphy Ryan David [37] has presented the experimental program and results of specimen tested to determine the losses of stirrups capacity of FRP reinforcement. Based on the test results, design equations are introduced to predict the strength of the stirrups.

Stratford Tim and Burgoyne Chris [38] have studied compatibility, equilibrium, and the material constitutive laws together to establish the actual conditions within an FRP-reinforced beam subjected to shear. A crack-based analysis is proposed to model shear failure in a beam with brittle reinforcement and the results are contrasted with the current shear design proposals for FRP-reinforced concrete.

Ahmed E. A. and E. Salakawy El F. [39] have presented the test results of two T-beams reinforced CFRP stirrups. The beams are designed to fail in shear to utilize the full capacity of the CFRP stirrups and performed well.

Ahmed K. Sayed El and Soudki Khaled [40] have compared the shear capacity in FRP RC structure suggested by American, Canadian, British, and Japanese guideline. The average predictions by all methods do varied by more than 260%. ACI recommendations found reasonably well.

F. Bond behavior

Bond between concrete and reinforcement has principal significance on structural behavior. Bond performance has an effect on flexural, shear and torsion load bearing capacity of reinforced concrete members and particularly on serviceability behavior. The bond of FRP tendons could be influenced by tensile strength, modulus of elasticity, hoyer effect, cross-sectional shape, surface preparation (braided, deformed, smooth), type and volume of fiber and matrix, method of force transfer; and concrete strength and cover [5],[9],[15],[16].

Malvar L. J., Cox J.V. and Bergeron Cochran K. [28] have experimentally analyzed the bond characteristics of four different types of carbon fiber reinforced polymer tendons with different surface deformations embedded in lightweight concrete. In a series of tests, local bond stress-slip data, as well as bond stress-radial deformation data, needed for interface modeling of the bond mechanics, are obtained for varying levels of confining pressure.

G. Transfer length

The transfer length in PC structure is the minimum length required to transfer the full prestressing force to the concrete. This transfer occurs gradually, rising from zero at the location where bond is initiated and increasing gradually until it reaches a constant value at the effective prestress level within the transfer length [5],[13],[16].

Lu Zhen, Boothby Thomas E., Bakis Charles E. and Nanni Antonio [29] have experimentally determined transfer length, development length and flexural behavior of FRP tendons in PC beams. The transfer length of FRP is reasonably well predicted as by ACI method. It is proposed to modify the ACI equation to account for the larger bond stress developed by the FRP tendons.

Grace Nabil F. [30] have investigated the parameters such as level of prestress at release, creep and the rate and method of release of prestress. DT girders are prestressed with CFRP and CFCC strands. It is observed that the calculated and measured transfer lengths are close in the case of CFRP tendons only. It is also noted that the level of release of prestress has no significant effect on transfer length.

V. LIFE CYCLE COST ANALYSIS

The structure reinforced with FRP proves to be cost effective. It has been found in the analysis of life cycle cost of prestressed concrete side-by-side box beam bridges [14]. Some of the specific reasons are:

- Traffic volume on and below the bridge significantly affects the life cycle cost. The cost effectiveness is greatest when located in an area with high traffic zones.
- The CFRP reinforced medium-span bridge is generally most cost-efficient.
- The four variables that have the highest effect on LCCA are: traffic speed on the roadway; real discount rate; speed reduction during construction; and traffic volume.
- In probabilistic analysis seven of the thirteen cases, CFRP are the most cost-effective by year 20 with the probability more than 0.9 except for a short span with low traffic on and below the bridge.

VI. FRP IN CIVIL ENGINEERING: INDIA

The overall composites market in India is relatively small, compared to consumption in other parts of the world. A few years ago consumption level of composites in India was only about 30,000 MT, as compared to about 2,00,000 MT in China. There is enormous scope of use of FRP in India, because of seismically deficient buildings, long coast line and long monsoon season forcing the use of non-corrosive FRP. FRP application for retrofitting is gaining attention in India, However, the same is not to the extent warranted by potential of the FRP that exist, as the material is still considered relatively new in this part of the world. There are many Indian projects to the credit of FRP retrofitting by various companies like Sika India Pvt Ltd, Fyfe (India) Pvt Ltd, Fosroc Chemicals (India) Pvt Ltd, etc. have [4].

VII. RESEARCH NEEDS

While there is a substantial volume of laboratory tests and field of installations of FRPs, a number of research areas remain to be investigated so that the research recommendations can be converted into the standards. The area requires major concerns are tendon and anchorage systems, anchorages, fire protection, harping devices, long-term bond, galvanic action, external post-tensioning for rehabilitation, tendon replacement, circular prestressed tanks, stressing procedure, reliability assessment, shear capacity; and bond & development [16],[32],[33],[34].

VIII. CONCLUSION

In this paper, discussion has been done for use of the FRPs in Prestressed concrete structure, starting from its requirement and historical development. Constituents, types, composition and properties of FRPs are mentioned briefly. Along with it, anchor devices, its types and subsequent development to improve its efficiency is also discussed. More specifically, this work has summarized and evaluated the previous researches and recommendations in this area of design and serviceability. Life-cycle cost analysis is discussed in which suggests that the FRPs are much more cost effective when the traffic volumes are higher. Status of FRPs in India compared to China is discussed, which suggests that there is a great potential for use of FRP in India.

The application of FRP in civil engineering is showing upward trend in India, however, FRP is still a specialty item. To improve this situation, there is a need of more research as well as Government-Industry-Institute partnership to exploit full potential of FRP for better performance of structure.

REFERENCES

[1] Uomoto T.; Mutsuyoshi H.; Katsuki F.; and Misra S.; "Use of Fiber Reinforced Polymer Composites as Reinforcing Material for Concrete." Journal of Materials in Civil Engineering, pp. 191-209, May/June 2002.

[2] Bakis C. E., L. Bank C., Brown V. L., Cosenza E., Davalos J. F., Lesko J. J., Machida A., Rizkalla S. H., and Triantafillou T. C.; "Fiber-Reinforced Polymer Composites for Construction—State-of-the-Art Review." Journal of Materials in Civil Engineering, pp 73-87, May 2002.

[3] Sharbatdar Kazem M., Saatcioglu M. and Benmokrane B.; "Seismic flexural behavior of concrete connections reinforced with CFRP bars and grids" Composite Structures 93, pp 2439–2449, April 2011.

[4] Shrivastava R., Gupta U. and Choubey U.B.; "FRP: Research, Education and Application in India and China in Civil Engineering." International Journal of Recent Trends in Engineering, Vol. 1, No. 6, pp 89-93, 2009.

[5] Borosnyoi A.; "Serviceability of CFRP Prestressed Concrete Beams." PhD Thesis, Budapest University of Technology and Economics 2002.

[6] Carolin Anders; "Carbon Fibre Reinforced Polymers for Strengthening of Structural Elements." PhD Thesis, Lulea University of Technology, Sweden, 2003.

[7] NEDRI Spanstaal BV, "Prestressing Wires." http://www.nedri.nl/.

[8] Wu Z., Wang Xin, and Iwashita K.; "State-of-the-Art of Advanced FRP Applications in Civil Infrastructure in Japan." Composites & Polycon, American Composites Manufacturers Association, October 2007.

[9] Bakis Charles E. and Nanni Antonio; "Design Recommendations for Concrete Structures Prestressed With FRP Tendons." Report for FHWA Contract DTFH61-96-C-00019, August 2001.

[10] Schmidt J.W., Täljsten B., Bennitz A., and Pedersen H.; "FRP tendon anchorage in post-tensioned concrete structures." Concrete Repair, Rehabilitation and Retrofitting II – Alexander et al (eds), pp 1181-1186, 2009.

[11] Bennitz Anders; "Externally Unbonded Post-Tensioned CFRP Tendons - A System Solution." PhD thesis, Lulea University of Technology, Sweden, 2011.

[12] Pincheira Jose A., and Woyak John P.; "anchorage of Carbon Fiber Reinforced Polymer (CFRP) tendons Using Cold-Swaged Sleeves.", PCI Journal, November-December, pp 100-111, November/December 2001.

[13] D. Svecova and S.H. Rizkalla, "Canadian Code Provisions for Design of Concrete Structures Prestressed with FRP." Google Search.

[14] Grace Nabil, Jensen Elin, Eamon Christopher, Shi Xiuwei and Matsagar Vasant; "Life Cycle Cost Analysis of CFRP Prestressed Concrete Bridges." US-Japan Workshop on Life Cycle Assessment of Sustainable Infrastructure Materials Sapporo, Japan, October 2009.

[15] Fico Raffaello; "Limit States Design of Concrete Structure Reinforced with FRP Bars", PhD Thesis, University of Naples Federico II.

[16] ACI Committee 440; "ACI 440.4R-04 : Prestressing Concrete Structures with FRP Tendons", 2004.

[17] Rodriguez-Gutierrez J. A.and Aristizabal-Ochoa Dario J.; "Short- and Long-Term Deflections in Reinforced, Prestressed, and Composite Concrete Beams", Journal of Structural Engineering, ASCE, PP. 495-506, April 2007.

[18] Schmidt Jacob W., Bennitz Anders, Täljsten Björn and Pedersen Henning; "Development of Mechanical Anchor for CFRP Tendons Using Integrated Sleeve", Journal of Composites for Construction, ASCE, PP 397-405, July/August 2010

[19] Terrasi Giovanni Pietro, Affolter Christian, and Barbezat Michel; "Numerical Optimization of a Compact and Reusable Pretensioning Anchorage System for CFRP Tendons", Journal of Composites for Construction, ASCE, PP 126-135, March/April 2011

[20] Bennitz Anders and Schmidt Jacob W.; "Failure modes of prestressed CFRP rods in a wedge anchored set-up".

[21] Mayah Al A., Soudki K., and Plumtree A.; "Mechanical Behavior Of Cfrp Rod Anchors Under Tensile Loading", ", Journal of Composites for Construction, ASCE, PP 128-135, May 2001.

[22] Zhang Burong, Benmokrane Brahim, and Chennouf Adil; "Prediction Of Tensile Capacity Of Bond Anchorages For Frp Tendons", Journal of Composites for Construction, ASCE, PP 39-47, May 2000.

[23] Burke Chad R. and Dolan Charles W.; "Flexural Design of Prestressed Concrete Beams Using FRP Tendons", PCI journal, PP. 77-87, March/April 2001.

[24] Kim Yail J.; "Flexural Response of Concrete Beams Prestressed with AFRP Tendons: Numerical Investigation", Journal of Composites for Construction, ASCE, PP 647-658, November/December 2010.

[25] Grace Nabil F., Jensen Elin A. and Noamesi Delali K.; "Flexural Performance Of Cfrp Prestressed Concrete Side-By-Side Box Beam Bridge", Journal of Composites for Construction, ASCE, January 2011.

[26] Grace Nabil F., Enomoto Tsuyoshi, Sayed George, Yagi Kensuke and Collavino Loris; "Experimental Study and Analysis of a Full-Scale CFRP/CFCC Double-Tee Bridge Beam", PCI Journal, PP. 120-139, July/August 2003.

[27] Abdelrahman Amr A. and Rzkalla Sami H.; "Serviceability limit states of concrete beams prestressed by CFRP bars".

[28] Malvar L. J., Cox J.V. and Bergeron Cochran K.; "Bond between Carbon Fiber Reinforced Polymer Bars and Concrete. I: Experimental Study", Journal of Composites for Construction, ASCE, pp. 154-163, MAY 2003

[29] Lu Zhen, Boothby Thomas E., Bakis Charles E. and Nanni Antonio; "Transfer and Development Lengths of FRP Prestressing Tendons", PCI Journal, PP. 80-91, March/April 2000.

[30] Grace Nabil F.; "Transfer Lrngth of CFRP/CFCC Strands for Double-T Griders", PCI Journal, PP.110-126, September/October 2000.

[31] Grace Nabil F., Roller John J., Navarre Frederick C. Nacey Richard B. and Bonus Wayne; "Load Testing a CFRP-Reinforced Bridge", Concrete international, pp. 1-7, July 2004.

[32] Nurbaiah M. N., Hanizah A. H., Nursafarina A., Nur Ashikin M.; "Flexural Behaviour Of RC Beams Strengthened With Externally Bonded (EB) FRP Sheets Or Near Surface Mounted (NSM) FRP Rods Method", IEEE pp. 1232-1237, December 2010.

[33] Cortés-Puentes W. L., Almansour H. and Palermo D.; "Towards Improved Shear Design for Reinforced Concrete Beams Strengthened with Externally Bonded Fibre Reinforced Polymers", 2nd International Engineering Mechanics and Materials Specialty Conference, Ottawa, Ontario, pp. 1-10, June-14-17, 2011.

[34] Nanni Antonio; "North American design guidelines for concrete reinforcement and strengthening using FRP: principles, applications and unresolved issues", Construction and Building Materials, ELSEVIER, July 2003

[35] Maruyama Kyuichi and Rizkalla Sami H.; "Shear Design Consideration for Pretensioned Prestressed Beams", ACI Structural Journal, pp.492-498, September/October 1988.

[36] Collins Michael P., Mitchell Denis, Adebar Perry, and Vecchio Frank J,; "A General Shear Design Method", ACI Structural Journal, pp.36-60, January/February 1996.

[37] Morphy Ryan David; "Behaviour Of Fibre Reinforced Polymer (Frp) St~Rrups As Shear Reinforcement For Concrete Structures", Thesis of Master of Science, University of Manitoba, June 1999

[38] Stratford Tim and Burgoyne Chris; "Shear Analysis of Concrete with Brittle Reinforcement", Journal of Composite for Construction, ASCE, pp.323-330, November 2003.

[39] Ahmed E. A. and E. Salakawy El F.; "Structural Behavior of Concrete Beams Reinforced with Carbon FRP Stirrups", Twelfth International Colloquium on Structural and Geotechnical Engineering, 2007.

[40] Ahmed K. Sayed El and Soudki Khaled; "Evaluation of Shear Design Equations of Concrete Beams with FRP Reinforcement", Journal of Composites for Construction, ASCE, January/February 2011.

[41] Rafi Muhammad Masood and Nadjai Ali; "Evaluation of ACI 440 Deflection Model for Fiber-Reinforced Polymer Reinforced Concrete Beams and Suggested Modification", ACI Structural Journal, pp. 762-771, November-December 2009.