The Application of Carbon Fibre Reinforced Polymer (CFRP) Cables in Civil Engineering Structures

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Abstract — *This review gathers the available literature on Carbon Fibre Reinforced Polymer (CFRP) cables. The behaviors of built-in structures are very crucial, especially structures with large dimensions and long service, usually involving advanced technology. Hence, there is the need to understand the behavior of carbon fibre reinforced polymer (CFRP) cable which is considered to be a new discovery for making composite materials. This review covers literature on the behavior and strength of CFRP cables in relation to bridges as well as the use of such cables in other civil engineering structures other than bridges. This paper also describes, briefly, some selected projects in which CFRP cables have been used to demonstrate the wide range of the current and potential applications of CFRP cables for Civil Engineering Structures*

Keywords — *Carbon fibre, CFRP cables, Bridge, Structures, Projects*

I. INTRODUCTION

Civil Engineers are known for realizing the limits of building structures and for discovering technologies to make the buildings go higher, last longer and consist of lighter materials. The challenge to reduce weight, increase spans, build higher or slender structures motivate the search for new materials such as a composite ones.

A composite material is multi-phased and a combination of two or more individual materials that differ in composition. An example of such material is the CFRP, a very common composite stuff used in a multitude of applications ranging from its use in space-related and aeronautic constructions to its use in building cars and ships. The use of composite materials in Civil engineering has been very slow in coming, probably because composites are more expensive compared to traditional materials such as steel. Yet, composite materials have the advantages of being lightweight, corrosion resistant and strong. In addition, the CFRP provides good damping characteristics and high resistance to fatigue. Indeed, CFRP materials are being extensively used as structure materials for bridges in various forms because of these advantages as well as their suitability for modular construction, environmental friendliness and low maintenance demand. [3]

Conventionally, common materials, especially steel, are used to construct bridges, but these can be replaced and bridges can be made from lighter and stronger composite materials. Initially, CFRP materials were used efficiently with restrictions. Researchers using these materials for engineering works especially bridges limited the usage to some parts of the construction works. However, in recent years, experiments have been conducted to investigate the applicability of CRFP composite materials in cable-stayed bridge structures. [4]

In view of the foregoing, this paper reviews some previous works in order to gather basic information on CFRP composite materials, including its structural behavior, pertaining to their civil engineering applications, especially in making cables and their acceptance in the construction industry in view of their success in automobile and aerospace industries.

II. DESCRIPTION OF CARBON FIBRE REINFORCED POLYMER (CFRP)

A. Carbon Fibre

One of the applications of high performance available for civil engineering is the carbon fibre stuff which is made by controlled pyrolysis and crystallization of precursors which are organic at temperatures usually above 2000^{O}C. This way, carbon crystallites aligned along the fibre length are produced. Three choices of precursor are available for the manufacturing process – rayon, polyacrylonitrile (PAN), and pitch options. The PAN types are the major ones for commercial carbon fibres and they produce a mass of around 50% of original fibre. Pitch types also produce high carbon yield at lower cost, even though they have less uniformity in the carbon fibres produced. It bears stressing that carbon fibres have higher fatigue strength and elastic modulus than glass fibres. In terms of service life, studies have shown that carbon fibres have more potentials than fibres of other materials [1] and the most important advantage in using carbon fibres as pre-stressing tendons is their chemical resistance. This is so because carbon is fully inert for nearly all chemicals, both in alkaline and acid environments. Indeed, it also resists all electrolytic or atmospheric degrading. [21].

B. Carbon Fibre Reinforced Polymer

Carbon Fibre Reinforced Polymer (CFRP) is a composite Polymer matrix reinforced with carbon fibres, which are very strong and light. In CFRP the reinforcement material is carbon fibre that provides the strength. The matrix is commonly a polymer resin like epoxy, which binds the reinforcement together.[2]. Thus, the CFRP is a combination of extremely thin carbon fibres of 5-10µm in diameter, embedded in polyester resin [8]. Figure 1 illustrates a thin carbon fibre of 5µm in diameter (in red).

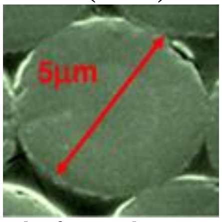

Figure1: An example of a 5µm diameter CFRP."SOURCE: Meier[23]"

CFRP can be manufactured with higher modulus of elasticity and higher strength than steel "thereby improving the flexural, shear strength and deflection of structural members".[5]. The tensile strength of a commercial carbon fibre is 3500-7000MPa with an elastic modulus of 230-650GPa and an elongation at failure ranging from 0.6 to 2.4%. [7].

C. CFRP Wires

CFRP wires are made through pultrusion, a process that ensures continuous extrusion of reinforced plastic materials. Roving strands of reinforcement are pulled through an impregnating tank containing epoxy resin, the forming die and finally a curing area. [12]. The process aims at producing a structural material that is workable and with adequate ductility while still retaining the favourable features of carbon. Since CFRP wires are resistant to corrosion, it is not required to apply any corrosion-inhabiting compound or grout. However, the wires still need to be protected against wind erosion and the attack of ultraviolet radiation because the combined effect of these two factors on the wires could lead to their degradation. For this reason, an UV-resistant polyolin sheath would be required for adequate shielding. [19]. Figure 2 illustrates rolls of CFRP and steel wires.

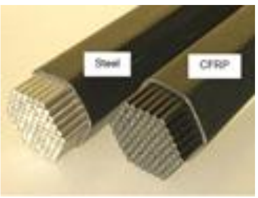

Figure 2: Steel and CFRP wire strands."SOURCE: Filiphbanck[14]"

D. CFRP Cables

CFRP cables consist of bundled parallel wires as shown in Figure 3. In line with the corrosion-resistant characteristic of CFRP wires cited above, the cables from them do not require any non-corrosive compounds. However, and for the same reason, the cables still need to be protected against wind erosion and the attack of ultraviolet radiation because the combined effects of these two factors on the cables could lead to the degradation of their surface. [4].

Figure 3: CFRP cable consisting of 241 wire."SOURCE: Meier[4]"

High specific strength and stiffness are properties of carbon fibre reinforced polymer cables. Their non-corroding, non-relaxing, stress-free attributes give them outstanding performance under fatigue loading, while their lightweight quality is a great advantage for the performance of long stays and for very long-span bridges.[4]. Stay cables, including post- and pre-tensioning cables, when made of steel, have resulted in high maintenance costs in the past 30 years. Consequently, steel hanger cables used in suspension bridges are being replaced regularly throughout the world. From the technical point of view as highlighted in this paper, there is no doubt that CFRP is today the best available material for such cables. [4]. Table 1 compares CFRP cables with steel cables to support this opinion.

TABLE 1: CFRP Cable Compared with Steel Cable

Properties	CFRP cable	Steel cable
Tensile strength	2700N/mm^2	>1670N/mm^2
Modulus of Elasticity	160,000N/mm^2	205,000N/mm^2
Elongation at rapture	1.6%	6.0%
Density	1600kg/m^3	7850kg/m^3
Thermal co-efficient of expansion	0.2 x 10^{-6} K^{-1}	1.2 x 10^{-5} K^{-1}
Poisson ratio	0.3	0.3

In the table, the tensile strength of steel cable is given as 1670N/mm^2 whereas that of CFRP cables is shown 2700N/mm^2. In other words, CFRP cable is about two times stronger than steel cable. The difference implies that an element under pure tension, if made of cable CFRP will have a cross-section and a weight that is only 50% of that made of steel cable.

It has been found that the equivalent modulus in steel cables decreases as the lengths increase. For example and according to Flaga [7], when E=210GPa when l=0, then E=163GPa when l=1000m to E=98GPa when l=2000m. The CFRP cables values are 165,163 and 162GPa respectively for the lengths stated. The data confirmed that for lengths greater than 2000m CFRP cables would be an appreciated material for large span engineering structure in the future).[7] Figure 4 illustrates the relationship between the equivalent modulus of the CFRP one stay cable and that of Steel.

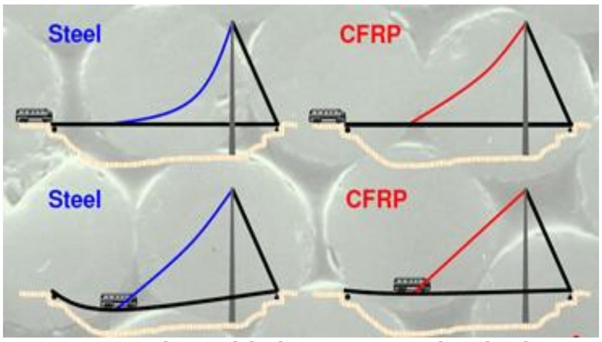

Figure 4: Equivalent modulus between CFRP and Steel with one stay cable."SOURCE: Meier[23]"

With light weight and superior strength, CFRP materials, as new materials for stay cables, can be utilized to improve the load-carrying efficiency of stay cables and effectively extend the span length of cable-stayed bridges to over 1000 m.[6]. CFRP materials can be expensive to produce but are commonly used wherever high strength-to-weight ratio and rigidity are required, such as in aerospace, automotive and civil engineering.

E. Anchoring CFRP Cables

The application of CFRP cables is faced by some problems which could impede their widespread application in the near future; the key one being how to anchor the cables. The impressive mechanical properties of CFRP wires explained are valid only in the longitudinal direction. The properties in the lateral direction, including inter-laminar shear are relatively poor. Thus, anchoring CFRP wire bundle to obtain the static and fatigue strength is very difficult. [4]

Consequently, the development of an anchorage system that permits multiple rods being anchored into an anchor block has become necessary for the introduction of carbon fibre cables. Also, the shape of the block is painstakingly controlled and the fixing resin added in layers, each with specific stress, in order to prevent the concentration of stress at the point where the rod enters the anchorage.[9].The anchorage system worked out by The EMPA laboratory solved the challenge by working out an anchorage system that employed a truncated cone-shaped locking block which was filled with casting material. The mechanical properties of the system change proportionately to the length of anchorage.[7]. The necessary radical pressure needed to increase the inter-laminar shear strength of the CFRP wires is provided by the conical shape inside the socket, [12] as illustrated in Figure 5.

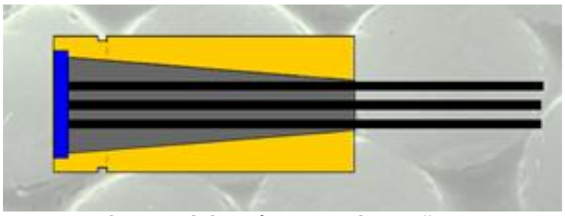
Figure 5: The conical shape for wire anchorage."SOURCE: Meier [4]"

F. Cost

The prices of carbon fibres have now fallen to $10 per kg compared with $35 per kg in 1998. The pultrusion process for the production of CFRP wires with new thermoplastic matrices was 50 times faster in 1996 with thermoset polymers and production cost has sunk accordingly.[22]. Based on this cost statistics by Meier [22], with time CFRP would be accessible like the traditional steel.

III.PREVIOUS RESEARCH WORK ON CFRP CABLES

Investigation on the behavior of CFRP cable in the last decade has become a very important research field. Theoretical and experimental applications were performed to study the behavior of CFRP cables and conclusions were drawn based on the various parameters influencing their behavior.

This material was first applied in the strengthening of the Ibach Bridge near Lucerne in Switzerland in 1991.[8]. Laminate bands of size 150mm x 1.75mm or 150mm x 2.0mm and 5000mm long glued to the reinforced zone, were used there. The T3000 fibres that form 55% of the laminated content have a tensile strength of 1900MPa and a longitudinal elastic modulus of 129GPa. Today, this technique of strengthening building structure is increasingly more often used.[7]. An 80m long carbon fibre cable Stay Bridge for pedestrian and emergency vehicles over a railway yard in Herning, Denmark [10] is believed to be the largest of its kind. It has 16 stay cables in two planes anchored to a central pylon and in addition, a part of its deck is pre-stressed with CFRP tendons.[11]

In 1996 in Winterthur, Switzerland, a cable stayed pylon bridge of 124m length was built (Figure 6). Here the CFRP stay cables were applied experimentally for the first time [7]. Each CFRP cable consisted of 241 wires with a diameter of 5mm and loading capacity of 12MN. The cables were subjected to loads three times greater than the permissible load. The characteristics of CFRP wires used in the stay cables were 1700S fibres, material density of 1.56g/m2, fibre content in wire 68%, tensile strength of 3300MPa, elastic modulus of 165GPa and a thermal expansion co-efficient of 0.2 x 10^{-6} K^{-1}. The CFRP cables with their anchorage have been equipped with conventional sensors and also with state of the art optical fibre sensors which provided permanent monitoring to detect any stress and deformation. Since

1996 this application has fully lived up to expectation. [19].

Figure 6: Stock-bridge with CFRP cables."SOURCE: Meier [23]"

Wei et al [6] carried out a study on six cabled stayed bridges with main span length of 1400m. Finite element model of the six bridges were created and designed strategies for each were conducted. Five of them were composite cable stayed bridges with CFRP stay cables and a CFRP deck; the results obtained were compared with the traditional steel concrete cable stayed bridge. The findings show that CFRP stay cables tend to reduce the global stiffness of bridges, though the decrease is insignificant and acceptable in engineering practice.

Adanurn et al[13] investigated the dynamic behavior of a cable stayed bridge for which CFRP cables were used in place of steel cables. The design parameters of Jindo Bridge built in Jeollanam, South Korea were considered except for the sectional properties of the cables. The equivalent stiffness and strength were used to determine the cross-sectional area of CFRP cables. Frequencies obtained from the equivalent strength and stiffness were close to that of steel. Steel and CFRP cables generally have similar mode shape. Hence, it was concluded that the use of CFRP cables is feasible for cable stayed bridges based on the results of the research.

A feasibility study was carried out by Filiph et al[14] on the static analysis of CFRP cables, both on cable stayed and suspension bridges with main spans longer than the longest bridge span, which is span > 2000 metres for suspension bridges and span > 1100 metres for cable stayed. The aerodynamic performance of CFRP cables is confirmed by the findings that CFRP cables has higher potential than steel cables for application in super long span bridges. However, problems related to low shear capacity and transverse weakness of the cables may arise in structures with such dimensions. These problems have to be solved by undertaking more research before using CFRP cables for long span bridges so as to make them practically feasible.

One of the main drawbacks of using CFRP cables is indeed in the extra care that must be taken with respect to friction and changes from a perfectly aligned geometry that induce extra stresses in the cables. Recent studies on this kind of issues have shown that CFRP cables may be well protected by using a grid of Ultra-High Molecular Weight(UHMW) piping so that the individual tendons could move through this connection, the radius of which would need to be about 1 metre at each point as recent studies on similar technological issues have shown.[16].

The authors [17] carried out an experimental study on the relaxation of CFRP cables with various fibre strengths and changing ambient temperature by using the standard method specified by the Japan Society of Civil Engineers. The results show that regardless of the varying strengths and ambient temperature, the straight line nature between the relaxation rate and logarithm of passing time was achieved. Hence, the effective data was obtained for practical structure design purpose.

Ozlem et al[18] investigated the stochastic seismic behaviors of two bridges: CFRP and steel cables by perturbation based SFEM and MCS methods. They concluded based on the stochastic seismic analyses results that the proposed CFRP cables and hangers cross-sections are adequate for the serviceability of long span bridges. Also, the fundamental frequencies of the bridges with CFRP cables are relatively high due to the lightweight and high strength. It was also concluded that for a long span bridge having the same span length and the same cable arrangement type, replacing conventional steel cables with the lightweight, high strength CFRP cables and hanger helped to enhance the rigidity of the structures. Similarly, Iwao et al[20] carried out an outdoor exposure test for 17 years to verify the long term durability of FRP cable but the review lays emphasis on CFRP cables. The cables were exposed to various conditions such as several initial pre-stressing tensile load with/without direct sunlight radiation and salt plash condition. The specimen was analyzed for several properties including the residual pre-stressing tensile load. The results obtained showed that the practical durability of CFRP was good.

Guoying et al[23] undertook a research on a cable stayed suspension bridges for which CFRP cables were used. The bridge has a main span of 800 metres. Equal cable stiffness and equal cable strength were adopted for its analysis and the results were compared those of steel cables. The conclusion drawn showed the same structural arrangement when steel cables were replaced with CFRP ones. Indeed, the loading carriage efficiency was improved so was the entire stiffness of the cable-stayed suspension bridge.

Recently in China, Mei [15] analyzed and designed a CFRP cable stayed pedestrian bridge in Southeast University which was erected in Jiangsu University, Zhenjiang 2005. As engineers have gained confidence in the performance of CFRP cables, new advancement should emerge to effectively utilize the properties of the material to gain the world spread use of such cables in civil engineering infrastructure.

IV. PROPOSED AREA OF APPLICATION

There are still visions which need to be achieved fully to realize the potentials of these promising materials. Though CFRP is an expensive material, the safety and life service of structures are paramount. Hence, the use of CFRP cables should not be limited to bridges as support, the cables should be used to support other civil engineering structures like the suspen-dome system.

V. CONCLUSION

The paper reviews the existing research on CFRP cables and examines the importance of such studies. Literature has confirmed that CFRP cables do not corrode nor suffer stress solution. They are easy to handle, exhibit outstanding fatigue behavior and have good efficiency in life cycle cost, even though the initial cost may be substantial.

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