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Modern Materials in Bridge Engineering

Matériaux modernes pour la construction des ponts

Moderne Baustoffe im Brückenbau

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SUMMARY

This paper begins with a discussion of the large variety of modern materials recently employed or soon to find application in bridge construction. The paper focuses on the use of fibrous composites. It gives an overview of the state of the art for these materials, and the example of carbon fiber-reinforced epoxies is used to illustrate developments that can be expected in the near and intermediate future.

RESUME

L'article donne un aperçu de la grande variété des matériaux modernes mis en œuvre récemment ou qui vont l'être sous peu dans la construction des ponts. L'accent porte plus particulièrement sur les composites renforcés de fibres. Il donne une vue générale de l'état actuel de la technique pour ces matériaux et illustre, à l'exemple des composites renforcés de fibres de carbone, les progrès réalisables à court et à moyen terme dans ce domaine.

ZUSAMMENFASSUNG

In der Einführung wird auf die Vielfalt der modernen Werkstoffe hingewiesen, die kürzlich erstmalig in Brücken eingebaut wurden oder vor dem ersten Einsatz stehen. Die Ausführungen beschränken sich auf Faserverbundwerkstoffe, stellen bei diesen den Stand der Technik dar und zeigen exemplarisch am Beispiel der kohlenstoffaserverstärkten Epoxidharze, welche Entwicklungen in naher und mittlerer Zukunft zu erwarten sind.

1. PRELIMINARY REMARKS

What are modern materials in bridge engineering? Shall we discuss bridge engineering needs of the 21st Century, e.g. intelligent materials [1] which restrain the advance of cracks by producing compression stress around them? This comes about through a volume change from a stress-induced transformation at the tip of the crack, when the cracks are produced due to repeated stress. Such materials would care for themselves through recognition, discrimination and redundancy. Or shall we go into the design of shape-memory alloy force and displacement actuators as active member control for vibration suppression in truss structures?

Since the symposium "Bridges: Interaction between Construction Technology and Design" will involve practical rather than theoretical presentations, to benefit those involved in actual bridge projects, we should deal with materials which are already commercially available today. Even if we exclude intelligent materials we still have a very broad variety of modern materials which are already being applied in bridge engineering. We should discuss "chemically bonded ceramics (CBC)", a whole new family of high-performance, low-cost materials made from Portland or other cements by new processing techniques to achieve components that are stronger and tougher than familiar concrete by at least one order of magnitude [2, 3]. We should treat new families of materials by combination [4]. Considering materials by combination we are very close to fibrous composites or even include them already. To be able to go into some details we will discuss "Modern Materials in Bridge Engineering" using the example of fibrous composites. Here we have to make a distinction between glass, aramid and carbon fibers, the materials presently most important for bridge engineering.

2. ADVANCED FIBROUS COMPOSITES IN BRIDGE ENGINEERING: STATE OF THE ART

The first significant self-supporting composite structures were designed in the late fifties. Pioneering work was undertaken by Prof. H. Isler, among others. His creations [5] are principally plate and shell structures, with some folded and tubular structures, made mainly of glass fiber reinforced unsaturated polyester resins. The plate elements consist of box structures characterized by a relatively large static depth. The thin-walled shell structures are predominantly designed with double curvatures. Such typical geometric configurations are required by the materials themselves: they compensate for the relatively low elastic modulus of the glass fiber reinforced plastics. These structures have proved themselves in practice over the past 25 years.

The first bridges employing advanced fibrous composites were realized in the seventies and early eighties in the U.S.A. [6, 7], Bulgaria [8], Israel, and China [9, 10]. The Beijing-Miyun road bridge built in 1982 [10] has a length of 20.2 m, a width of 7 m and a beam depth of 1.67 m. It is composed of five prefabricated box sections which were glued together on the site. The self-weight of the bridge is 300 kN, i.e. 80% lighter than an equivalent steel-reinforced concrete bridge. Little information is available as of yet about the long-term behavior of these bridges.

Large-scale tests with glass fiber reinforced plastic (GFRP) tendons have been conducted in the Federal Republic of Germany since 1978. Such prestressed tendons were used for the first time in a small concrete bridge in 1980. In 1986, in

Düsseldorf, a concrete bridge designed for heavy traffic loads was reinforced with prestressed GFRP elements [11] -- a world premiere.

Aramid fibers and aramid fiber-reinforced plastics have also been used for prestressing, bracing and staying, and in particular the anchoring of oil drilling platforms [12, 13].

The use of carbon fiber reinforced plastics (CFRP) for applications in bridge construction, in particular as cables for cable-stayed and suspension bridges [14, 15, 16, 26], and more recently as prestressing tendons, has already been discussed for several years. A first, 80 meter long prestressed bridge with a partial reinforcement of CFRP tendons was realized in Ludwigshafen in 1990 [17].

What are the reasons for the increasing amount of money being invested in research and development of applications of fiber composites in bridge construction over the past few years? Worldwide, highway agencies are struggling to cope with the increasing problem of deteriorating bridges, coupled with and compounded by shrinking resources, budgets and manpower. For example, the proportion of Interstate bridges in the U.S. classified as deficient rose from 10.6 percent in 1982 to 15.9 percent in 1988. In fact, 42 percent of all U.S. bridges are considered to be deficient [18]. One key to improving these conditions may lie in the development and application of advanced composite materials.

Fiber reinforced plastics offer the potential of eliminating many problems associated with adverse environmental influences resulting in the corrosion of metals. Universities, governmental agencies, and industrial firms throughout the world have been working on applications of advanced composites in bridge construction and repair. The result of these still relatively small research programs can serve as a basis for further research, development, and field applications of advanced composites for highway bridges.

As mentioned earlier, glass, aramid, and carbon fibers are the prime candidates for applications in bridge construction. Based on their exceptional properties and on further expected reductions in price, I think that the greatest potential lies with carbon fibers. These are characterized by following properties:

- excellent corrosion resistance
- excellent resistance to fatigue
- low density coupled with very high stiffness and strength, i.e. very high specific stiffness and strength
- very low linear thermal coefficient of expansion in the fiber orientation

The following discussion will therefore focus on carbon fiber composites.

3. CARBON FIBERS

The ideal construction materials are based on the elements found principally toward the middle of the Periodic Table. These elements, including carbon, form strong, stable bonds at the atomic level. Materials held together by such bonds are rigid, strong and resistant to many types of chemically aggressive environments up to relatively high temperatures. Furthermore, their density is low and the raw materials are available in almost unlimited quantities.

Carbon fibers have been known since the last century. Thomas Edison used carbon filaments made of bamboo fibers in his first light bulb.

Carbon fibers are manufactured by extrusion of a polymer into a continuous filament. The filament undergoes a stabilization treatment in air at 200°C to 350°C, after which it is heat treated (carbonized) at temperatures between 350°C and 1600°C in an inert gas atmosphere to remove H, O, N and other contaminating elements. The mechanical properties of the resulting fibers can be modified by a subsequent heat treatment at temperatures typically reaching 1300°C to 3000°C. Commercial carbon fibers with elastic moduli of about 230 GPa are known as high-strength, or low-modulus fibers. High-modulus fibers have values in the range of 480 to 700 GPa. Significant improvements in the mechanical properties of carbon fibers are still being realized in research laboratories today, and may be incorporated in the commercial products of tomorrow. The theoretical modulus of perfectly aligned fibers would be about 1000 GPa. The theoretical strength [19] is given in Fig.1 along with the strength and stiffness values of commercially available fibers.

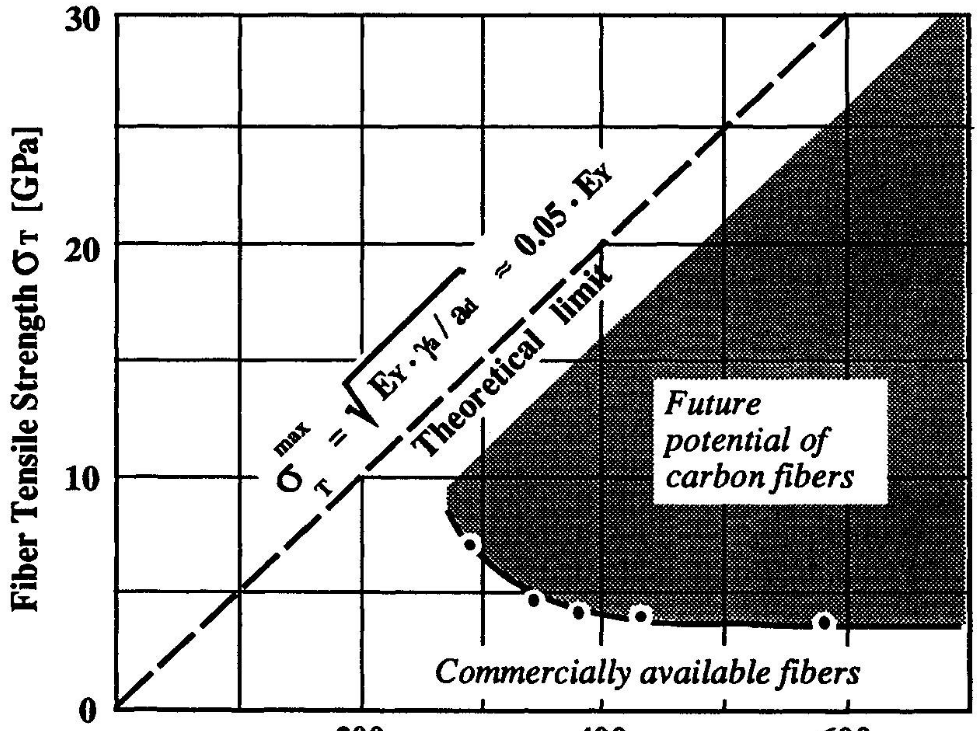


Fig.1 Future potential of carbon fibers

γ_a = surface energy per unit area needed to separate two planes in the crystal = 4.2 J/m^2

a_d = distance between the planes

• = commercially available fibers (ultimate values)

4. CARBON FIBER REINFORCED PLASTICS (CFRP)

A composite built up of fibers and a matrix might seem unnecessarily complicated at first sight. Why not simply take carbon or graphite rods to reinforce our bridges? Carbon would be, as was pointed out above, a very rugged material, having the outstanding properties shared by elements from the middle of the Periodic Table. Such materials have, however, seen little use as structural materials in the past due to their brittleness. A fine notch at the surface or a micron-sized dislocation or other flaw within the homogeneous bulk can lead to a sudden, premature, and catastrophic failure of a structural element made of such a material. The presence of such flaws in structural elements of a certain size can not be avoided. Structural and statistical considerations, however, show that the strength of graphite can be greatly increased by producing it in the form of fibers.

The probability of a material sample containing a flaw large enough to lead to a brittle failure decreases with the volume of material in the sample. Furthermore, the crack in a composite rod or plate does not propagate as suddenly as in a compact body. A flaw in a fiber does not inevitably lead to the failure of a structural element. When the fiber is embedded in a matrix, it can again take up full load a short distance away from a crack.

The great rise in importance of advanced fibrous composites in engineering is best explained by the fact that the properties of the individual materials (fiber and matrix) can be combined in a customized way to yield new, unique properties that would only be achieved with great difficulty or at high costs with conventional materials.

The preceding section gives a slight hint of the wide range of properties of carbon fibers. Facing the possible spectrum of combinations of fibers and matrix systems as well as the possibility of including other types of fibers in order to produce hybrid composites, it is hardly possible to imagine the almost endless range of resulting material properties that can be created. One can speak without reserve of a "custom tailored material." This is one of the most positive attractions of composites for bridge engineering applications.

Thirty years of intense research activity in aeronautical and astronautical engineering have provided us with excellent theoretical tools, supported by numerous experiments, for the determination of the most detailed properties of fibrous composites. A simple example to illustrate this: the elastic properties of a unidirectional laminate or wire, with fibers only in the axial direction, can be described by just four independent basic elasticity constants.

5. EXAMPLE: STRENGTHENING OF STRUCTURES WITH CARBON FIBER REINFORCED PLASTIC (CFRP) LAMINATES [24]

Research on the post-strengthening of existing reinforced concrete structures through the bonding of steel plates [22, 23] has been conducted over the past 20 years at the Swiss Federal Laboratories for Materials Testing and Research (EMPA). This system is very successful but it also has some disadvantages, such as the difficulty in handling the heavy steel plates at the installation site, the possibility of corrosion at the steel/adhesive interface, and the problem of forming clean butt joints between the relatively short plates. These difficulties led to a research project

at the EMPA in Dübendorf, whose goal was to investigate how to replace the steel plates by very lightweight CFRP laminates [16, 21].
Such laminates are characterized by their low weight, extremely high stiffness, excellent fatigue properties, and outstanding corrosion resistance. Their price by volume, however, is about 9 times higher than that of the steel used up to this date (FE360) for the post-strengthening of existing structures. Do the unquestionably outstanding properties of CFRPs then justify their extremely high price as strengthening materials for existing reinforced and prestressed structures? Considering that for a specific sample application 94 kg of steel plates that have to be maneuvered to a difficult-to-reach construction site can be replaced by a mere 4.5 kg of CFRP, the concept and the price no longer seem so farfetched. Furthermore, it must be kept in mind that in the strengthening application considered, material cost is only about 20% of the total compared to 80% for the labor cost. The easy handling strongly reduces the labor cost.

Table 1 Properties of unidirectional CFRP laminate [21]

Tensile strength σ_u:		1482	N/mm^2
Elastic modulus E:		115340	N/mm^2
Density ρ:		1.48	g/cm^3
Thermal expansion** α:	(longitudinal)	0.23×10^{-6}	m/m/°C
** (values by Toray)	(transverse)	34.0×10^{-6}	m/m/°C

Figures 2 and 3 give typical force/deflection and force/strain curves for concrete beams strengthened with CFRP laminates. In the diagram of Figure 2, a classical steel-reinforced concrete beam without any external reinforcement is compared with a similar beam strengthened with an 0.3 mm x 200 mm wide CFRP laminate. Strengthening with this very thin laminate nearly doubles the ultimate load. The deflection at this load, however, is only half that of the unreinforced beam. In the case of a 7 m beam with a typical steel reinforcement and a 1 mm CFRP laminate, the increase in the ultimate load was about 22% [20], with an observed failure in bending similar to that in Fig.3. After the appearance of the first cracks in the concrete, the internal steel reinforcement and the external CFRP laminate carry the tensile stresses. As soon as the internal steel bars reach yielding, only the CFRP laminate contributes to an additional increase of the load. Finally, the laminate fails in a brittle manner (tensile failure). As mentioned earlier the deflection of the strengthened beams is smaller, but it is still sufficient to predict impending failure. The bending cracks have a classical distribution.

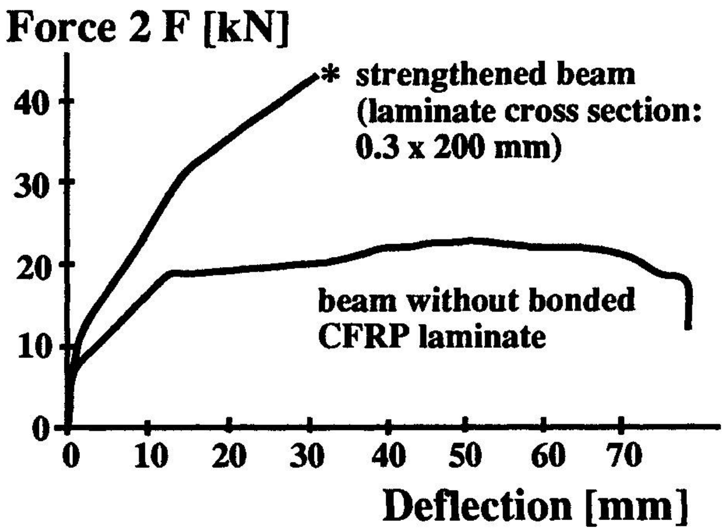


Fig.2 Results of 4 point bending tests with 2 m span beams. Loading points 0.66 m from the supports. Total load is 2 F.

Various failure modes were observed in the load tests:

- Tensile failure of the CFRP laminate, as described above. The laminate failed suddenly, with a sharp, explosive snap. The impending failure was always announced relatively far in advance by repeated cracking sounds;
- Classical concrete failure in the compressive zone of the beam;
- Continuous peeling-off of the CFRP laminate due to an uneven concrete surface. For thin laminates applied with a vacuum bag, a completely even bonding surface is required. If the surface is too rough, the laminate will slowly peel off during loading;
- Sudden peel-off during loading due to the development of shear cracks in the concrete. The peeling-off is caused by a relative vertical displacement of the crack faces. This is a dangerous case which calls for a careful consideration of the shear problem during design.

The influence of bonded CFRP laminates on the development of bending cracks is shown in Figure 4. A more even distribution of the cracks and a smaller total crack opening can be achieved at the same load by reinforcing a beam with CFRP laminates.
At the present time, further EMPA studies on the subject are dealing with the possibility of using prestressed CFRP laminates for the post reinforcement of concrete structures. Prestressing of the bonded strengthening plate could present a significant contribution toward improving the serviceability of a structure.

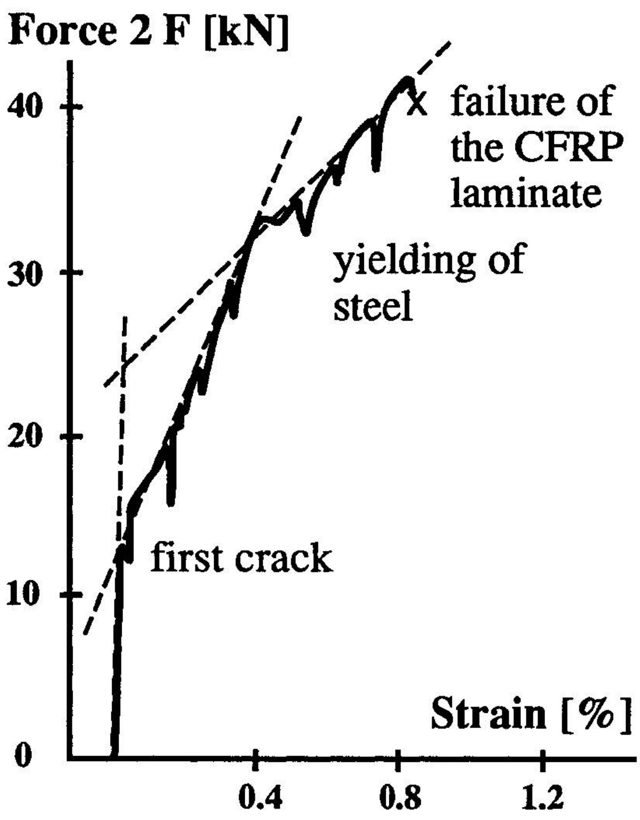
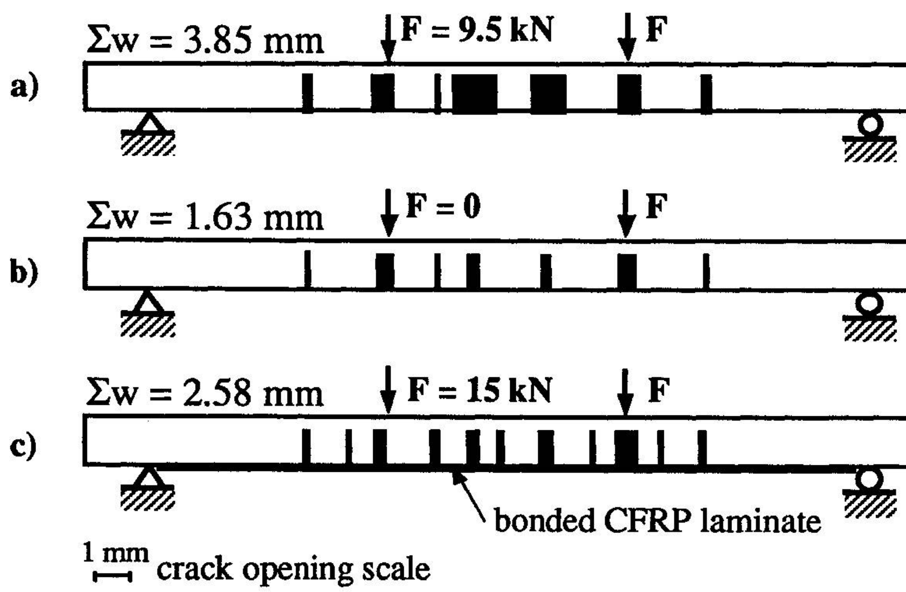


Fig.3 Force vs. strain diagram for a beam with 2.0 m span and strengthened with an 0.3 mm thick CFRP laminate. The force F is given for each loading point, i.e. total load = 2F. The strain was measured in the center of the beam on the CFRP laminate.

Fig.4 Crack width w

a) 2 m beam as in Figure 1 without post-strengthening, load 2F = 19 kN
b) same beam after unloading
c) same beam after strengthening with an 0.75 mm CFRP laminate, load 2F = 30 kN



6. EXAMPLE: CABLES FOR SUSPENDED STRUCTURES [25]

CFRP cables offer a very attractive combination of high specific strength and modulus (ratio of strength or modulus to density), good fatigue performance, good corrosion resistance, and low axial thermal expansion. The high specific strength permits the design of structures with greatly increased spans [26, 27]. The high specific modulus translates into a high relative equivalent modulus. When a load is applied to a cable with a horizontal as well as a vertical span, the elongation consists of the material deformation augmented by a geometric deformation due to the straightening out of the cable. The ratio of the applied load to the observed "strain" (elongation /original distance between the end points) is called the relative equivalent modulus (Fig.5). This factor is very important in view of the deflection constraints imposed on bridges. A relatively high modulus coupled with a low mass density give CFRP an advantage that increases with the length of the horizontal span and the initial tension.

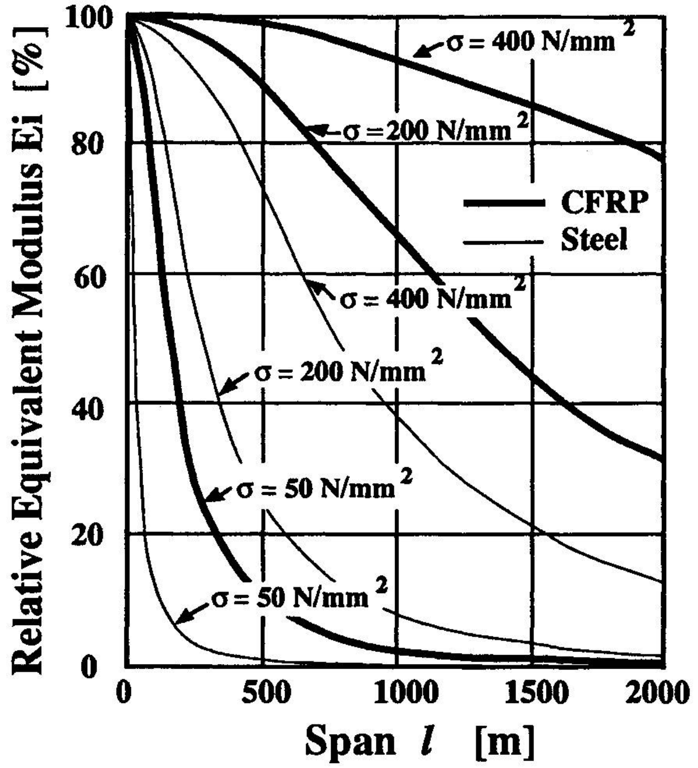


Fig.5 Equivalent modulus vs. span length and pretension

Large cyclic load amplitudes in cable stayed bridges call for a material with outstanding fatigue behavior. Tests performed on 19-wire cables at the EMPA showed the superior performance of CFRP under cyclic loads (see Table 2). At least three times higher stress amplitudes and higher mean stresses than with steel are possible without damage to the cable for 2 x 10^6 cycles.

The mechanical performance, durability, reliability and serviceability of cables in large suspended structures are all adversely affected by corrosion. The large costs associated with the maintenance of exposed steel structures, especially in corrosive environments such as in marine, urban,or industrial areas underline the economical value of the good corrosion resistance of CFRPs.

Finally, the climatic conditions to which large structures are exposed can result in large thermal fluctuations whose effect on the structure should be minimized. In this respect, the extremely low axial thermal expansion of the carbon fibers can be of great advantage.

Two types of cable materials in the form of pultruded wires have been tested at the EMPA. The first set of wires consists of T300 fibers and an epoxy matrix. The wires currently under study for applications in large structures are made up of 24k rovings of T700 fibers and an epoxy resin system. Their measured properties are listed in Tables 2 and 3.

Table 2 Performance of CFRP cables, tests conducted at EMPA.
T300 / (LY556/HY917/DY070) CFRP wires

Single-wire:		
Strength σ_u:	1'680	N/mm^2
Elastic modulus E:	145'000	N/mm^2
Density ρ:	1.56	g/cm^3
19-wire cable:		
Mean Stress σ_m:	550	N/mm^2
Double amplitude $2\sigma_a$:	900	N/mm^2
Cycles N:	2 x 10^6	(no damage)

Table 3 Properties of T700 / (LY556/HY917/DY070) CFRP wires

Tensile strength σ_u:		~ 3'300	N/mm^2
Load capacity of ø 6 mm wire:		85-90'000	N
Elastic modulus E:		~ 165'000	N/mm^2
Density ρ:		1.56	g/cm^3
Fiber content %V:		~ 68	%
Thermal expansion** α:	(longitudinal)	0.2 x10^{-6}	m/m/°C
** (values by Toray)	(transverse)	35.0 x10^{-6}	m/m/°C

CFRP cables are produced as assemblies of the above-mentioned wires. The design considerations for cables made of unidirectional CFRP wires are similar to those for steel cables, with a few exceptions due to the highly anisotropic nature of the material. The principal objectives are minimal strength loss of the wires in a bundle as compared to single wires, protection against impact, preventing friction between wires, shielding against decay due to environmental factors such as erosion and UV radiation, compactness of the section to minimize aerodynamic drag, and ease of handling. The strength requirements are met to a great extent by using a parallel arrangement of the wires without twist. Twisting or weaving the wires into a cable, while advantageous for handling, results in lateral stresses within the loaded cable, with associated losses in strength, and a loss of stiffness. Embedding the wires in a lightweight polymer matrix, enclosing them in a sleeve, or even producing a carbon fiber reinforced carbon (CFRC) cable are solutions to the other requirements presented above. A design solution should strive for a combination of durability, with the prospect of a 80-100+ years lifetime, as well as high mechanical performance and costs in a realistic range.

7. CONCLUSIONS

One of the major problems facing structural engineers is the aging and deterioration of the majority of highway bridges built during the boom in highway bridge construction after World War II. The repair and rehabilitation of these structures poses a large and urgent challenge for engineers. Modern materials, as demonstrated by the example in section 5, can and will play key roles in repair and rehabilitation.
For new bridge construction, the use of more durable materials is one alternative to effectively face the corrosion and fatigue problems of today's bridges.
Modern materials may in fact be the key factor for new developments in bridge engineering in the distant future, e.g. for cable-stayed or hybrid bridges with extremely long spans [26, 27]. Many problems remain to be solved in the meantime. A crucial issue is developing the confidence needed for a broad acceptance of modern materials. The introduction of new materials in bridge engineering has as a rule been conducted through small, less significant works. A classical example for steel bridge construction is the Iron Bridge built in England in 1779. Such a gradual progression from small to large spans, however is economically not realistic for CFRP bridges. Figure 6 gives the CFRP/steel price relation as a function of bridge span for a classical suspension bridge. The "break-even span," i.e. the span at which a change from steel to CFRP would be economically justified at the current price level of the materials, is about 4200 meters. On the other hand, it is clearly not realistic to think of actually building such a structure without a solid base of long-term experience with the concerned materials. What are the solutions to this problem?
Modern materials will probably start making significant inroads in the area of bridge repair and maintenance. Typical applications will also certainly not be

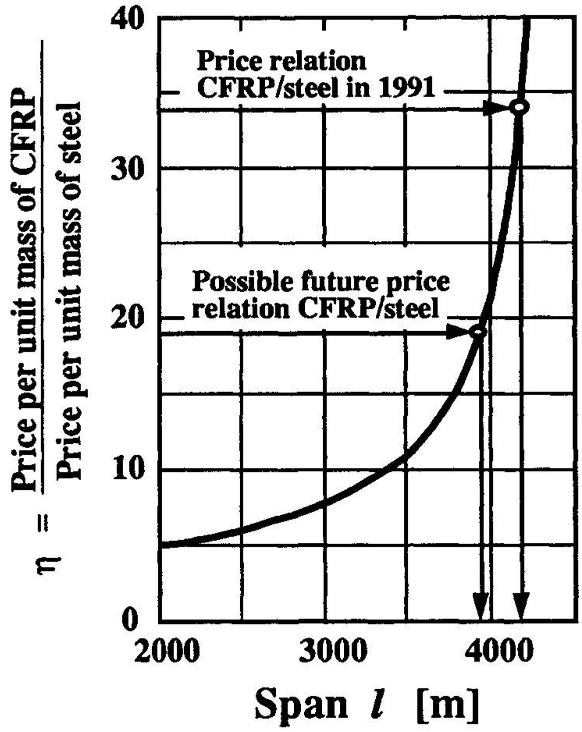


Fig.6 "Break-even span" for today's CFRP/steel price relation = 4200 m, for a classical suspension bridge

limited to strengthening laminates, as outlined in section 5, but will include cables for external prestressing and extreme high-strength cables for cable-stayed bridges (section 6). Closely monitored pilot projects will gain in importance as reliable sources of experience for design in the future.
Modern materials will not only increase in significance as a result of the requirements of innovative bridge construction; they will also themselves become a catalyst for innovation.

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