Application of Composites in Infrastructure – Part I and II
(a brief report on materials and construction)

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Abstract:

Composites have been in application for the past 3 – 4 decades, but only in the last decade that engineers have been given any serious consideration for its application in civil infrastructure: such as bridges, roads, earthquake retrofitting of buildings etc. In this paper the growth of application of composites in civil infrastructures and some of its implications are discussed. This paper is divided into 3 parts: Part-I) Materials aspect - fundamentals of composite materials, the matrix and fibers used, Part-II) Composites industry viewpoint: outlook of an engineer of the Australian branch of a worldwide composites manufacturing company towards infrastructure applications, and Part-III) a Structural engineer's observation on the increased application of composites in civil infrastructure **(this part is in the next paper)**.

Part I: Fundamentals of Composites as new engineering / structural materials

The construction materials that men used for the buildings and bridges have always identified human civilization at any given time. In the beginning it was wood, then came stone, followed by bricks and mortars. Lately we saw the use of cast iron and steel, followed by reinforced concrete and prestressed concrete. The civilization moved from the Stone Age, to the age of advanced steel and concrete. However, since 1970 a new age has started – the age of composite construction materials. Composite materials have already been extensively used in the aircraft industry, space industry, and auto and transportation industry. In the beginning the military usage were predominant. Various aircraft, helicopters and rockets were built using composites and high strength adhesives. Initially certain parts were made of composites. Gradually entire structural frames and the bodies were built by composite material. It was found to be an easily repairable material. At present some of the engine parts are made of composite materials. Gradually commercial airlines started to use the same materials (CFRP, GFRP and AFRP). At present, large number of automobile manufacturers, throughout the world, is using composite material bodies. Large trucks, shipping containers, ships and even moving engine parts are now made of composite materials

1.1 Composite materials are:
* structured combinations of continuous and discrete phases in which
* the stronger and stiffer discrete phase (reinforcement) is held
* in the weaker and softer continuous phase (the matrix) by interfacial bonding.

1.2 Recognized widespread applications of composites so far are:
* significant use in modern aircraft;
* structural and non-structural applications such as in automotive, marine vessels, utility industry, sports, chemical industry, printed circuit board base and elsewhere. The use is continuously on the rise, and that is the attractiveness of composite materials.

1.3 Types of Composites: Virtually all composites are fiber-reinforced plastics – FRP providing substantial weight savings leading to superior specific properties i.e. value of the property on a weight-to-weight basis.

1.4 Fibers Used:
*Glass: typical temp limit: 350° C
*Carbon (graphite)
a) PAN based (Torray) high strength (> 2000° C); High modulus (>2000° C)
b) Pitch based High Modulus (Amoco) (>2000° C)
Aramid -Kevlar 49 [R] (Du Pont) and other (250° C),
UHMW Polyethylene (Spectra) (Dyneema): 120° C
Boron
Other ceramics
Other: including natural fibres and natural material derived matrices are also finding increasing use in applications.

Plastics: a) Thermosets, b) Thermoplastics, and c) Rubber [elastomeric]

Thermosets – Most Commonly used polymer matrix:

** Unsaturated Polyesters – the big performer of the FRP industry, cheapest
** Vinyl Esters – have good chem resist of epoxies and easy processing of PE tougher grades
** Epoxy: Ideal for aerospace applications; low shrinkage; expensive
** Phenolics: inherently fire retardant
** Urethane Methacrylate: similar to Vinyl esters but with low viscosity

Thermosets are cured – ie a network structure is formed.
** Mol wt/viscosity goes up rapidly
** A Gel Point occurs at a well-defined and predictable stage of cure
** Further cure results in the formation of a glassy state
** Tg – Glass transition temp is an important parameter.

Fibre types:
Continuous Fibres (Roving, Fabrics)
Discontinuous Fibres (Chopped strand mat)
Prepregs
Fabrics
Preforms

Orientation
Random
Unidirectional
Cross – ply
Other
Tailor-made

Manufacturing of FRPs (Thermoset resins)
Wet lay up

Liquid Moulding
Autoclave
Filament Winding
Pultrusion
Resin Transfer Moulding, SRIM and *more*

Composite properties influenced by fibres
Rigidity (Modulus of elasticity): Rule of Mixture gives maximum gain – often unrealistic
Tensile Longitudinal Strength
Initiation of fracture of fibres

Composite properties determined by the matrix
Transverse mechanical properties
Interlaminar shear strength
Compressive strength
Plasticisation of the matrix
Service temp
Fire and corrosion resistance
Tool design and fabrication process

Properties controlled by Interface / bonding:
a) Fracture energy/Fracture toughness: Often a strong fibre held with an intermediate bond strength in a weak matrix gives improved fracture energy; e.g GFRP: 50 kJ/m^2, far higher than the matrix (2 – 3 kJ/m^2) or the fibre (0.1 kJ/m^2);
b) Interlaminar fracture energy also depends on the fabric type

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Typical Material Properties of selected fibres and matrix

Material	Density	Modulus	Strength
	g/cm^3	GPa	MPa
Fibers			
E-glass	2.6	73	3,500
S- Glass	2.5	87	4,600

Carbon (graphite) fibre –			
a) Pan Base			
High strenth	1.76	230	3,500
High modulus	1.94	588	3,900
b) Pitch based High mod	2.18	830	2,200
Aramid Kevlar 49	1.45	25	2,700
UHMWPE	0.97	87	2,700
Cellulose	1.61	60	1,200
Matrix			
Epoxies	1.2 – 1.4	2 – 5	40 – 85
Polyesters	1.1 – 1.4	1.3 – 4.5	45 – 85
Vinyl ester	1.13	3.2 – 3.3	60 – 70

PART II: A Composite Manufacturer's perspective: Development of carbon fibre woven Fabric, carbon fibre reinforced plastics plate, other products and adhesives for gradual infrastructural use

Background:

Increased service loads, growing traffic volumes, changes in use, deteriorated reinforcement, errors in design and construction, and structural modifications means that in many cases reinforced concrete structures need to be repaired or re-constructed. External plate bonding has been widely used in this instance to increase the strength of these under reinforced structures. This system works by transferring stresses from the structural element to the additional reinforcement plates, which are adhered, or bolted and adhered, to the structure.

The use of advanced composite materials such as carbon fibre reinforced plastic (CFRP) strips, externally bonded to existing structures to strengthen them, and is an economical and practical solution for extending the service life of structures. Since the early 1970's, flexural and shear strengthening of reinforced concrete structures using steel plates, externally bonded to the substrate, has been well established. When comparing CFRP to this conventional method of strengthening, a number of issues are raised. CFRP has superior properties with respect to strength, weight, durability, creep, fatigue and fire resistance. But, the material costs of the CFRP strips are quite high. However, the overall costs are reduced significantly with faster construction times, lower transportation costs and easier handling.

Since 1967 it has been possible to bond steel plates to existing reinforced concrete structures to increase bending resistance. Empirical values and design tables are now available. Bonded steel plates as external reinforcement can be considered as an external state of the art system. Pioneered in South Africa and France, it involves mild steel strips glued and bolted to the surface of the existing structure.

The introduction of high strength carbon fibre reinforced polymer has widened the horizons for the use of plate bonding for strengthening reinforced concrete structures. This technique has been developed in Switzerland, Canada, the USA and Japan and as a result, it is now possible to replace the heavy steel plates with light carbon fibre material.

Adhesives – The Key:

Because both steel and carbon plate bonding rely on the transference of the stresses in the structure directly to the plates, the adhesive is the key to the success of the system.

Therefore, to be effective, the adhesive must have long-term stability and durability, especially with respect to creep. In the case of steel plates interface, corrosion by water absorption can be a problem.

Research proves that the two-part epoxy resin adhesives used for bonding the plates absorb water and that, of the two-hardener types, polyamines have better resistance to moisture uptake than polyamides. Therefore the polyamine-based thixotropic, Sikadur-30, which has extremely low moisture absorption – less than 1% compared with other adhesives which pick up 5 or 6% - is also much less susceptible to creep.

Temperature is important where adhesives are concerned. Technically an adhesive should cure in temperatures between 10°C and 30°C with minimal shrinkage, and should be tolerant of small variations in the proportions of the mix.

The adhesive will also be much stronger in shear than the concrete to which it is bonded – with shear strength greater than 8 N/mm^2 (1161 psi) including a safety factor. The adhesive should have a static fatigue performance reasonably consistent over temperatures from -20°C to +40°C.

While it should remain stiff enough not to creep significantly under sustained load, the adhesive should also be flexible enough to cope with high local stress concentrations, which can arise from strain incompatibles at plate ends. The bulk flexural modulus should be between 4 and 10 GN/m^2 (14.5x10^6 psi).

Dissimilar color components make a 40 minute potlife adhesive easy to use by ensuring thorough mixing, while its paste-like consistency facilitates good grip and easy spreading onto vertical, horizontal and overhead surfaces, in thickness of up to 10mm, to allow for surface irregularities.

Using a similar adhesive to that used in steel plate bonding, and principally the same concept, the Sika-Carbo-Dur system is based on carbon fibre reinforced epoxy resin plates, bonded to the concrete structures.

Carbon Fiber Reinforced Polymer Plates:

A fraction of the weight, and ten times stronger than the comparative thickness of steel, carbon fibre plates not only simplify handling, but also eliminate costly temporary support.

Manufactured by the pultrusion process, to the Swiss Federal Laboratories for Material Testing and Research (EMPA) specification, it enables virtually any length to be produced, and the epoxy resin is reinforced with carbon fibre plates.

The Sika CarboDur system consists of three types of plate. Type S provides a tensile strength of 2,400 N/mm^2 (348,100 psi) in tension, five times as strong as some structural steel, with an elastic modulus of 155,000 N/mm^2 (22.5x 10^6 psi). Type M has a design tensile strength of 2,000 N/mm^2 (290,100 psi) but gives an elastic modulus of 210,000 N/mm^2 (30.5 x 10^6 psi) similar to that of mild steel. The Type H, used exclusively for timber structures, has a tensile strength of 1,400 N/mm^2 (203,000 psi) with an elastic modulus of 300,000 N/mm^2 (43.5 x 10^6 psi)

While it has been proved that the use of epoxy resin as the base for the adhesive in the Sika CarboDur process is expensive and takes longer to cure, it out-performs systems using other materials.

The high tensile capacity carbon fibre plate can be supplied in thickness of 1.2mm (0.05 inch) with outstanding fatigue resistance. The plates have high strength and rigidity in the longitudinal direction of the fibres, corresponding to the stress orientation, so that the laminate has unidirectional structure.

Normally supplied in 250m rolls (820 ft), the carbon fibre plate is flexible and eliminates the need for any form of jointing. The carbon fibre plate can than be cut to any length of strip required. These can be pre-cut at the warehouse or cut to suit on site. In wide-span structures, with dividing walls, this eliminates the need to demolish and rebuild the walls.

Extremely light composite carbon plate can be easily rolled, handled and transported and, being unaffected by the weather, it does not require special storage facilities, a further advantage on sites where access is restricted. Heavy steel plates may require special transport and cranage to unload, as well as weatherproof storage facilities. They will also require mechanical abrading, vacuum cleaning, priming and special treatment prior to use.

Criteria	Composite	Steel
Self-weight	Very low	High
Plate thickness	Very low	Low
Length of plates	Any	Limited
Application	Light tools	Heavy lifting gear
Supports	None	Temporary
Transport	Light	Heavy
Fixings	Only at each end	Possibly
Plate preparation	Minimal	Considerable
Tensile capacity	Very high	Acceptable
Fatigue behaviour	Outstanding	Adequate
Handling	Flexible – easy	Rigid – difficult
Corrosion	No	Yes
Laps	Easy	Complex

Carbon Fiber Woven Fabrics

Carbon fiber fabrics are very light woven mats that can be found in unidirectional or two-directional forms. The fabric is extremely lightweight, and is commonly distributed in rolls, which are easily transported.

The Sika⁻ Wrap fabric system consists of a carbon fibre fabric, woven in one direction, and can be applied by two different methods – a wet or a dry application. The wet application involves impregnating the carbon fibre fabric in a resin bath, using pull-trusion equipment. The fabric is applied to a well-prepared substrate. The dry application involves impregnating the prepared substrate-using adhesive, before applying the carbon fibre fabric. The fabric placed over the wet adhesive, pressure is applied, and then a final coating of adhesive is applied.

The carbon fiber fabrics used in the industry have varying tensile strengths and elastic modulus. Generally, the fabrics will have tensile strengths varying between 1500 and 3500 MPa (217.5 ksi to 507.6 ksi), and a modulus of elasticity of 160,000 MPa (23.2 x 10^3 ksi) 230,000 MPa (33.4 x 10^3 ksi).

Normally supplied in rolls of varying length, the carbon fibre fabrics are extremely flexible and eliminate the need for any form of jointing. The carbon fibre plate can than be cut to any length of strip required. These can be pre-cut at the warehouse or cut to suit on site. In wide-span structures, with dividing walls, this eliminates the need to demolish and rebuild the walls.

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Other CFRP product:

There are now numerous possibilities throughout the composite industry where CFRP can be utilized. These currently include the production of L shaped carbon fibre plates, produced to strengthen beams in shear. The plates or “stirrups” are designed to be applied in a similar pattern to a steel stirrup cage. The differences being that the CFRP stirrups are placed externally. Numerous research centers throughout the world have investigated this procedure with excellent results.

Pre-stress carbon fiber plates are also an exciting new application, aimed at reducing the costs involved with typical external pre-stress cable applications for under designed bridges. The application and the material costs are significantly different, with carbon fibre plates proving a less costly exercise. Research and testing in this area continues today, particularly in Europe, and recent results have proved extremely positive.

Applications:

Carbon fiber plate bonding has been used to strengthen many reinforced concrete structures around the world for a varying degree of reasons. Details of three recent structural retrofitting works are given below.

Westfield Shopping Centre, Marion, South Australia

One recent project was at the Westfield Shopping Centre in Marion, South Australia, which has been refurbished and expanded, making it the largest shopping centre in the Southern Hemisphere. The entire complex was made of typical reinforced concrete. Slab sections in the existing shopping mall were being cut out to make room for escalators and lifts, thus reducing the area of steel and leaving the slabs under-designed. Other areas of the mall have been extended with new shops being set up on top of existing ones. This resulted in an increase in live load from a nominal 3 kPa (62 5 psf) to the standard 5 kPa (104.5 psf), and hence, insufficient steel reinforcement in the existing slab.

Being a busy retail sector, the mall could not close down during the day, so contracting times were extremely important. Use of steel plates would have required long application times and large amounts of propping and bolting equipment, leading to extensive shutdown times for the retail outlets involved.

The Sika CarboDur system chosen was a carbon fibre laminate 80mm (3.15 inch) wide and 1.2mm thick (0.05 inch). Because of the low self-weight, the need for extensive propping and stitch bolting was eliminated. As a result, the re-strengthening exercise was completed quickly and efficiently.

Westfield shopping center retrofitting work in progress (Photo)

Oberriet – Meiningen Bridge, Switzerland

The bridge, built in 1963, crosses the Rhine River, linking Switzerland to Austria. Due to increased traffic loads, post-strengthening of the concrete bridge deck became necessary. The deck was made of typical poured in place reinforced concrete. The application of a total length of 670m (2,198 ft) of CFRP strip has proved to be successful, in strengthening the bridge.

Thorough investigations have shown that beside regular maintenance, the deck was in need of transverse strengthening, resulting from the increase in design truck-load (14 tone to 28 tone).

Different solutions were available to guarantee the structural safety of the bridge. These are:

- Replacing the entire deck
- Improving the cross-section by providing additional depth
- Post strengthening by bonding additional reinforcement to the existing deck

Because the concrete was in good condition and the chloride concentrations were below the critical values, it was decided that deck would not be replaced. Adding concrete to increase the depth, to reach the necessary transversal flexural capacity, would have caused major longitudinal stresses for the superstructure. As a result, bonding external reinforcement plates was the only option. Bonding transverse CFRP strips on the bottom of the slab and adding 80mm (3.15 inch) of concrete on top of the slab made it possible to meet all requirements.

Oberriet – Meiningen Bridge deck retrofitting in progress (Photo)

Narrows Bridge - Perth, Western Australia

In 1999 the Department of Roads of Western Australia looked into the viability of external strengthening of the Narrows Bridge in Perth using carbon fibre laminates. The bridge was made of typical poured in place reinforced concrete. Due to changes in traffic volume and load, the bridge was being duplicated, with the original bridge requiring an external strengthening system.

After the design analysis was carried out, the contractor was instructed to apply Sika CarboDur S1214 laminates to the soffit of the 5 reinforced concrete spans under the bridge. The strengthening requirements increased towards midspan, with the largest strip length designed to 55 meters (180.5 ft).

As part of the project the contractors were expected to perform two important tasks - (i) place the entire system, including preparation, within a four weeks time frame, and (ii) place the system during the day when traffic was constantly moving over the bridge.
The first-track would have been impossible using steel plates or external post tensioning. However, due to the nature of the system, and careful planning and application by the contractor, material was placed well within the expected time frame.

Sika had previously addressed the second issue. The issue of application on a dynamically moving system was tested at the Swiss Federal Laboratories for Material Testing and Research (EMPA). Laminates were applied to test beams under dynamic load, before testing to failure. The results showed no difference if the system was applied to a structure at rest.

The 55-meter (180.5 ft) laminate was the longest continuous strip of carbon fibre plate applied in the world. The strip was applied to the prepared substrate using the epoxy adhesive Sikadur-30, finger and roller pressure. The plate was then held in place without clamps due to the excellent green strength of the Sikadur-30 adhesive.

Narros Bridge Perth – FRP wrapping around columns (Photo)

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