Strengthening Structures Using Unstressed and Prestressed CFRP Plates

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Introduction

The use of composite materials for strengthening and rehabilitation of bridges and buildings is fast gaining momentum in Europe, America, Canada & Japan due to its many inherent advantages over the conventional methods of strengthening, not least in terms of durability and whole life costs. The main applications of composites in the construction industry in the last 7 years have been as bridge enclosures and storage tanks using GFRP, but more recently using CFRP pultruded plates to increase the flexural and shear capacity of existing structures. Research Projects are now underway to demonstrate the use of composites as deck units in new-build applications for carrying 40t loads in bridges and heavy industrial loads in buildings.

CFRP plates are now being accepted in the UK construction industry as an effective alternative to replacement and other traditional methods of strengthening. Over the past 18 months over 100 bridges and other structures have been strengthened with CFRP plates in the UK. Around 8,000 metres of plates have been used to strengthen bridges, culverts, shopping centre structures, industrial plants, power station structures and marine structures. This number is set to grow dramatically over the next year as a result of the positive findings contained in the final report (ref 1) of the 3 year, UK, Department of Trade and Industry sponsored ROBUST project, initiated and headed by Mouchel Consulting Limited, which was completed in July 1997.

Mouchel has recently held high level discussions with major asset owners outlining the benefits of the technique over conventional strengthening techniques, in terms of time and plant costs on site, and more importantly in terms of whole life costs. Mouchel is currently developing an outline business case to demonstrate the benefits of using composites for strengthening for a major infrastructure owner with in excess of 40,000 bridge spans, of which at least 15% are in need of strengthening and rehabilitation.

All bridges in Europe were supposed to carry 40 tonne vehicles by 1st January 1999, however, following assessment, many of the bridges in the UK have been found to be in need of strengthening or replacement and have not met this requirement. This has led to weight restrictions being imposed on many bridges around the UK, causing re-routing and severe disruptions, resulting in loss of trade. Extensive research work undertaken in the UK under the ROBUST project has demonstrated that CFRP plates can be used more economically than steel plates. Composite materials offer advantages such as low weight, excellent handle-ability, a range of elastic moduli, high resistance to corrosion, high strength, availability in long lengths avoiding the need for lapping, and good fatigue, creep and fire resistance

characteristics. In addition the CFRP plates can be pre-stressed, a technique which was successfully demonstrated under site conditions in the ROBUST project.

The ROBUST Project

As lead partner and manager of this recently completed project, Mouchel has been responsible for initiating and implementing one of the most comprehensive investigations ever undertaken into the use of advanced composite materials in the construction industry.

The consortium was set up involving all facets of the construction process to develop the technique. It included a client authority, Oxfordshire County Council; three academic partners, The Royal Military College of Science, Oxford Brookes University & Surrey University; designers and project managers, Mouchel Consulting Limited; material suppliers, Sika Ltd, Vetrotex Ltd & Fibreforce Ltd and specialist contractors, Balvac Whitley Moran Ltd and Concrete Repairs Ltd. James Quinn Associates Ltd provided specialist composites advice.

The testing programme was devised to address as many of the potential risks to implementation as possible in order to allow development of realistic and practical design rules. Approximately 130 flexural tests using pre-stressed and unstressed plates were carried out on model beams in the laboratory and also on actual beams removed from an existing deteriorating bridge at a purpose built test facility in Oxford. In addition 110 tests on the composite materials were carried out to characterise the materials and to examine them for long term durability.

To supplement the experimental work, Mouchel carried out non-linear, 3 dimensional finite element analysis to calibrate the performance of the beams in the laboratory tests and to provide sufficient data for development of design guidance. The consortium has drawn up a specification for CFRP plate bonding.

The results of the ROBUST project have indicated that plate bonding using CFRP plates is a viable and cost effective alternative to other methods of strengthening. The method can be applied to a wide range of structural types to increase their flexural capacity.

Bonding with CFRP plates

CFRP plates can be bonded to concrete, masonry, timber, cast/wrought iron and steel. Bonding the CFRP plates requires similar preparation to that of conventional steel plate bonding. The substrate must be good, prepared by grit blasting and then vacuumed to remove dust. The adhesive is applied to both the substrate and the plate, as shown in Figures 1 & 2. The CFRP plate is then offered up to the substrate manually (being light enough to lift), pressed and rolled into position with no need for props or bolts. Clearly, CFRP plate bonding is a much quicker operation than steel plate bonding and results in cost savings in plant and time.

As a result, the industry is increasingly turning to CFRP plates to strengthen conventional structures in flexure, to cure deflection problems in buildings and to strengthen masonry walls against earthquake and blast loads.

Figure 1

Figure 2

Actual CFRP plate bonding projects

Mouchel has recently been involved in providing carbon fibre strengthening design solutions to a number of buildings and bridge structures. Listed below are a few examples of current or completed CFRP strengthening schemes.

Hythe Bridge, Oxfordshire, UK

Mouchel was appointed by Oxfordshire County Council to investigate the possibility of strengthening Hythe Bridge, a historic cast iron structure, constructed in 1861 and servicing a major arterial route into Oxford (Figure 3). Assessment of the existing structure showed that it was capable of carrying 7.5t and needed to be strengthened to 40t. A feasibility study was undertaken by Mouchel to evaluate all the possible options for the bridge including re-construction. The report concluded that the most cost-effective way of strengthening the bridge was to use pre-stressed CFRP plates, a technique, which had been demonstrated in the recently completed ROBUST project. It was necessary to stress the plates to mobilise locked-in dead load stresses in the cast iron beams to enable them to carry live loads. Alternative techniques such as steel plate bonding or unstressed CFRP plate bonding proved expensive and impractical due to limited headroom requirements. Re-construction was by far the most expensive option, and would have involved road closures presenting unacceptable costs and disruption.

Figure 3: Hythe Bridge, Oxford

Mouchel developed an all-purpose pre-stressing device to undertake this strengthening scheme. The device was developed such that the end anchorages could be clamped to the bottom flanges of the cast iron beams, eliminating the need to drill into the cast iron, which is basically a brittle material. Trials were carried out on a site in Oxfordshire to demonstrate the newly developed device and its applicability to cast iron, before approval was given to go-ahead with the actual contract. The trials proved successful, and one span of the bridge, which includes 16 beams, is currently being strengthened, with the second span due to be completed by the end of April 1999. A total of 500 m of CFRP plates, manufactured by Fibreforce Ltd, were used for this contract. The adhesive was supplied by Exchem Ltd. The scheme costs were estimated to be £100,000 cheaper than any other strengthening alternative. The system can be applied to any beam that has a flange and is particularly useful where conventional strengthening is restricted by access. Major asset owners are now considering the technique for use on their structures. This is the first metal structure in the world where pre-stressed CFRP plates have been used.

Haversham Bridge, Milton Keynes, UK

Mouchel in conjunction with Concrete Repairs, a specialist contractor, were appointed by Milton Keynes Council to strengthen Haversham Bridge to the new 40 Tonne EC weight limit. Haversham Bridge carries a single carriageway over the Great Ouse River and has a three span reinforced concrete beam and deck slab spanning 50 metres. Using this innovative plate bonding technique, the longitudinal beams were strengthened using CFRP plates bonded to their top surface to give extra hogging flexural capacity, the first application of its kind in the UK. Figure 4 shows the CFRP plates being bonded on the top of the deck on one side of the road.

Figure 4: Haversham Bridge, Milton Keynes

The other lane was kept open during this operation. 768 m of CFRP plates manufactured by Fibreforce Ltd were bonded to the deck using a specially developed structural adhesive, supplied by Sika Ltd. Special consideration was given to the temporary effect of increased temperature on the plates during re-surfacing of the road. The CFRP plate bonding method proved to be much cheaper than the steel plate bonding technique, with the added value of improved durability.

Devonshire Place Bridge, Skipton, UK

Mouchel was appointed by North Yorkshire County Council to repair Devonshire Place Bridge in Skipton, North Yorkshire. The bridge has a pre-cast pre-stressed concrete hollow sectioned edge beam. A number of the tendons in the edge beam were damaged during an inspection, weakening the edge of the bridge.

Using knowledge gained from the extensive work done on project ROBUST, a single sheet of Carbodur plate, manufactured by Sika Ltd, was bonded to the underside of the bridge to replace the lost flexural capacity. The traditional approach of bonding steel plates was clearly not suitable for this bridge due to access restrictions, and also the fact that the existing concrete was not thick enough to support bolting. The plate was bonded to the bridge with a specially formulated 2-part cold curing paste epoxy adhesive supplied by Sika. The plate bonding required no bolts or scaffolding, and the bridge remained open during the process, which was completed within one day.

Chocolate Factory, Tutbury, UK

The main beams supporting floors in a chocolate factory in Tutbury were strengthened using CFRP plates as shown in Figure 5. 11 beams were required to have their flexural capacity increased by 30% to cater for installation of new plant and processing equipment. This was achieved by bonding 120 mm wide by 1.2 mm thick strips of CarboDur plates to the soffits of the beams. Around 100 m of CFRP plates were required. No heavy scaffolding equipment was required, which meant minimum disruption to the factory operations, which was a major requirement of the contract.

Figure 5: Nestle Factory, Tutbury

Abertillery Leisure centre, Wales

Beams in a swimming pool in Gwent were strengthened using 100 metres of CarboDur plates. In this instance, corrosion of the reinforcement and loss of section of the concrete due to chloride ingress had weakened the structure considerably, and carbon fibre strips were bonded to the soffits to re-instate the lost capacity, following remedial works on the concrete. This solution was particularly welcomed, as carbon fibre is very resistant to aggressive environments.

MerseyWay Shopping Centre, Stockport, UK

Floor beams supporting shop units in this shopping complex were strengthened using around 40 m of CarboDur plates. In this instance the new tenants of the units required additional floor space and increased floor loading, which necessitated some supporting members to be removed. The adjacent members were thus strengthened with the CFRP plates prior to

removal of supports. The strengthening works were carried out in under 2 days, with minimal equipment required and little disruption to adjacent shop units, highlighting the benefits of the technique.

Applications of the CFRP plate bonding technique

Although the work carried out under the ROBUST project investigated the use of the technique on concrete structures, it can equally be applied to other materials such as wood, cast iron, wrought iron and steel. However, it is important that the right adhesive is chosen to ensure that the integrity of the bond is maintained for the life of the structure. As outlined in the Hythe Bridge example above, the CFRP plate bonding technique has been further developed by Mouchel to incorporate strengthening of metal structures. This has important implications for many of the older structures owned by organisations such as London Underground, Railtrack, Highways Agency and Local Authorities. It has now been demonstrated that these structures can be strengthened to current standards using this novel technique.

Applications of composites for decking units and for new-build applications

Many reinforced concrete decks and orthotropic steel deck members on existing bridges today are suffering from major problems due to corrosion and are in need of replacement. Existing technologies are expensive and time-consuming and involve bridge closures, which bridge owners under extreme pressure to minimise. As composites have started to make an impact in the construction industry in plate bonding applications due to their lightness, ease of installation and low maintenance costs, it has become quite clear that a composite alternative is required to help alleviate this problem.

A strong and lightweight decking system for bridges and buildings is currently being developed in advanced composites by a European consortium led by Mouchel. The four-year research project, worth £2.8-million, has started with £1.5-million funding from the EU Brite-Euram III Programme.

Called ASSET (Advanced Structural System for Tomorrow's Infrastructure) the innovative decking is formed by pultruding advanced composites through a die to produce lengths of multi-cell prismatic profiles. These can be rapidly assembled into a multitude of structural shapes for different load bearing applications.

It will provide a complete structural system for small to medium sized bridges and buildings, and act as a heavy-duty deck or flooring system. Such adaptability will bring far-reaching benefits to infrastructure owners, developers and contractors.

The profile has been designed to make the best structural use of the properties of advanced composites. Top European composites manufacturer Fiberline A/S is developing the pultrusion dies for ease of manufacture of the profiles.

ASSET's greatest advantages over traditional structural materials are its enhanced durability, much lower weight, superior strength, speed and ease of construction. These, together with its good fire resistance, improved fatigue performance and minimal maintenance requirements, will provide engineering structures with low whole-life costs.

A full-scale ASSET highway bridge to carry 40-tonne vehicles will be constructed for Oxfordshire County Council in year 2001. It will be monitored by Oxfordshire's engineers and the resulting performance data made available for acceptance by technical approval authorities and for proof of the technology.

Conclusions

Advanced composites are increasingly being used in the construction industry due to their inherent advantages over traditional materials including their lightweight, high strength, ease of application and low maintenance costs.

CFRP plate bonding has been shown to be a viable alternative to steel plate bonding, with savings in both cost and time. The benefits of the technique for rehabilitation of structures have been demonstrated within the extensive programme of laboratory and field-testing. Application of numerical modelling for prediction of beam behaviour when strengthened with CFRP plates has been shown to give extremely good agreement with the results of the laboratory and field tests. Design procedures and a specification have been developed.

The performance of composite materials when subjected to harsh environmental conditions has shown to be superior to steel. The technique can be applied to materials other than concrete. Confidence among clients is growing rapidly following implementation of early applications in the UK, to the extent that major asset owners are now developing outline business cases to demonstrate the economic advantages of using composites in place of traditional materials. It is envisaged that composites will soon be used as the primary load bearing components in new-build applications. It is hoped that the advantages of using composites will soon be apparent to an increasing number of clients leading to greater market demands and further cost benefits.

Reference

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