

## INNOVATIVE ASSET MANAGEMENT

### Full Paper

# **DEVELOPMENT OF A USER FRIENDLY GUIDE FOR REHABILITATION OR STRENGTHENING OF BRIDGE STRUCTURES USING FIBER REINFORCED POLYMER COMPOSITES**

**A Nezamian and S Setunge**

*CRC for Construction Innovation*

*School of Civil and Chemical Engineering, RMIT University,*

[abe.nezamian@rmit.edu.au](mailto:abe.nezamian@rmit.edu.au) & [sujeeva.setunge@rmit.edu.au](mailto:sujeeva.setunge@rmit.edu.au)

## ABSTRACT

A worldwide interest is being generated in the use of fibre reinforced polymer composites (FRP) in rehabilitation of reinforced concrete structures. As a replacement for the traditional steel plates or external post-tensioning in strengthening applications, various types of FRP plates, with their high strength to weight ratio and good resistance to corrosion, represent a class of ideal material in external retrofitting. Within the last ten years, many design guidelines have been published to provide guidance for the selection, design and installation of FRP systems for external strengthening of concrete structures. Use of these guidelines requires understanding of a number of issues pertaining to different properties and structural failure modes specific to these materials. A research initiative funded by the CRC for Construction Innovation is currently underway (primarily at RMIT) to develop a decision support tool and a user friendly guide for use of fibre reinforced polymer composites in rehabilitation of concrete structures. This paper presents the development of the user friendly guide and recommended procedures for the design and construction of externally bonded FRP systems for strengthening of aging reinforced concrete bridge based on the design guidelines reported by ACI committee 440, the European design guideline (FIB 14), AS 3600 (2002) and Austroads Bridge design code (1992).

**Keywords: Bridges, rehabilitation, strengthening, user friendly guide line, design and construction.**

## 1 INTRODUCTION

Rehabilitation and upgrading of existing civil engineering infrastructure has been of great importance during the last decades. There are number of situations where the structural capacity of a structure in service needs to be increased. Fibre reinforced composite (FRP) systems can be used for the strengthening or retrofitting of existing concrete structures to resist higher design loads, correct deterioration-related damage, or increase ductility. These advanced composites used in bridge rehabilitation are being developed from fibres, polymers, metals and composites of these materials. While the concept of composites have been used in building industry for several millennia, the application of fibre reinforced polymer (FRP) for rehabilitation and strengthening of reinforced concrete structures is relatively new. Externally bonded FRP systems have been used to strengthen and retrofit existing concrete structures overseas and in Australia, eg, Westgate Bridge and Little Bridge Victoria (Kalra and Neubauer, 2003 and Shepherd and Sarkady 2002). The number of projects utilizing FRP systems has dramatically increased worldwide, from a few ten years ago to several thousand today (Bakis et al. 2002). The FRP composites combine the strength of the fibres with the stability of the polymer resins. They are defined as polymer matrix, that are reinforced with fibres or other reinforcing material with a sufficient aspect ratio (length to thickness) to provide a desirable reinforcing function in one or more directions. The FRP composite materials are different from traditional construction materials such as steel, aluminium and concrete because they are anisotropic; i.e., the properties differ depending on the direction of the fibres.

FRP composites gain their strength largely from the fibres, which are usually glass, carbon, or Aramid fibre. FRP materials are lightweight, non-corrosive, non-magnetic and exhibit high tensile strength. Additionally, these materials are readily available in several forms ranging from factory made laminates to dry fibre sheets that can be wrapped to conform to the geometry of a structure before adding the polymer resin. Although the fibres and resins used in an FRP system are relatively expensive compared with traditional strengthening materials like concrete and steel, labour and equipment costs to install FRP systems are often lower. FRP systems can also be used in areas with limited access where traditional techniques would be difficult to implement.

Due to the characteristics of FRP materials, behaviour of FRP strengthened members, and various issues regarding the use of externally bonded reinforcement, the development of design guidelines for FRP system is ongoing in Europe, Japan, Canada and the United States. Within the last ten years, many design guidelines have been published to provide guidance for the selection, design and installation of FRP systems for external strengthening of concrete structures. However there is still little independent user friendly guidance on the design and construction of the FRP strengthening systems. Some FRP suppliers provide limited advice but this tends to be system specific and may not be compatible with Australian design codes. Because of this lack of design and construction guidance, a user friendly guide in rehabilitation and strengthening of reinforced concrete bridge structures is being developed as part of the CRC-Construction Innovation funded project of "Decision Support Tool in Rehabilitation of Concrete Infrastructures", which would be applicable to all types of FRP and all strengthening systems, and set in the context of the Australian codes and standards. The aim of this paper is to briefly describe the background, nature and mechanics of producing the user guide. Set in the context of limit state philosophy, the guide provides design guidance on flexural and shear strengthening of the beam and columns, and flexural, axial compressive and ductility

enhancement of columns. The construction procedures are also briefly explained including material types and properties, field applications, workmanship and installation.

## **2 SCOPE OF THE USER GUIDE**

The user guide generally aims to provide design and construction guidance on strengthening of concrete structures with fibre composite materials in accordance with Australian design codes and standards. The design procedures are the key feature of the guide, which may be applicable to all FRP materials and strengthening techniques. The procedures are based on generally accepted principles, and in line with the approaches developed elsewhere based on extensive research, particularly such as in USA and Europe. The material and physical properties of FRP materials and manufacturing methods are reviewed in so far as they have a direct impact on the design and construction of the FRP strengthening system. Information on the properties of commercially available materials is also presented and a list of the suppliers and their contact details are included. Surface preparation of the substrate concrete and installation of FRP are vital aspects and have therefore been covered in the guide. Some guidance in quality control and inspection and monitoring are included.

It is required to assess suitability of an FRP system for a particular application. A condition assessment of the existing structure should be performed and the best treatment option should be then determined based on the assessment (ACI, 440, 2002). The condition assessment can be performed based on AS 3600(2002), Austroads Bridge design code (1992) and other related Australian codes and standards. The recommended assessment procedures are outlined in the user guide.

## **3 MATERIAL PROPERTIES**

FRP composite materials for strengthening of civil engineering structures are available today mainly in the form of:

- thin unidirectional strips (with thickness in the order of 1 mm) made by pultrusion
- flexible sheets or fabrics, made of fibres in one or at least two different directions, respectively (and sometimes pre-impregnated with resin)

FRP systems come in a variety of forms, including wet lay-up systems and pre-cured systems. FRP system forms can be categorized based on how they are delivered to the site and installed. The FRP system and its form should be selected based on acceptable transfer of structural loads and ease and simplicity of application. The manufacture of FRP materials is outlined and some general guidance on selection of FRP system and materials for particular strengthening applications are also provided. Indicative physical and mechanical material properties of some FRP prefabricated strips and fibres are included in the guide. The other related aspects of FRP materials such as durability, fire and electricity resistance, safety and environmental impact on material properties for different types of fibres are also discussed.

## 4 STRENGTHENING TECHNIQUES

To help the users in selection of an appropriate strengthening system, a brief summary of the available strengthening techniques and projects where externally bonded FRP has been applied for rehabilitation of existing concrete structures have been given. The references to published articles and guidelines are provided wherever possible. These will provide the users with a source of further information and help to identify and select the most suitable technique for a particular case of strengthening.

## 5 DESIGN GUIDELINES

Since the use of FRP composites for strengthening of reinforced concrete structures is a relatively new technique, the development of design guidelines for externally bonded FRP system is ongoing in Europe, Japan, Canada and the United States. Within the last ten years, many design guidelines have been published to provide guidance for the selection, design and installation of FRP systems for external strengthening of concrete structures. Applications of provisions of the two major guidelines of Task Group 9.3 of the international Federation for Structural Concrete published bulletin 14 (FIB 14) and ACI Committee 440 in rehabilitation of the headstock were discussed and compared by Nezamian and Setunge (2004). It was then concluded that the use of ACI 440 design guideline may be more appropriate for FRP strengthening applications in Australia. The design concepts and philosophy used by ACI is similar to those adopted by AS3600 (2002). However, in considering the failure of FRP composites in de-bonding and anchorage zones, use of FIB appears to be more appropriate since it systematically covers all possible scenarios. The design guidance in the user friendly guideline is developed mainly based on the ACI 440 (2002) recommendations. The FIB recommendations in preventing the delamination of the FRP were included to check debonding.

## 6 DESIGN GUIDANCE

In accordance with the Australian codes of practice for structural design, the design methods are based on limit-state design philosophy. This ensures that a strengthened member will not become unfit for its intended use. It will not also fail at an accidental overload during its design life with 95% confidence. All necessary design situations and load combinations need to be considered according to Austroads Bridge design code (1992). This approach sets acceptable levels of safety against the occurrence of all possible failure modes. The nominal strength of a member is then assessed based on the possible failure modes and subsequent strains and stresses in each material (see Figure 1).

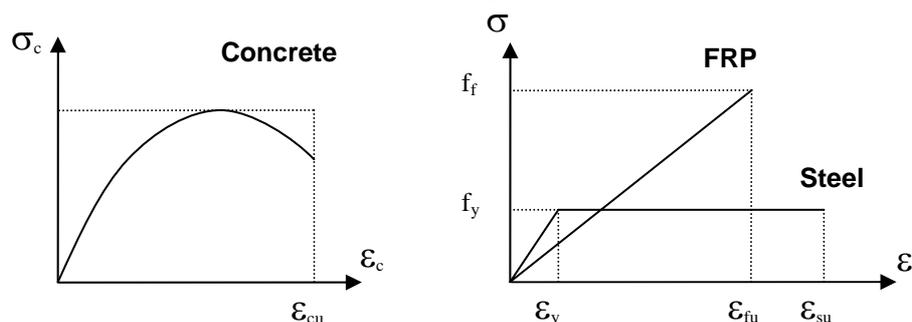


Figure 1: Idealised stress-strain curves for constitutive materials at ULS

The design of the FRP composites involves assessing the effects of the additional FRP reinforcement provided to the section (designed assuming full composite action) and the ability of transferring forces by means of the bond interface. All possible failure modes should be investigated for a FRP strengthened section (Ganga Rao and Vijay 1998). In general, the failure modes can be subdivided to those assuming full composite action between the reinforced concrete / pre-stressed concrete member and the FRP and those verifying the different de-bonding mechanisms that may occur. The state of the structure prior to strengthening is taken as a reference for the design of the externally bonded FRP reinforcement. The strength of strengthened member depends on the controlling failure mode. However, the user guide identifies and discusses limit states relevant to the use of FRP for strengthening and rehabilitation of concrete structures. It also includes checks for FRP separation and other requirements, which are peculiar to this method of construction. The user guide contains procedures for the Flexural, shear and torsional strengthening of the beams and slabs and axial compressive and ductility enhancement of columns. The recommended design procedures are briefly reviewed in the following subsections. Worked examples will be provided illustrating each design scenario.

## **6.1 FLEXURAL STRENGTHENING**

Bonding FRP to the tensile soffit of the beam increases the flexural strength of the concrete elements. In the section analysis for the ultimate state in flexure, the user guide follows well established procedures using the idealised stress-strain curves for concrete, FRP and longitudinal reinforcement (Figure 1). These curves, along with the following assumptions, form the basis for the capacity analysis of a concrete element strengthened in flexure. Design calculations are based on the actual dimensions, internal reinforcing steel arrangement, and material properties of the existing member being strengthened.

- The strain in reinforcement and concrete are directly proportional to the distance from the neutral axis, that is, a plane section before loading remains plane after loading.
- There is no relative slip between external FRP reinforcement and the concrete
- The shear deformation within the adhesive layer can be neglected since the adhesive layer is very thin with slight variations in its thick

The cross section analysis identifies all possible failure modes. Failure of the strengthened element may then occur as a result of various mechanisms as follows:

- Crushing of the concrete in compression before yielding of the reinforcing steel
- Yielding of the steel in tension followed by rupture of the FRP laminates
- Yielding of the steel in tension followed by concrete crushing
- Shear/tension de-lamination of the concrete cover
- De-bonding of the FRP from the concrete substrate

The design principles are shown in Figure 2

### **6.1.1 Anchorage**

Experimental investigations show that the FRP rupture is a rare event and de-lamination of FRP strips is more likely to occur before stress in the FRP reach the

ultimate level. De-bonding implies the complete loss of composite action between the concrete and FRP laminates. Bond failure will be a brittle failure and should be prevented. The guide place a limitation on the strain level in the laminate to prevent de-lamination of FRP from the concrete substrate.

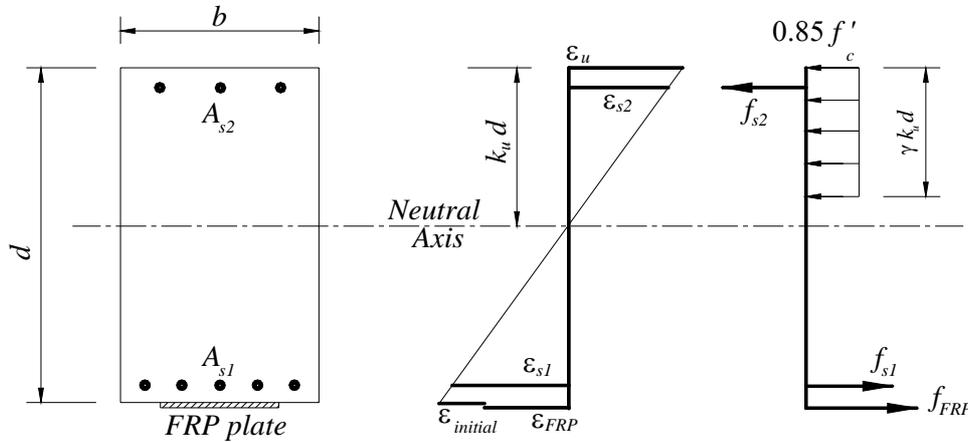


Figure 2: Internal strain and stress distributions for the beam cross section

With due consideration to the conclusions of the comparison between the ACI and the FIB guidelines conducted by Nezamian & Setunge (2004), the following failure modes were also considered in the user guide to prevent de-lamination of FRP.

- De-bonding in an un-cracked anchorage zone
- De-bonding caused at flexural cracks
- De-bonding caused at shear cracks

## 6.2 SHEAR AND TORSIONAL STRENGTHENING

Externally bonded FRP laminates and fabrics can be used to increase the shear strength of reinforced concrete beams or columns. It can be seen that the shear capacity of columns can be easily increased by complete wrapping of FRP around the element. Shear strengthening of beams is likely to be more problematic due to the difficult access to all faces of a beam element. This increases the risk of debonding at the beam / slab junction. The design for shear strengthening of a reinforced concrete member is generally based on truss model and superposition principle with some considerations for the orthotropic behaviour of the CFRP material. The shear strength of a strengthened member is determined by adding the contribution of the CFRP reinforcing to the contributions from the concrete and shear reinforcement.

$$\phi V_n = \phi (V_{uc} + V_{us} + \psi_f V_f) \quad \text{Eq. 1}$$

To calculate the shear resistance of the FRP wrapping, the design strain in the FRP need to be evaluated. Its value depends on the failure mode of the strengthening member. The following failure modes are also considered to cover the possible failures.

- Loss of aggregate interlock
- FRP rupture

- Delamination of the FRP from the concrete surface

Design involves calculating the design strain and determining the shear capacity of the FRP wrapping system.

Strengthening for increased torsional capacity may be required in conventional beams and columns, as well as in bridge box girders. The principles applied to strengthening in shear are also valid in the case of torsion. There are a few minor differences, which are highlighted in the user guide.

### 6.3 STRENGTHENING OF THE COLUMNS

Bonding hoop FRP to the column surface enhances axial load capacity, shear capacity and ductility of columns. FRP wrapping exerts a continuously increasing confining action. The amount of this action depends on the lateral dilation of concrete, which in turn is affected by the confining pressure. Thus, FRP-confined concrete models should account for the interaction between the laterally expanding concrete and the confining device. Predictive equations of the ultimate strength and strain of FRP-confined concrete should also consider this peculiar behaviour. The confinement delays rupture of the concrete, thereby enhancing both the ultimate compressive strength and ultimate compressive strain of the concrete. The compressive strain to failure of the concrete due to the hoop wrapping should be known to calculate the effect of hoop wrapping in axial compressive enhancement of columns. The axial compressive strength of a strengthened concrete member confined with FRP wrapping may be calculated using the confined concrete strength. The formulations of the confinement model and axial capacity of the strengthened member are presented in the user guide.

The method of selecting the jacket thickness for a target displacement ductility factor  $\mu_{\Delta}$  is a relatively straightforward procedure: First the equivalent plastic hinge length  $L_p$  for a given column is calculated based on the yield stress and diameter of longitudinal rebars. From  $L_p$  and  $\mu_{\Delta}$  the curvature ductility factor  $\mu_{\phi} = \Phi_u / \Phi_y$  is established. The yield curvature  $\Phi_y$  may be found from moment-curvature analysis of the cross section, whereas the maximum required curvature  $\Phi_u$  may be obtained (again from section analysis) in terms of the ultimate concrete strain. Hence the required value for  $\epsilon_{cu}$  can be established and an appropriate confinement model can be used to solve for the required FRP thickness.

### 6.4 OTHER CONSIDERATIONS

The user guide suggested imposing reasonable strengthening limits to guard the strengthened member against failure of the FRP strengthening system and collapse of the structure due to fire, vandalism, or other causes. It is recommended that the existing strength of the structure be sufficient to a level of load as described by below Equation.

$$(\phi R_n)_{existing} \geq (1.2S_{DL} + 0.85S_{LL})_{new} \quad \text{Eq. 2}$$

where  $S_{DL}$  is dead load and  $S_{LL}$  is live load.

Environmental conditions affect the performances of the FRP system. The mechanical properties of FRP systems degrade under exposure to certain

environments, such as alkalinity, salt water, chemicals, ultraviolet light, high temperatures, high humidity and freezing and thawing cycles. The user guide accounts for this degradation using the environmental reduction factor for the design material properties of FRP.

## **7 SURFACE PREPARATION AND FRP INSTALLATION**

Clearly, the design guidance is only valid if the installation of the fibre composite materials is carried out correctly. Condition of FRP application should be examined carefully during the winter season or in cold zones. Temperature, relative humidity, and surface moisture at the time of installation can affect the performance of the FRP system. Conditions need to be observed before and during installation include surface temperature of the concrete, air temperature, relative humidity, and corresponding dew point. An auxiliary heat source can be used to raise the ambient and surface temperature during installation

If the FRP installation is to remain effective, focusing on the condition of the existing substrate is an essential requirement. The behaviour of concrete members strengthened or retrofitted with FRP systems is highly dependent on a sound concrete substrate and proper preparation and profiling of the concrete surface. An improperly prepared surface can result in debonding or delamination of the FRP system before achieving the design load transfer. All problems associated with the condition of the original concrete and the concrete substrate that can compromise the integrity of the FRP system should be addressed before surface preparation begins.

Externally bonded FRP systems should not be applied to concrete substrates suspected of containing corroded reinforcing steel. The expansive forces associated with the corrosion process are difficult to determine and could compromise the structural integrity of the externally applied FRP system. The cause(s) of the corrosion should be addressed and the corrosion-related deterioration should be repaired before the application of any externally bonded FRP system.

Some FRP manufacturers have reported that movement of cracks 0.3 mm and wider can affect the performance of the externally bonded FRP system through delamination or fibre crushing. Consequently, cracks wider than 0.3 mm should be pressure injected with epoxy. Smaller cracks exposed to aggressive environments may require resin injection or sealing to prevent corrosion of existing steel reinforcement. Prior to FRP installation, the surface of the concrete must be cleaned so that is free of laitance, dust, grease and other bonding inhibiting materials that are likely to effect bond strength between FRP and the concrete. Uneven concrete surface irregularities (off sets) must be ground and smoothed to less than 1 mm. Where fibres wrap around the corners of rectangular cross sections, the corners should be rounded to a minimum 13 mm radius to prevent stress concentrations in the FRP system and voids between the FRP system and the concrete. Roughened corners should be smoothed with putty. Obstructions, re-entrant corners, concave surfaces, and embedded objects can affect the performance of the FRP system and should be addressed. Obstructions and embedded objects may need to be removed before installing the FRP system. In applications involving confinement of structural concrete members, surface preparation should promote continuous intimate contact between the concrete surface and the FRP system (ACI 440, 2002).

## 8 QUALITY CONTROL AND INSPECTION

There will be a need to check the FRP strengthening system as part of the regular inspections and monitoring. Quality assurance and quality control programs and criteria are to be maintained by the FRP system manufacturers, the installation contractor and others associated with the project. The quality-control program should be comprehensive and all aspect of the strengthening procedures needs to be covered. Quality assurance is achieved through a set of inspections and tests such as adhesion testing, load testing and tensile pull-off test to evaluate acceptability of the FRP installation. A qualified inspector or licensed engineer shall observe all aspect of on site material preparation and application, including surface preparation, resin component mixing, application of primer, resin and FRP, curing of composite, and the application of protective coating. The surface of the fibre composite should also be inspected visually for signs of crazing, cracking or delamination. De-bonding of the FRP material from the concrete may be determined by acoustic tapping or thermography tests.

FRP strengthening system needs to be evaluated and accepted/rejected at the end of construction based on conformance with the design drawing and specifications. This includes FRP material properties, installation within specified placement tolerances, presence of the delaminations, cure of resins, and adhesion of the FRP material to substrate.

## 9 CONCLUSIONS

The paper described the development of the content of a user guide for design and construction of strengthening schemes using FRP composites for bridge structures complying with the Australian standards. After wide industry consultation, following areas were identified as essential elements to be included in the user guide. The paper describes reasoning behind the content of each segment and a brief description.

- Scope of the user guide
- Material properties
- Strengthening techniques
- Design guidelines
  - Flexural strengthening*
  - Shear and torsional strengthening*
  - Strengthening of the columns*
  - Safety considerations*
- Worked Examples
- Surface preparation and FRP installation
- Quality control and inspection

The user-guide being developed is the first of its kind published to the best of the authors' knowledge.

## 10 ACKNOWLEDGEMENTS

The work of preparing the user guide was supported and funded by Cooperative Research Center for Construction Innovation of Australia. The Department of Main Roads Queensland, Queensland, Australia also supports the project as the major industrial partner.

## 11 REFERENCES

- American Concrete Institute Committee 440, (2002). "Guide for the design and construction of externally bonded FRP systems for strengthening concrete structures"
- AS3600 (2002), "Concrete Structures", Australian Standard, Standards Association, Australia,
- Austrroads (1992), "Bridge design code", Section 2: Design loads
- Bakis, C.E.; Bank, L.C.; Brown, V.L.; Cosenza, E.; Davalos, J.F.; Lesko, J.J.; Machida, A.; Rizkalla, S.H.; and Triantifillou, T.C. 2002 "Fiber-Reinforced Polymer Composites for Construction-State-of-the-Art Review," *Journal of Composites in Construction*, V. 6, No. 2, pp. 73-87.
- GangRao, H.V.S., and Vijay, P.V. (1998) "Bending Behavior of Concrete Beams Wrapped with Carbon Fabric" *Journal of Structural Engineering*, V.124, No.1, pp. 3-10
- Kalra, R. and Neubauer, U. (2003). "Strengthening of the Westgate Bridge with Carbon Fibre Composites - A Proof Engineer's Perspective" *21st Biennial Conference of the concrete institute of Australia*, Brisbane, Australia, pp. 245-254
- Nezamian, A., Setunge, S. (2004). "Comparison between ACI 440 and FIB 14 Design Guidelines in Using CFRP for Strengthening of s Concrete Bridge Headstock" *Proceeding 4th International Conference on Advanced Composite Materials in Bridges and Structures*, July 2004, Calgary, Canada
- Nezamian, A., Setunge, S.,and Kumar, A. (2004). "Decision Support in Using Fiber Reinforced Polymer (FRP) composites in Rehabilitation of Concrete Bridge Structures" *Proceeding of Innovative Materials and Technologies for Construction and Restoration*, June 2004, Lecce, Italy
- Shepherd, B. and Sarkady, A. (2002) "Carbon Fibre Fabric Strengthening of Little River Bridge" *Proc. IABSE Symposium, Melbourne Australia*, Sept 11-13, 2002
- The international federation for structural concrete (CEB-FIB), technical report bulletin 14 (2002). "Externally bonded FRP reinforcement for RC structures"