FRP REINFORCEMENT IN CONCRETE STRUCTURES

Thanongsak Imjai [1]
Pratuang Inkoom [2]

[1] *Structural Engineer (thanongsak@iec-thailand.com)*
[2] *Managing Director (prataung@iec-thailand.com)*

International Engineering Consultants Co., Ltd, (IEC-Thailand)
Ratchadaphisek Road, Klongtoey, Bangkok, THAILAND

ABSTRACT : The increased use of FRP in reinforced concrete construction is largely driven by the requirement for improved durability especially for those applications subjected to the most severe environmental conditions. However, the adoption of FRP as embedded reinforcement in new structures has been much slower than in repair and strengthening applications. This is due to the limited availability of curved FRP reinforcing elements. In addition, the mechanical performance of the bent portions of FRP bars is significantly reduced under a multiaxial combination of stresses, and the tensile strength can be as low as 40% of the uniaxial tensile strength. This paper presents and discusses potential issues relating to the use of curved FRP bars as embedded reinforcement in concrete and uses as an example one of the case studies that was examined during the European funded Project, CurvedNFR. A 6 m long concrete plank reinforced with thermosetting FRP bars as longitudinal reinforcement and thermoplastic FRP strips as shear reinforcement was manufactured and tested. The use of FRPs allowed the reduction in the required concrete cover without compromising durability. This study shows that current design recommendations for FRP RC structures are effective in predicting deflections and crack widths at service load. It is also shown that in FRP RC, serviceability limit state can control the design.

KEYWORDS : *Curved FRP reinforcement, FRP, Design, Reinforced Concrete, Deflection, Crack width.*

1. INTRODUCTION

Fibre Reinforced Polymer (FRP) reinforcement has rapidly emerged as an effective alternative to conventional steel reinforcement to overcome the problem of corrosion[1]. Owing to its superior durability characteristics, the use of FRP reinforcement can extend the lifespan of concrete structures and reduce the need for maintenance or repair. However, although FRPs are already adopted quite extensively in various sectors of the construction industry (e.g. strengthening and repair of existing structures), their use as internal reinforcement for concrete is limited only to specific structural elements and does not extend to the whole structure. The reason for the limited use of FRPs as internal reinforcement can be partly attributed to the lack of commercially available curved or shaped reinforcing elements used for shear reinforcement or complex structural connections[1,2].

Most of the shaped steel reinforcing bars currently used in concrete structures are provided pre-bent and cut in the factory. These may be supplemented by a small quantity of special one-off shapes bent directly on site. Whether bending occurs on site or at the factory, conventional steel reinforcing bars have a major advantage since, due to their elastoplastic behavior, they can be easily formed by cold bending, and hence, most detailing needs can be easily met at very low cost. Existing guidelines for the cold bending of steel reinforcement specify, for mild steel, a bend radius to diameter ratio of 2 (for example BS 8666:2000[3]), which would induce a plastic strain value of 20% in the material (Figure 1). FRP bars in tension behave substantially as a linear material up to rupture. When cold bending FRP bars, however, the bar can either rupture in tension or fail due to buckling of the fibers located in the compression side. The typical ultimate longitudinal strain value of FRP products varies between 1% to 2.5%, hence, the amount of strain that is induced in the fibers needs to be carefully controlled to avoid premature failure of the reinforcing bar[4]. As a result, cold bending of FRP bars requires very large bend radius to diameter ratios as shown in Figure 1.

In cases where tight radii are needed (i.e. for the manufacture of shear links and hooks), preformed curved bars of FRP are required. The high production costs and lead times that are associated with the manufacturing of

FRP curved elements may reduce the interest in using FRPs for these types of applications. In addition, various studies[5, 6, 7] have shown that the tensile strength of FRP bars can substantially reduce under a combination of normal and transversal stresses. This phenomenon can often become an issue whenever non-straight unidirectional composite elements are used as concrete reinforcement, and especially when the fibers are designed to carry high tensile stresses, since premature failure can occur at the corner portion of the composite.

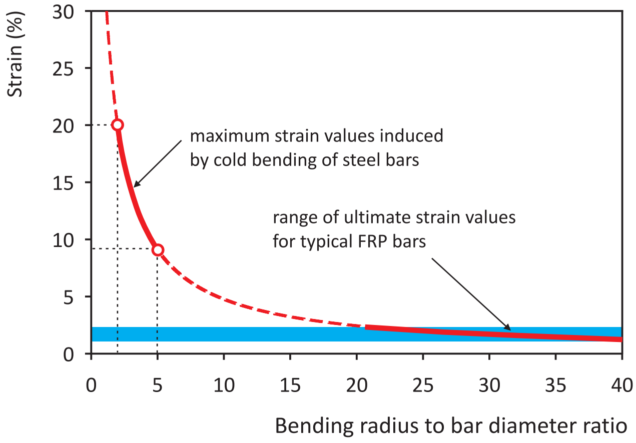


Figure 1 Strain induced in cold bent bar [4]

In fact, tests by different authors have shown that the tensile strength of a bent portion of a composite bar can be as low as 40% of the maximum tensile strength that can be developed in the straight part[5, 6]. The reduction in strength that occurs at the corners of an FRP bar can be quantified using empirical models such as the one initially proposed by the Japan Society of Civil Engineers (JSCE)[8], which is currently adopted in several design recommendations for FRP RC structures including those proposed by the American Concrete Institute Committee 440[9]; ISIS Canada[10] and the Institution of Structural Engineers[11]. However, the equation included in the current design guidelines to predict the strength degradation at the bent portion of a FRP bar is an empirically derived equation which is mainly a function of bar geometry and does not seem to yield consistent results when different types of composite are used[6]. Recent development of a macromechanical predictive model that is proposed by the author[7] could adequately capture strength degradation due to the change in geometry of the bent portion of the FRP bar.

One of the main advantages of using FRP reinforcement is that the concrete cover can be kept to a minimum and thin and light structural elements can be developed. One such example is the support structure for a light transport system which will be used as an example of an FRP RC structure which needed extensive use of curved FRP. This paper will introduce this structure and present some of the experimental work undertaken during the design stage. The main issue that needed to be examined was compliance with the serviceability limit stages.

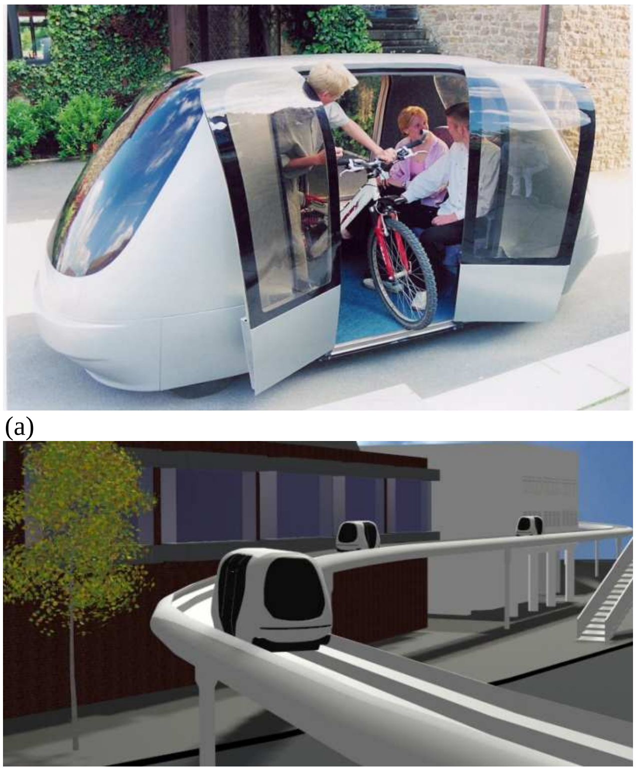
The experimental testing program conducted in this study was part of the CurvedNFR project [12] funded by the European Commission Framework 5 GROWTH Program, aiming to develop material, methodology and manufacturing process for a low-cost, curved fiber reinforced plastic (FRP) rebar. The project partnership, which ended in 2005, included 8 specialist SME (Small and Medium-size Enterprises) and 3 RTD (Research and Technology Development) organizations across 6 European countries.

2. ULTRA GUIDEWAY PROJECT

The ULTra-light Transport (ULTRa)[13] guideway project was used by CurvedNFR as a case study to design and analyse an RC plank using straight and curved FRPs as internal reinforcement. Before giving more structural details, a brief introduction is presented on the ULTra system.

2.1 The ULTRa system

This transport system, ULTra, offers an advanced form of environmentally friendly personal transport system that uses a fleet of low power, electrically driven vehicles on a dedicated guideway network of routes (see Figure. 2). The system is designed so that there is no waiting, no stopping and no transfers.


(a)

(b)

Figure 2 (a) Driverless automatic ULTra vehicle (a) and (b) artistic impression of the overhead portion of the ULTRa guideway system

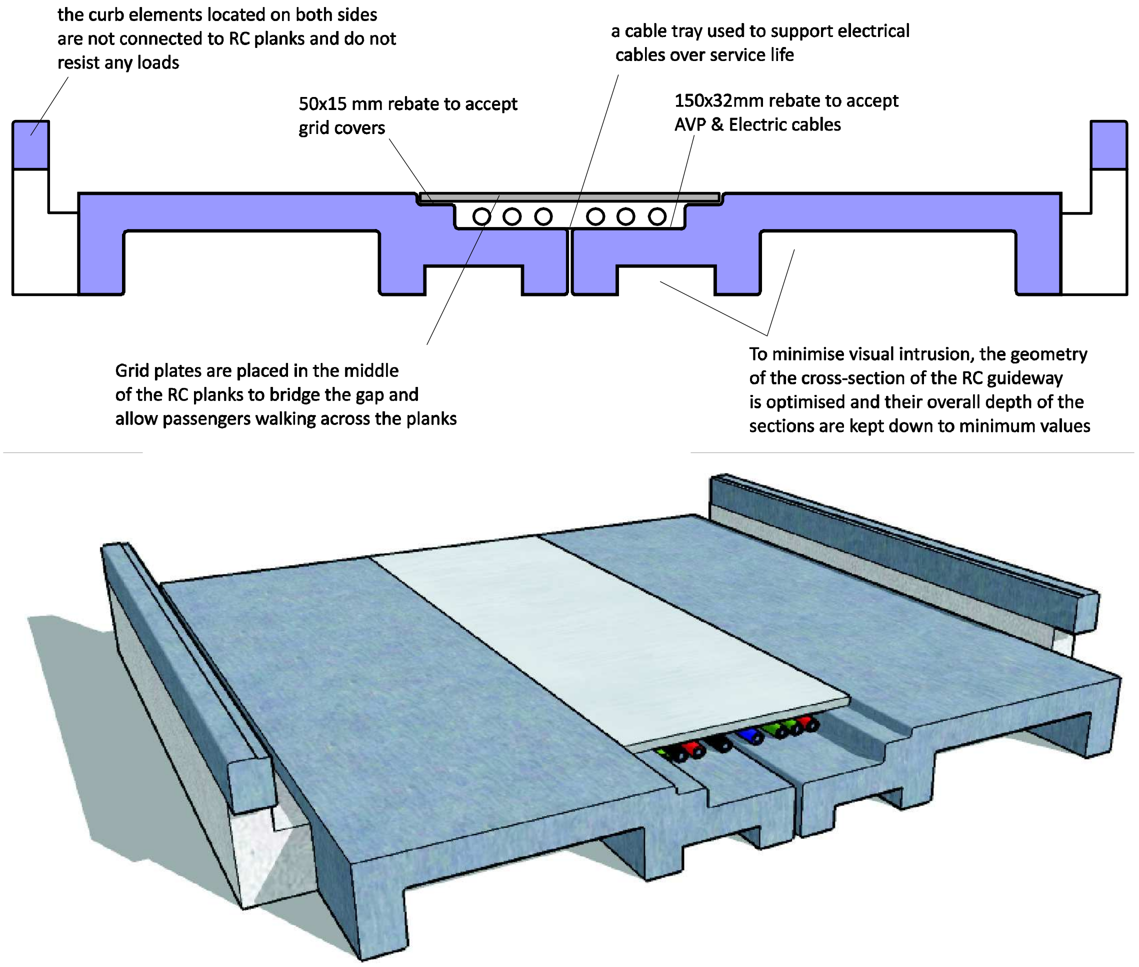


Figure 3 Cross section of ULTra guideway

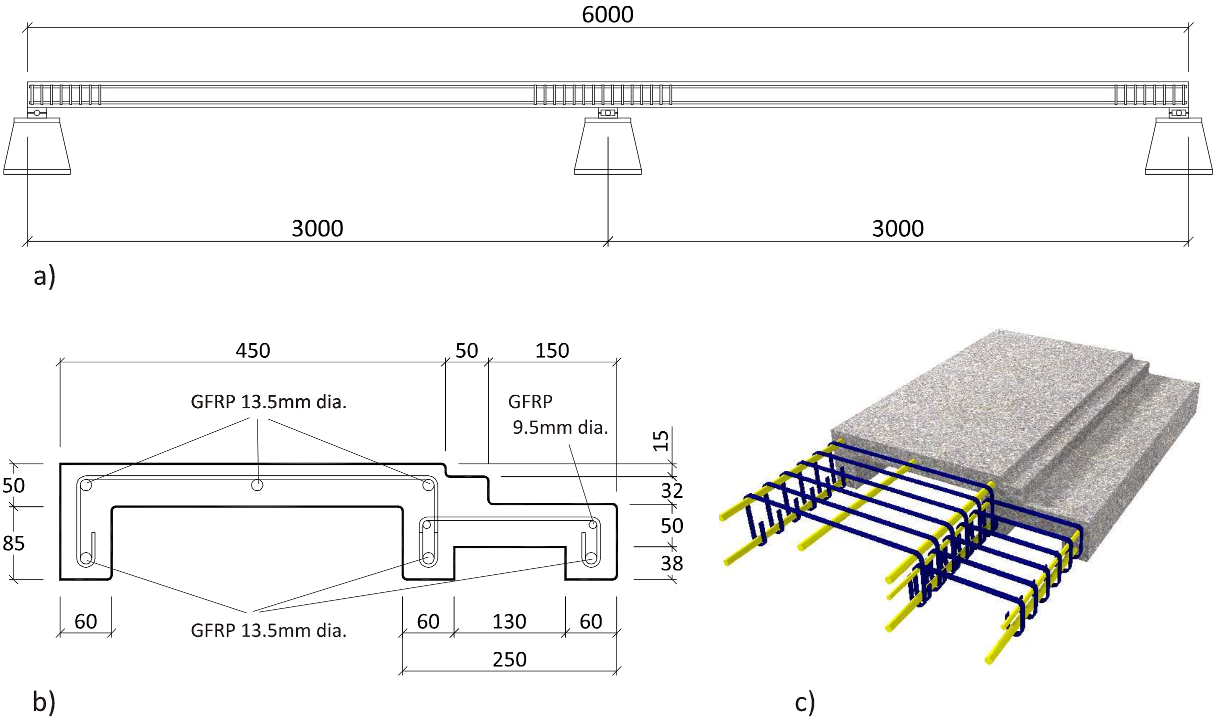


Figure 4 Reinforcement arrangement for the ULTra guideway (a) and cross section of the guideway (b, c) (all measurements in mm). The concrete section is reinforced with glass FRP bars and the shear links are made of glass fiber thermoplastic strips

Important aspects of the ULTra guideway project included: 1) analysis of the environmental impact of the infrastructure; 2) visual intrusion from the overhead portions of the structure (Figure 2b) evaluation of the durability of the structural elements. As a result, a very slim guideway system was conceived and FRP reinforcement was chosen to reinforce the concrete planks to provide an elegant and durable solution and limit the overall weight and deflections. The optimised cross-section is shown in Figure 3. The main structural elements are two independent RC planks.

2.2 FRP RC Plank design

The geometry of the cross section of the reinforced concrete guideway has been optimised during the design and an attempt was made to keep the overall depth of the structural elements down to minimal values to reduce visual intrusion (Figures 3 and 4). A span/effective depth of 27 was selected to avoid excessive deflections and to verify the suitability of simple design rules when applied to FRP RC elements. The design process focused on providing sufficient reinforcement to resist the applied loads (ultimate limit state design) and to control deflection and cracking under operating conditions (service limit state design). The design recommendations proposed by ACI committee 440[9] and the IStructE[11] were adopted at the design stage. Standard sectional analysis was used to determine the flexural properties of the FRP RC section. At the ultimate limit state the RC section was designed to fail due to concrete crushing in compression (over-reinforced section). However, it should be noted that the design was governed by the serviceability limit state of deflection and cracking. The maximum deflection allowed at service was 12 mm (span/250) and the maximum crack width was 0.5 mm.

3. TEST PROGRAM

3.1 Beam preparation and material properties

Glass FRP thermosetting bars (f_{fu}=700 MPa, ε_{fu}=0.017 and E_f=45 GPa) were used as longitudinal reinforcing material, and shear reinforcement was provided in the form of links manufactured from FRP thermoplastic strips (f_{fu}=720 MPa, ε_{fu}=0.019 and E_f=28 GPa). Owing to the physical characteristics of FRP, the overall weight of the reinforcing cage was only about 13.5 Kg, which amounts to about 2% of the total weight of the concrete. By comparison, a similar reinforcing cage made of steel reinforcement would weight approximately 50 Kg (8% of the total weight of the concrete). The thermoplastic shear links were bent in the laboratory at the University of Sheffield by heating the composite with an air gun at a controlled temperature and shaping it around a custom made mould. The geometry of the specimen is illustrated in Figure 4b along with a schematic view of the cross section showing the reinforcement details.

Foil-type electric strain-gauges were positioned at various locations along the flexural and shear reinforcement to monitor variations in strains. The positions where the strain gauges were to be located were accurately marked on each bar and link and the surrounding areas were appropriately prepared to guarantee a successful installation of the gauges. Prior to the application of the gauges on the GFRP bars, glue was used to seal the surface. Cement glue was used to attach the strain gauges to the bars and electrical wires were soldered to the terminal of each gauge for subsequent connection to the data logger. A ready mixed concrete obtained from a local supplier was used to manufacture the test specimens. The specifications of the mix were: concrete C40 with 10 mm maximum aggregate size and cement type OPC with a slump of 100 mm.

3.2 Test set-up

Figure 5 shows the loading patterns to which the beam was subjected during two successive phases of testing.

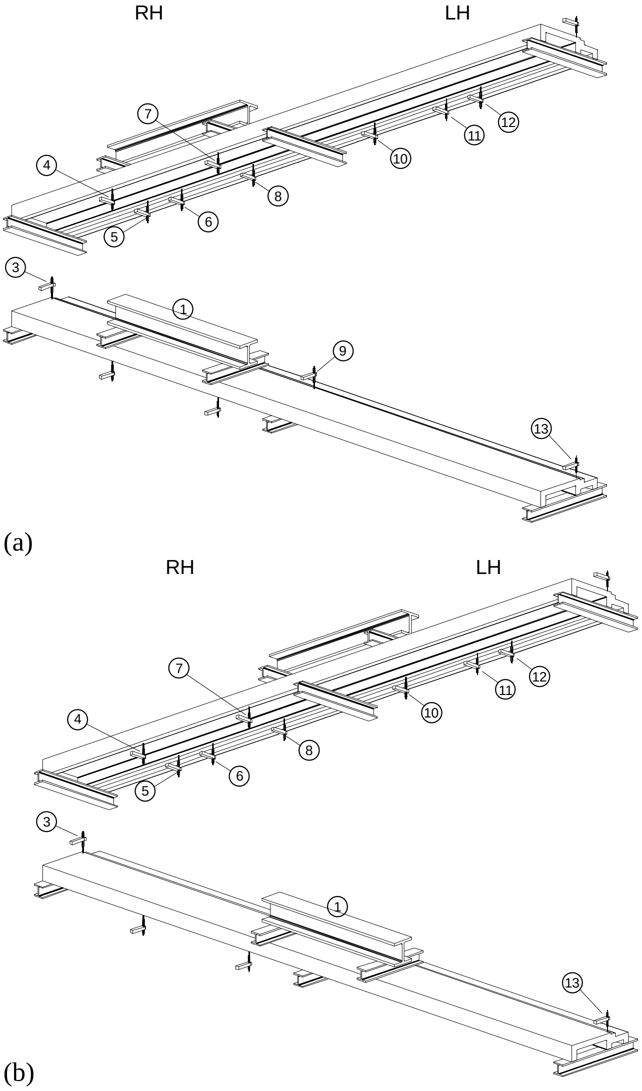


Figure 5 Test set-up and instrumentation for (top) load case 1 and (bottom) load case 2

Load case 1 (Figure 5a) was applied to generate the maximum positive bending moment in the RH span, whilst the load case 2 (Figure 5b) was applied to generate the maximum negative moment over the central support. In both cases, the load was applied in increments of about 1 kN. At each load step, cracks were marked and the widths of selected target cracks were measured. Overall deflections of the beam were measured at different locations using several Linear Variable Displacement Transducers (LVDTs).
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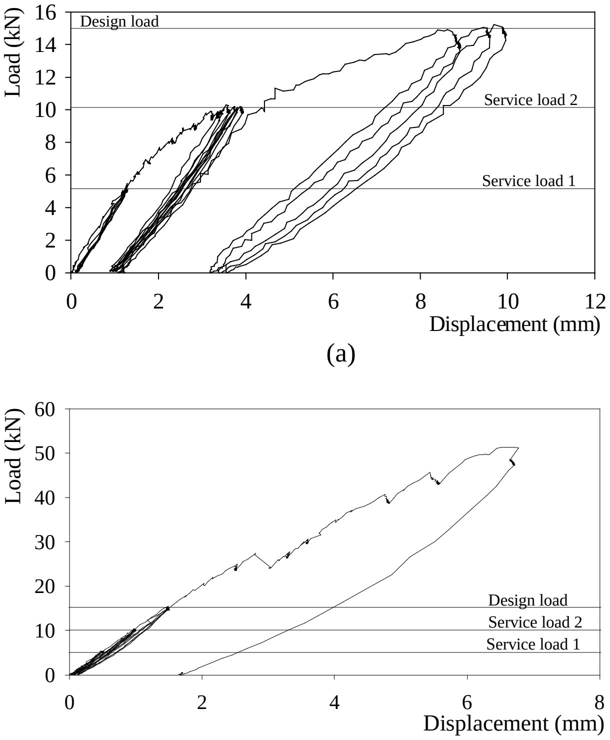
4. DISCUSSION OF THE RESULTS

Three load cycles were performed at load levels corresponding to (a) the load induced by standard ULTra passenger-carrying vehicles (service load 1, about 5 kN); (b) the load induced by a road sweeper (service load 2, about 10 kN) and (c) the design load (1.5 times the maximum service load, about 15 kN). In the case of load case 2, after reaching the design load, the applied load was increased to about 50 kN with no severe repercussions on the structural integrity of the RC element. The load–displacement behavior for both load cases is shown in Figure 6.



(a)

(b)

Figure 6 Load-deflection response of ULTra beam: load condition 1 (top) and load condition 2 (bottom)

Table 1 shows a comparison of the results obtained from the test performed during the first phase of testing (load case 1) with the values predicted according to the recommendations proposed by the American Concrete Institute for the design of concrete structures reinforced with Fibre Reinforced Polymer Reinforcement. This table shows clearly that conservative values are generally predicted by the design recommendations and that the tested FRP reinforced beam meets all of the serviceability requirements.

Table 1 Test results and design equation predictions: Load condition 1

Load stage	*Prediction*		*Experiment*	
	w_{max} (mm)	δ_{max} (mm)	w_{max} (mm)	δ_{max} (mm)
Service load 1	0.15	4.75	0.10	1.3
Service load 2	0.29	9.19	0.25	3.6
Design load	0.41	11.97	0.35	8.8

5. CONCLUDING REMARKS

Based on the experimental work undertaken as part of the CurvedNFR Project, the following conclusions may be drawn:

- Thermoplastic composites seem to offer a valid solution for the manufacturing of FRP bends and complex shapes.
- Current design recommendations for FRP RC elements such as the ACI recommendations by committee 400, although conservative, can be used to estimate both performance at ULS and at SLS.
- For slim FRP RC elements, serviceability limit states govern the design.
- The use of FRPs in applications where durability is a main concern, can lead to significant reductions in the required amount of concrete, thus contributing to the development of more elegant and sustainable structural solutions.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the financial assistance of the European Union for the Marie Curie Research Training Network En-Core, and the CRAFT RTD project CurvedNFR.

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