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FIBRE REINFORCED POLYMER COMPOSITE DECK ELEMENTS FOR HIGHWAY BRIDGES IN DEVELOPING COUNTRIES

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Abstract

Fibre Reinforced Polymer (FRP) composite bridge decks are increasingly being accepted by bridge owners and designers as a suitable alternative to traditional construction materials such as reinforced concrete, steel and masonry. This is because FRP as a material has several advantages such as high strength to weight ratio and high durability due to inherent corrosion resistance properties. Additionally, the material lends itself to a large degree of prefabrication which saves construction time thus minimising traffic disruptions. This paper explores the possible application of FRP to bridge construction in developing countries and its implications on project management and delivery.

Keywords: Fibre reinforced polymers, bridges, developing countries.

1 Introduction

In the global context, a considerable number of concrete bridges have deteriorated and Uganda is host to some of them. The main causes of deterioration have been attributed to corrosion of steel reinforcement, surface concrete spalling, increase in traffic loads and volumes, inadequate detailing: especially concrete cover and poor workmanship during construction. The most common bridge deck types in Uganda are simply supported steel/concrete composite and reinforced concrete decks. Over 85% of the 151 bridges inspected on the Uganda National Road Network as of March 2009 comprised of either steel/concrete composite or reinforced concrete decks (Cox & Stiff, 2009).

Deteriorated infrastructure imposes serious financial burdens on asset owners. Ensuring the longevity of existing infrastructure demands substantial funding resources that could otherwise have been dedicated to new-build projects and other development goals. Furthermore, Hearn (2015) notes that major outcomes of climate change such as rise in sea levels, variations in rainfall patterns and increased temperatures impose additional demands on infrastructure durability. The author emphasizes the vulnerability of the African continent to effects of weather variations as well as climate change and projects road infrastructure damage amounting to US$ 184billion by the year 2100. Infrastructure damage of this magnitude could cripple investment in rural access development and livelihood improvement in countries like Uganda and a majority of other countries in Sub-Saharan Africa.

The requirement to guarantee safety, serviceability and low maintenance costs throughout the service life of the engineering structure (generally 100 years according to Eurocodes) has attracted bridge designers to start considering FRP composite bridge decks as suitable alternatives to conventional concrete/steel composite and reinforced concrete bridge decks. The objective of this paper is to explore potential application of this material to bridge deck construction in developing countries.

1.1 Fibre reinforced polymer composite material

Composites are materials made up of more than one constituent such as reinforced concrete (concrete and reinforcing steel) and timber (cellulose fibre and lignin). According to Mazumdar (2002), fibre reinforced polymer (FRP) composites are made from a combination of reinforcing fibre and a polymer resin/matrix, with the properties of the composite being superior to those of the individual fibre and polymer resin. In order to understand the behaviour of composites, knowledge of properties of constituent materials is imperative.

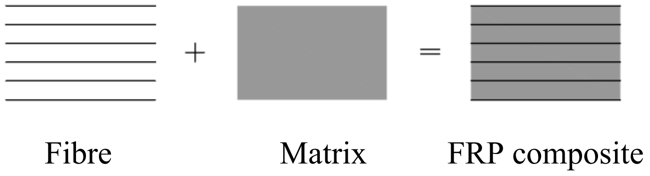

Figure 1-1 FRP composition from fibre and matrix based on Mazumdar(2002)

There is a general consensus that in FRP composite material, the fibre typically constitutes the high modulus and high strength component, thus has the responsibility of mobilising a majority of the strength and stiffness in the material. The matrix is the low modulus and low strength constituent whose roles are to ensure inter-fibre stress transfer and provide protection to fibre from damage (Hollaway & Head, 2001). It has been explained by Hollaway & Head (2001) that when FRP is subjected to stress, plastic flow of the matrix lends itself to transfer loads onto fibre which results in a high modulus and high strength composite material. The purpose of merging the two constituents is to create a two-phase material in which the fibre comprises the primary phase whilst the matrix makes up the secondary phase. Therefore, any FRP has three constituents, namely: fibre, matrix and interface.

The use of FRP composites in Africa dates back to the 1960s when a sandwich polymer composite skeletal dome structure manufactured in the United Kingdom (UK) was erected in Benghazi, Libya (Hollaway, 1993); other early applications included structural strengthening of buildings in South Africa.

1.2 Pultrusion technology

This is the method commonly used in the manufacture of FRP composite profiles for bridges. In this method, fibre reinforcement is pulled through a resin reservoir and heated die. Fibre reinforcement may be in form of rovings, chopped strand mats or other designed forms. An alternative approach to pulling fibre through the resin reservoir is impregnation of fibre by injection of resin via port holes of a heated die as fibre is passing through it. The key parameters to be monitored during pultrusion are: fibre layout, pull speed, resin formulation, die temperature and catalyst level (Hollaway & Head, 2001).

1.3 Failure modes and criteria

The anisotropic characteristics of FRP composites result in very complex mechanisms when subject to static and fatigue loading. Several failure mechanisms in FRP composites with off-axes plies often result in stress redistribution and hence a non-linear stress-strain relationship. The basic failure modes of FRP composite material are: matrix cracking, fibre breakage, delamination and interface debonding. The assessment of strength and failure can be carried out using: maximum stress, maximum strain, Tsai-Wu failure, Tsai-Hill failure and Hashin's failure criteria. Hollaway (1993) and Tsai & Wu (1971) have discussed these failure criteria in detail.

1.4 Existing design standards

Currently, there are no comprehensive national design codes for FRP composite structures. However, design guides have been produced over the last decade or so by industry practitioners and researchers, key examples include:

- *Eurocomp design code and hand book*: This was particularly developed for the design of Glass FRP composites structures and is written in the context of European Practice. It is based on limit state design approach and provides specifications of ultimate and serviceability limit state criteria to be fulfilled (Clarke, 1996).
- *Structural plastics design manual*: This was developed by the American Society of Civil Engineers (ASCE) Structural Plastics Research Council in order to guide the use and design of structural plastics. It also adopts limit state design approach and details the FRP material characteristics, structural behaviour and design considerations (ASCE, 1984).
- *BD 90/05 (UK) Design of FRP bridges & highway structures*: This departmental standard outlines the requirements for approval of highway bridges and structural schemes designed using FRP composite materials in the UK (The Highways Agency, 2005)

2 Case studies

The use of FRP composite material is a relatively new approach to bridge construction when compared to traditional construction materials. The successful performance of FRP as a primary structural material for bridge decks must therefore be demonstrated through the following case studies.

2.1 West Mill Bridge, UK

This bridge over the river Cole in Oxfordshire, England, was completed in October 2002 as part of a 4 year research project funded by the European Commission called Project ASSET (**A**dvanced **S**tructural **S**yst**E**m for **T**omorrow's Infrastructure).

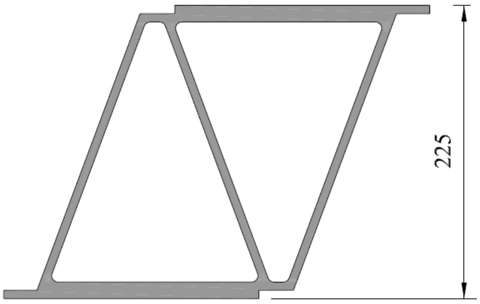

Figure 2-1 Section through ASSET profile based on Canning *et al.*, (2007)

The new 6.8m wide bridge with a span of 10m replaced 3.5m wide 19th century cast iron bridge spanning 7.5m. The bridge deck essentially comprises of 34 adhesively bonded pultruded FRP composite ASSET profiles that span transversely over Glass/Carbon FRP hybrid longitudinal primary beams. The four primary beams are spaced at intervals of 1.75m (Canning *et al.*, 2007). The authors have stated that, the bearing resistance of longitudinal primary beams on superstructure bearings was improved by filling their ends with concrete. The design loading was taken from United Kingdom (UK) Design Manual for Roads and Bridges (BD 37/88, 1998) and it comprised full Highest Axle (HA) loading and 37.5 units of Highest Body (HB) loading. The parapet beam, railing and posts at edges of the superstructure were designed using the traditional approach comprising reinforced concrete beams. However, owing to alkaline properties of concrete, which can result in Glass FRP composite deterioration, isolation joints were provided in all areas where in situ concrete came into contact with FRP material.

The presence of some degree of composite action is recognised between the ASSET deck, reinforced concrete edge beams and longitudinal primary beams in the West Mill Bridge. This behaviour can markedly improve flexural rigidity of the bridge superstructure (Sebastian *et al.*, 2013). However, it is understandable that this behaviour was not taken into consideration given the lack of rigorous test data at the time of the design of this bridge. The findings of the performance and 8 year load tests have confirmed that composite action still exists between longitudinal main beams, concrete parapet beams and Glass FRP deck. It must however be pointed out that the surfacing has demonstrated some signs of cracking and may thus not be relied upon for provision of additional composite action (Canning, 2012). A number of aspects not considered in the design of the West Mill Bridge have been addressed in the design of the Friedberg Bridge in Germany.

2.2 Friedberg Bridge, Germany

According to Knippers & Gabler (2008), the superstructure of this bridge comprises of 225mm thick pultruded multi-cellular ASSET profiles supported on longitudinal steel girders spaced at 2.4m apart. The authors have argued that this hybrid approach results in a more economic structure relative to adopting the ‘all FRP’ approach to the superstructure. Bridge analysis and design assumed fixed boundary conditions for longitudinal girders at both abutments. This implies that frame action is present which consequently reduces internal forces within the superstructure thus significantly increasing its stiffness in comparison to pinned boundary conditions. The result of application of this concept was a slim structure which eliminated need for a pier at mid span.

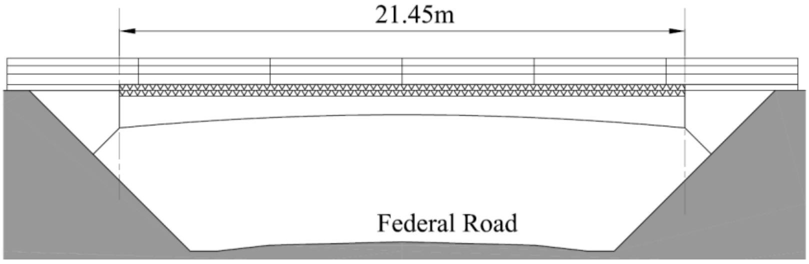

Figure 2-2 Longitudinal view of Friedberg bridge based on Knippers & Gabler (2008)

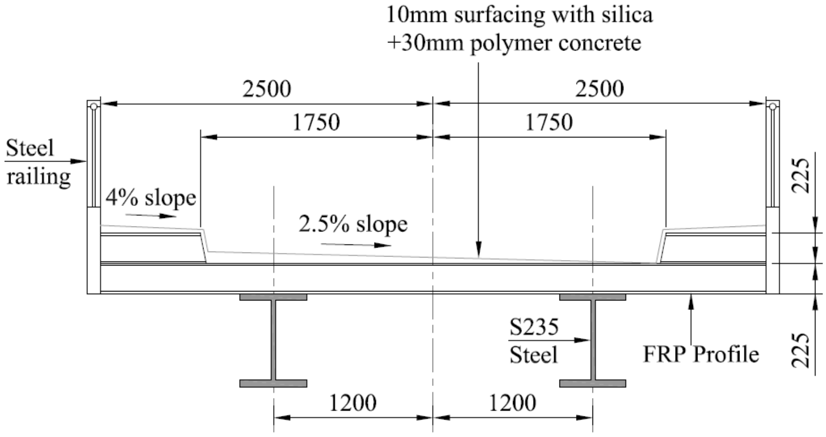

Figure 2-3 Cross-section of Friedberg bridge based on Knippers & Gabler (2008)

Disadvantages of introducing a pier at mid span could have been: need for construction space, traffic flow interruptions on the federal road and can cause of accidents. The loading values used in the design are consistent with those provided in Eurocode 1, BSI (2003).

3 Existing research into FRP composite deck behaviour

Canning *et al.* (2007) has undertaken large scale tests on ASSET profiles to confirm their failure modes and load carrying capacities. Both single and multiple profiles were subjected to wheel loads over one and two spans. A pseudo-ductile failure mode was exhibited by the profile owing to its structural redundancy. Failure initiation within a single web plate occurred at a load of 800kN and comprised of buckling and delamination. This was followed by failure of a single web/flange joint which resulted in transfer of concentrated loads to other intact webs until they also failed at an applied load of 1100kN. The load was sustained even with occurrence of large deflections and failure of a significant number of webs. This finding demonstrates that although FRP composites are thought to be brittle materials that fail without sufficient warning, under certain circumstances and with appropriate design provisions, adequate ductility and thus warning can be achieved. Omoding (2015) explored the design of an ‘all FRP’ composite deck highway bridge spanning longitudinally between abutments in accordance with Clarke (1996) and checked against the provisions of ASCE, (1984). The bridge deck was simulated using a nonlinear finite element analysis software to explore its behaviour at serviceability and ultimate limit states. It was found that deck failure was governed by material failure rather than buckling. Serviceability requirements were satisfied at the design load and when checked using Tsai-Wu failure criterion, ultimate limit state (ULS) requirements were also satifisfied at ultimate design load. However, when maximum stress failure criterion was applied at ULS, it was found that in-plane shear failure occured in the top plate, thus underlining the sensitivity of the design to choice of FRP failure model.

4 Impact of FRP technology on project management

With regards to project delivery and whole-life management in developing countries, FRP composite bridge decks have the following advantages over conventional materials:

- High strength to weight ratio which results in relatively lighter structures which can translate into cost savings in the substructure and reduced need for specialist cranes.
- Ability to adopt a large degree of pre-fabrication due to use of pultruded profiles ensures high quality assurance of products. According to Kakitahi *et al*. (2015) construction projects in Uganda often suffer non-compliance to quality requirements for various reasons such as poor procurement processes for instance, reliance on lowest bid prices in contractor selection and poor attitude towards materials quality testing.
- The pre-assembly of the structural elements significantly reduces the erection time of these bridge decks, avoiding the need for detours and minimising traffic jams.
- Ease of material handling on site and;
- Inherent corrosion resistance which improves durability of bridge decks.

As much as FRP composite bridge decks have significant advantages over traditional materials, barriers to their use in developing countries like Uganda do exist:

- The material is not locally available and hence requires importation which may increase initial project costs.

- Most local designers are not familiar with the behaviour of FRP material and structures. Also, the local workforce does not have experience in the construction of this type of bridge decks. Moreover, lack of generally accepted national design codes for FRP composites further makes their use prohibitive.

5 Conclusion

The use of FRP composites in bridge construction is still a relatively new concept in comparison to traditional construction materials. FRP composites however have some significant advantages for infrastructure management in developing countries that perennially suffer from the social and economic impact brought about by deterioration of key assets such as bridges. Although the initial material costs of FRP may be greater than conventional materials (depending on the type of FRP adopted), the associated whole-life costs have the potential to be lower than steel or concrete counterparts. Developing countries like Uganda now need to explore the use of innovative construction materials such as FRP composites.

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