Composites: Part B 63 (2014) 77–84

Contents lists available at ScienceDirect

Composites: Part B

journal homepage: www.elsevier.com/locate/compositesb

Structural limits of FRP-balsa sandwich decks in bridge construction

Michael Osei-Antwi, Julia de Castro, Anastasios P. Vassilopoulos, Thomas Keller *

Composite Construction Laboratory (CCLab), Ecole Polytechnique Fédérale de Lausanne (EPFL), Station 16, Bâtiment BP, CH-1015 Lausanne, Switzerland

ARTICLE INFO

Article history:
Received 3 March 2014
Accepted 31 March 2014
Available online 13 April 2014

Keywords:
A. Layered structures
A. Hybrid
B. Elasticity
C. Finite element analysis (FEA)
Bridges

ABSTRACT

The span limits of two glass fiber-reinforced polymer (GFRP) bridge concepts involving GFRP-balsa sandwich plates are discussed. The sandwich plates were either used directly as slab bridges or as decks of a hybrid sandwich-steel girder bridges. In the latter case, the potential of the sandwich decks to replace reinforced concrete (RC) decks was also evaluated. Taking the limits of manufacturing into account (800 mm slab thickness), maximum bridge spans of approximately 19 m can be reached with FRP-balsa sandwich slab bridges, if a carbon-FRP (CFRP) arch is integrated into the balsa core. Above this limit, hybrid sandwich-steel girder bridges can be used up to spans of 30 m. RC deck replacement requires timber and steel plate inserts into the balsa core above the steel girders. GFRP-balsa sandwich slabs or decks exhibit full composite action between lower and upper face sheets. Stress concentrations occur at the joints between balsa core and timber inserts which however can effectively be reduced by changing from butt to scarf joints.

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1. Introduction

Glass fiber-reinforced polymer (GFRP) composite bridge systems offer favorable characteristics such as high strength per unit weight, resistance to corrosion, excellent fatigue performance, increased live load ratings in the case of bridge replacement and rapid field installation with minimized traffic disruptions [27,18]. Two basic concepts of GFRP bridge systems exist: orthotropic systems composed of adhesively bonded pultruded shapes and sandwich constructions. Both are used either as bridge decks in deck-girder bridges or as slabs in the case of slab bridges. Sandwich decks or slabs have the advantage, amongst others, of flexible thickness contrary to pultruded decks or slabs and can thus be used for much larger spans. Currently, they are composed of GFRP face sheets and honeycomb or foam cores. In the latter case, additional GFRP webs are normally required to provide sufficient shear capacity of the core [24]. However, the honeycomb walls and internal GFRP webs in the foam core provide a non-uniform stiffness support for the upper face sheet, which – under frequent wheel loads – may lead to the debonding of the upper face sheet from the core [23]. To overcome this drawback, i.e. provide a core with sufficient shear capacity and uniform support for the upper face sheet, balsa wood was used as core material in the new Avançon Bridge, in Bex, Switzerland [20]. The use of balsa with fibers transverse to the upper face sheet and thus in line with the wheel load direction did no longer require reinforcements by internal webs and provided a high indentation resistance against concentrated wheel loads. The new 11.45 m span and two-lane Avançon Bridge, composed of a GFRP-balsa sandwich deck adhesively bonded onto two steel girders, replaced an old one-lane reinforced concrete (RC) bridge.

A further disadvantage of pultruded decks is manifested in the case of RC deck replacement. RC decks normally act as top chord of hybrid RC-steel girders in the longitudinal bridge direction. Pultruded GFRP decks, however, have low stiffness in this direction (which is transverse to the pultrusion direction) and are thus not able to transfer the longitudinal forces which are in the RC chord. Furthermore, depending on the geometry of the cells, composite action between the upper and lower face sheets may be reduced, which further decreases the possible contribution as top chord [19]. The effects of these drawbacks are increased deflections in the longitudinal bridge direction and significant longitudinal stress increases in the upper flanges of the steel girders, which may require an additional strengthening of the bridge. This was demonstrated in the study by [17], where the compressive and tensile stresses in the upper and lower steel girder flanges increased by 109% and 12% respectively, if the RC deck of a 17.5 m span bridge would have been replaced by a pultruded GFRP bridge deck. The increased compressive stresses would have exceeded the compressive strength of the steel flanges and the deflection limit would no longer have been met.

GFRP sandwich slabs, however, have demonstrated their capacity to replace RC slab bridges because high slab thickness can be manufactured to provide the required bending stiffness.

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* Corresponding author. Tel.: +41 21 6933226; fax: +41 21 6936240.
E-mail address: thomas.keller@epfl.ch (T. Keller).

http://dx.doi.org/10.1016/j.compositesb.2014.03.027
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An example is the 7.6 m span Bennetts' Creek Bridge, in Rexville (NY), where the RC slab was replaced by a GFRP-foam sandwich deck composed of 12.8 mm GFRP face sheets and 621 mm foam core [2].

In parallel to the above mentioned Avançon Bridge project, structural concepts for GFRP-balsa slab bridges with thick balsa cores have also been developed. It has been shown that the balsa core thickness can be reduced by a complex core assembly composed of an upper high-density and lower low-density balsa core layer, separated by a circular FRP arch to improve the shear and bending capacity [22]. Furthermore, composite action of the GFRP-balsa sandwich in the RC deck replacement case can be improved by replacing the softer balsa wood above the steel girders by timber with fibers oriented in the bridge direction. In a case of even higher deck stiffness requirements, additional thin steel plates can be inserted between the timber inserts and the upper face sheet.

This paper investigates the span limits of new GFRP-balsa sandwich slab and deck bridges. The potential of replacing RC decks with GFRP-balsa sandwich decks is further explored. Also discussed are structural effects arising from timber inserts such as local stress concentrations at the balsa/timber joints in the core and the face sheets.

2. Structural concepts and materials

2.1. GFRP-balsa sandwich slab bridges

The span limits of three types of slab bridges were evaluated: (1) sandwich slabs with a uniform high-density balsa core (designated S-U concept), (2) sandwich slabs with a complex core composed of high- and low-density balsa and an GFRP arch in the interface, as shown in Fig. 1a (S-G concept), (3) the same case as S-G but instead with a carbon-FRP (CFRP) arch (S-C concept). The S-G and S-C cases correspond to the concept shown in Osei-Antwi et al. [22]. In this concept, the high-density balsa is required to prevent indentation and wrinkling of the upper face sheet and provide sufficient shear strength and stiffness in the support region of the slab. In the less-stressed lower zone between the supports, low-density balsa can be used to minimize the deck weight. The vertical components of the FRP arch forces reduce the shear load borne by the balsa core.

A two-lane bridge of 7.50 m width was investigated; the span was varied up to the limit span. The GFRP face sheets and GFRP/CFRP arch laminates were 30 mm thick and the upper and lower balsa cores together had a thickness of 710 mm, which resulted in a total sandwich slab thickness of 800 mm. From the experiences gained with the Avançon Bridge construction, these thicknesses were considered as the limits given by the manufacturing process (vacuum infusion). The GFRP face sheets were composed of E-glass fibers and vinylester resin. The E-glass architecture was orthotropic with the same amount of unidirectional (UD)-layers in the bridge longitudinal (0°) and transverse directions (90°). The same resin was used for the arch laminates but the UD E-glass and carbon (T-700) fiber layers were arranged only in the longitudinal direction. The fiber volume fraction was 49% for both laminates. The fibers of the balsa cores were oriented perpendicular to the faces sheets, thus providing the required indentation and shear resistances. The lowest possible thickness of the upper high-density balsa layer at mid-span was 50 mm, resulting in a maximum arch rise of 690 mm. The properties of the high-density (SB150) and low-density (SB50) balsa cores and the GFRP/CFRP UD-layers are listed in Table 1. The bridge slab was covered by an asphalt layer of $h_a = 60$ mm thickness (similar to the Avançon Bridge).

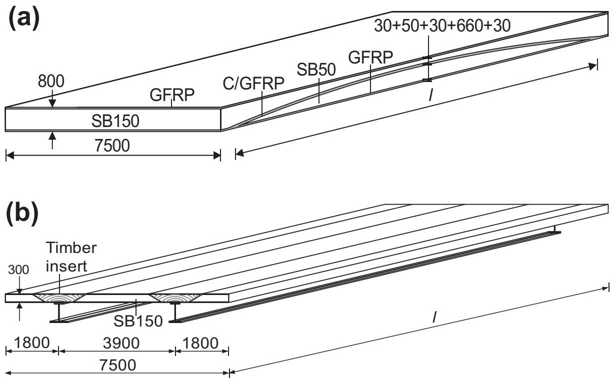

Fig. 1. Sandwich bridge concepts for (a) S-C/S-G slabs and (b) D-TI deck on steel girders (dimensions in mm).

2.2. GFRP-balsa sandwich deck bridges

Three types of GFRP-balsa sandwich deck bridges were investigated. All three bridges had the same width of 7.50 m (for two lanes) as the slab bridges. The deck, however was adhesively bonded onto two steel girders, which were identical in all three cases, see Figs. 1b and 2. The differences were only in the core composition above the steel girders where: (1) the bridges designated D-U had a uniform high-density balsa core over the whole width, (2) the balsa in bridges D-TI was replaced by timber inserts above the steel girders, (3) additional steel plates were placed in bridges D-T/SI between the timber inserts and the upper GFRP face sheets.

The timber and steel plate inserts were arranged to increase the longitudinal stiffness and thus contribute to the top chord of the hybrid sandwich-steel girders. The fibers of the timber inserts were oriented in the longitudinal bridge direction accordingly. A timber width of 1500 mm was selected as a compromise between efficiency, deck weight and cost. The adhesively bonded balsa-timber joints were designed as scarf joints with 40° angles of termination to reduce stress concentrations, see Fig. 2. The steel plate insert had a width of 1500 mm and the thickness was $h_{SI} = 10$ mm. Steel grade S355 was selected, according to Eurocode 3 [11]; the properties are listed in Table 2. The total deck thickness was $h_D = 300$ mm and was kept constant across the deck width. The face sheets had the same thicknesses (30 mm) and GFRP composition as in the slab bridges. High-density balsa (SB150) and different types of timber inserts (spruce, Douglas fir (Df), birch, ash and cedar) were evaluated; their properties are listed in Table 3. The edges of the 1.90 m overhangs were reinforced by longitudinal 100×20 mm^2 CFRP strips, adhesively bonded onto the outer layers of the upper and lower face sheets, in order to reduce edge deflections due to concentrated wheel loads.

The welded steel girders had upper/lower flange widths of 300/540 mm and thicknesses of 20/34 mm and a web thickness of 18 mm. The height of the webs was varied in order to obtain a slenderness ratio of $h/l = 1/20$, where h is the total girder height (including the deck) and l is the longitudinal span of the bridge. The steel grade was the same as used for the steel inserts. Again, a 60 mm asphalt layer was taken into account.

2.3. RC bridge deck replacement

The RC bridge was composed of a RC deck joined by shear studs to two welded steel girders, as shown in Fig. 3. The deck width and position of the steel girders were the same as in the D-bridges. The RC deck had a constant deck thickness of $h_{RC} = 250$ mm; a concrete class C30/37 was selected according to Eurocode 2 [10]. The steel

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