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Rotational stiffness of web-flange junctions of pultruded GFRP decks

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ABSTRACT

The rotational behavior of the web-flange junctions (WFJs) of a pultruded glass fiber-reinforced polymer (GFRP) bridge deck system with trapezoidal cell cross-sectional geometry was investigated. The rotational response of three WFJ types, in two bending moment directions each, was characterized. An experimental procedure based on three-point bending and cantilever experiments conducted on the web elements and simple analytical models was used. The WFJs generally exhibited non-rigid and nonlinear behavior. The overall moment-rotation relationships, rotational stiffness, strength and failure modes differed depending on the web type, the location of the WFJ within the deck profile, the existing initial imperfections and the direction of the bending moment applied. This evidenced the relevance of separately characterizing the response of all WFJ types in the two possible bending directions. Simplified expressions to model the WFJ rotational behavior were derived. The validity of the experimental and idealized rotational responses was assessed by means of numerical simulations of full-scale experiments conducted on the GFRP deck.

1. Introduction

Glass fiber-reinforced polymer (GFRP) bridge decks nowadays constitute one of the most developed and extended applications of FRP materials for primary, load-bearing structural members in the civil engineering domain. Since the 1990s, GFRP bridge decks have been increasingly employed in road and footbridges, both for new construction and rehabilitation purposes, due to favorable characteristics in comparison with decks composed of traditional structural materials – e.g. reinforced concrete (RC) or steel. Advantages of GFRP materials when used for bridge slabs include high specific strength and low self-weight. GFRP decks weight about 10–20% of the structurally equivalent RC deck [1], which in replacement applications allows increase of the live load capacity via dead load reduction. Other main advantages of GFRP materials for deck applications comprise high fatigue resistance, improved durability and corrosion resistance, which result in low bridge maintenance and reduced life-cycle costs. Furthermore, GFRP decks offer manufacturing versatility (the cross-sectional geometry can be designed and/or the material constituents and fiber architecture tailored to meet structural requirements) and allow high construction speed with minimized traffic disruption times [1,2]. Reviews regarding the development and implementation of several all-FRP and hybrid FRP-concrete deck systems can be found in [1–4].

GFRP bridge decks fulfill two structural functions, namely: (i) distribution and transmission of the traffic loads applied to the bridge to the underlying superstructure; (ii) participation in load transfer in the bridge's longitudinal direction by acting as the top chord of the main girders when there is sufficient composite action between the girder and deck. The latter function is particularly relevant in the case of concrete deck replacement – supplementary strengthening of the main girders is required if the upper chord function is not maintained. Pultruded GFRP deck systems exhibit orthotropic behavior owing to material orthotropy and different load-bearing mechanisms in their longitudinal (parallel to pultrusion) and transverse (perpendicular to pultrusion) directions. Their performance concerning the above-mentioned two structural functions is influenced by the deck's transverse behavior. The deck system's orthotropy ratio and therefore its structural performance as a slab depend on the contribution of the transverse-to-pultrusion direction to carrying applied concentrated loads [5]. The deck's participation as the upper chord of main girders is affected by its transverse in-plane shear stiffness, which governs the shear transmission within the deck (from its bottom to its top flange) in the bridge's longitudinal direction [6].

In a previous investigation [7], the behavior in the transverse-to-pultrusion direction of a GFRP deck with trapezoidal cell geometry, *DS*, was experimentally studied. The cross section of the *DS* unit module profile consists of a rectangle shaped into two trape-

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Nomenclature

$E_{f,y}$	elastic flexural modulus of web laminates in transverse-to-pultrusion direction
$E_{t,y}$	elastic tensile modulus of web laminates in transverse-to-pultrusion direction
K^{rot}	rotational stiffness of rotational spring
K^{rot}_{l}	linearized value of rotational stiffness
K^{rot}_{0}	initial tangent rotational stiffness
$K^{rot,av}_{0}$	initial tangent rotational stiffness (average response of three specimens)
L_{cant}	cantilever span length
L_{3pb}	span length of simply supported beam subjected to symmetric three-point bending
M	bending moment
M_{pl}	maximum bending capacity of web-flange junction (*RP* model)
M_{ult}	ultimate bending moment of web-flange junction
M^{av}_{ult}	ultimate bending moment of web-flange junction (average response of three specimens)
P_{cant}	load in cantilever configuration
P_{3pb}	load in symmetric three-point bending configuration
P_{ult}	ultimate load in cantilever configuration
R_{cant}	support reaction in cantilever configuration
R_{3pb}	support reaction in symmetric three-point bending configuration
X	horizontal coordinate of experimental set-up (along specimen's web)
Y	vertical coordinate of experimental set-up (across specimen's web)
b	width of specimen's web
t_w	thickness of specimen's web
ΔX	distance between target points along specimen's web for video extensometer system
$\Delta X'$	distance between target points across specimen's flange for video extensometer system
$\Delta Y'$	distance between target points along specimen's flange for video extensometer system
δ	deflection
$\delta_{cant,f}$	deflection of fixed cantilever
$\delta_{cant,sr}$	deflection of partially fixed cantilever
δ_{ult}	deflection at failure (corresponding to ultimate load P_{ult}) in cantilever configuration
δ_{φ}	deflection of partially fixed cantilever due to rotation of semi-rigid end
δ_{3pb}	mid-span deflection in symmetric three-point bending configuration
ε	strain
φ	rotation
$\varphi_{M,ult}$	rotation at failure of web-flange junction
$\varphi^{av}_{M,ult}$	rotation at failure of web-flange junction (average response of three specimens)
φ^{av}_{max}	maximum rotation of web-flange junction (average response of three specimens)
σ_f	flexural strength of web-flange junction

zoidal cells by a slightly inclined inner web connected to the deck's flanges, as shown in Fig. 1. The slab is formed by adhesively bonding the dual-cell unit profiles along their vertical (outer) webs using a structural polyurethane adhesive, see Fig. 2(a). The loading configuration used and the load-deflection response recorded at mid-span are illustrated in Fig. 2(a) and (c), respectively. The load transfer mechanism, failure mode and system transverse in-plane shear stiffness were investigated. The deck exhibited a frame-governed behavior whereby the load was mainly transmitted by local shear and bending moments in the web and flange elements (Vierendeel frame mechanism). Progressive cracking occurring in the web-flange junctions (WFJs) resulted in a stiffness reduction without leading to the deck's final failure. The sequence of the cracks observed, their location and the corresponding load levels are shown in Fig. 2(a) and (c), on the right side. A non-brittle failure was observed and a sustained load-bearing capacity under the development of large displacements was recorded owing to the system redundancy – gradual local bending failures occurred in

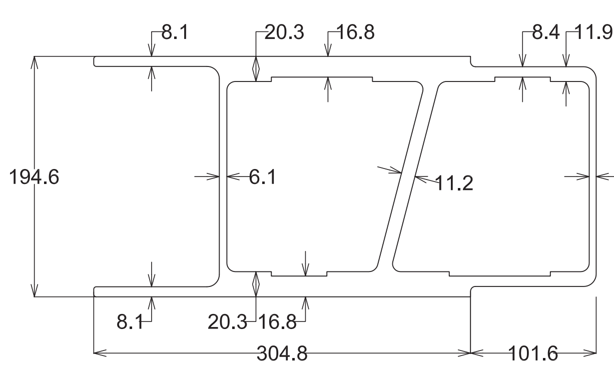

Fig. 1. Unit module geometry of *DS* bridge deck system; dimensions in mm.

the WFJs. The system transverse in-plane shear modulus, before any local failure was detected, was estimated from the experimental deflection data based on existing equations for composite beams with flexible shear connections that were originally developed for timber-concrete composite girders. The thus calculated in-plane shear modulus agreed well with the experimentally determined value reported in [6] from in-plane shear experiments, see Fig. 2(b) and (d).

The research conducted in [7] provided a comprehensive basis for the evaluation, by means of further models, of the bidirectional behavior of decks and the composite behavior of hybrid beams with GFRP decks acting as their top chord. Prospective models for the *DS* deck should consider additional local features, i.e. the rotational behavior of the WFJs, since the nonlinearity of its global transverse bending behavior originated from progressive cracking in the WFJs prior to final failure. Moreover, the above-mentioned procedure to calculate the transverse in-plane shear modulus is restricted to the linear elastic range behavior. Nevertheless, the in-plane shear modulus of *DS* may not be constant (nonlinear in-plane shear behavior) due to gradual local failures in the WFJs [6,7]. The local rotational response and strength of the *DS* WFJs is unknown, however. The characterization of the WFJ rotational behavior is therefore required in order to develop reliable numerical models for accurately predicting both the initially linear (before any cracking occurrence) and subsequently nonlinear transverse behavior of the deck [8]. Once the models are developed, the complete characterization of the system in-plane shear modulus up to failure would be possible and its effects on the global performances of both the slab (orthotropy ratio) and hybrid girder (composite action) could be assessed.

The WFJ characterization has been highlighted as a topic of interest for research on FRP pultruded profiles. The local behavior of the WFJs, with distinctive fiber architecture and material properties, has been found to be crucial for the global performance of