Fibre Waviness in Pultruded Bridge Deck Profiles : Geometric Characterisation and Consequences on Ultimate Behaviour

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ABSTRACT

Conventional tests cannot be used to establish the important influence of fibre waviness, a manufacturing legacy at the flange-web joints (FWJs) of pultruded GFRP bridge decks, on the local ultimate behaviour of such decks. Hence a novel, simple and reliable three-step experimental scheme for that purpose is presented herein, using one pultruded deck profile as an exemplar. First, for the given profile, the different individual and bonded deck-deck joint geometries which must be targeted for testing are identified. Second, an effective manual method is put forward to map this waviness at the FWJs. Third, a quasi-static test setup is introduced which enables statically determinate loading of one joint at a time, while also ensuring continuity between this joint and the remaining deck so that the real load paths within the deck are preserved. During the tests failure always occurred by fracture of the wavy fibre-resin interfaces within the FWJs, with a distinct inverse correlation between fibre waviness and failure load, and with the influence of bonding on joint failure behaviour depending on the local flange-web layout. It is concluded that this simple test is sufficiently reliable for extension to assessing local fatigue behaviour at the joints.

KEYWORDS : GFRP ; Bridge decks ; Mechanical testing; Pultrusion ; Fibre Waviness

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1. INTRODUCTION

Pultruded, cellular GFRP units bonded together are increasingly used as road bridge decks. The modularity, superior specific stiffness and strength, low-weight and corrosion-resistance of the units translate into easy assembly, rapid installation, low foundation costs and high durability of the bridges [1]. As traffic loads become more onerous and as the pultruded sections evolve in shape, in material composition and in local detail, the understanding of the ultimate behaviour of the decks must keep pace.

A crucial issue is that such decks are typically designed to idealised material property and structural geometry assumptions, but not from an as-manufactured quality perspective. Indeed, Coogler et al. [2] state that the stress limits specified in codes for GFRPs are independent of manufacturing-induced imperfections in the materials, which may reduce these limits. Consequently, the strong link between manufacture and actual deck performance in service remains concealed. This, in turn, means that when the manufactured decks are loaded, process-induced imperfections such as resin-rich zones and out-of-plane fibre waviness (or wrinkles) induce stress concentrations that influence failure in ways not accounted for at the design stage. Insight into the associated high local stress effects is important, because as pointed out by Ellingwood [1], FRPs (unlike steel) do not yield and so can be of limited redistribution capability. The complexity of the problem is compounded by the random – and so uncertain – nature of the imperfections. In addressing this complexity, it is important to develop strategies for characterising the imperfections and for understanding their role in ultimate behaviour.

Coogler et al. [2] highlighted the spectrum of process-induced imperfections that can arise in the cross sectional planes of pultruded GFRP decks. They observed that fibre waviness can be particularly pronounced within the flange-web joints, or FWJs, to the extent that the fibres often return upon themselves, essentially describing U-trajectories. Now an impressive feature of these joints is that they successfully transmit large, multi-directional loads between the adjoining webs and flanges through small cross-sectional areas. As a result the FWJs develop high, multi-axial stresses that are exacerbated by the fibre waviness. Moreover, curing conditions unique to the joints induce local residual stresses and microcracks that cause the fibre-resin interfaces in the as-manufactured decks to be of different bond strengths within the joints relative to within the web and flange straights between joints. Unsurprisingly, therefore, fracture of the wavy interfaces within the joints is a key manifestation of failure in GFRP decks loaded to ultimate.

Notably, a literature survey reveals that these wavy interface fractures occur at FWJs irrespective of structural layout (the deck acting alone or as part of a hybrid), of spatial influence (local or global) of the load, and of directionality (key actions along or transverse to the direction of pultrusion). Indeed, such fractures have dominated ultimate behaviour in GFRP deck-steel beam hybrids (Keller and Gurtler [3]) and GFRP deck-concrete beam hybrids (Sebastian et al. [4]) under global flexure normal to the direction of pultrusion. Wavy interface fractures have also governed failures in isolated decks under local load effects (Gabler and Knippers [5], Sebastian et al. [6, 7]), in an isolated deck system under global flexure along the direction of pultrusion (Zi et al. [8]), and also in deck systems under global flexure normal to the direction of pultrusion (Yanes-Armas et al. [9]). This last case [9] induced both Vierendeel and truss actions in the decks, thereby causing progressive fracture within and associated load redistribution between multiple joints of each test specimen in the approach to failure. Subsequently, Yanes-Armas et al. [10] conducted web cantilever tests on FWJs cut out from one of the decks.

Pultruded I-section GFRP profiles also exhibit FWJ failures due to wavy fibre-resin interface fractures. In those cases too, previous studies have highlighted the randomness of the wavy profiles and the consequences of the resulting uncertainties in fracture patterns. For example, in Fig. 14 of [11], Turvey and Zhang provide evidence of strong asymmetry of the fibre architecture and of the associated wavy interface fracture patterns between the FWJs at both ends of the web in a pultruded I-section. From three-point bend tests on portions of the web rotationally restrained at the ends by clamping the FWJs, they surmised that this asymmetry led to inconsistent moment-rotation characteristics between the FWJs of different specimens. Feo et al. [12], Fascetti et al. [13] and Quadrino et al. [14] also observed wavy fractures at the FWJs during vertical pull-out tests on pultruded I-sections. For the publications describing these above cited studies on pultruded decks and I-sections, Table 1 identifies the Figures which show the wavy interface fractures within the FWJs.

Other experimental studies have investigated the effects of fibre waviness on the structural integrity of FRPs at a fundamental level. In these studies the test specimens have been manufactured in the laboratory, to enable good quality control on fabrication of simple, but physically meaningful fibre wave geometries. Given this laboratory manufacturing, pultruded FRP specimens have been precluded. The method of generating the waviness has varied between studies. For example Adams and Hyer [15] used copper wire and aluminium foil to artificially generate the wave forms, while Bloom et al. [16] used a manufacturing method which sought to replicate the "organic" mechanism of formation and hence the natural morphology of the wrinkles found in wind turbine blades. The wavy fibre laminates have been subjected to either tensile or compressive axial loads.

Note that in the study by Adams and Hyer [15], prepreg tape was employed to fabricate laminates with isolated fibre layer waves. Using optical microscopy, they characterised the wave geometry via the amplitude, δ, the wavelength, λ, and the maximum angle of fibre rotation, θ_{max}, also termed the angle of misalignment. Both θ_{max} and the ratio δ / λ were alternately used to define the severity of the waves. On subjecting these laminates to axial compression, a 36% reduction in static strength was obtained for laminates of severe waviness ($\delta / \lambda \approx 0.06$), although the wavy layers accounted for only 20% of capacity. The observed failure mode was often brooming, namely through-thickness splaying of layers accompanied by several delaminations near the waves.

Bloom et al. [16] used aerospace grade glass fibre-epoxy prepregs in a three-stage manufacturing process (layup onto an aluminium tool plate, vacuum bagging, autoclave curing) to produce their laminates. Three sets of specimens were manufactured, namely unwrinkled laminates which served as control specimens, also laminates with 50% wrinkled plies and laminates with 100% wrinkled plies. They found that both visual observation and optical microscopy were useful for characterising the wrinkles in terms of angle of misalignment and height. Where the tows were looped or kinked, two additional angles were measured. On testing the 100% wrinkled ply specimens in axial tension they observed a 38% knockdown of strength, relative to the control laminates, for a 30.5° misalignment angle. Failure was by cracking along the path of misalignment, which fractured the wrinkled plies.

Progression from laboratory-manufactured to commercially produced specimens was made by Sutcliffe et al. [17], who characterised fibre waviness for industrial components already manufactured by resin transfer moulding (RTM) and by prepreg/vacuum consolidation. They showed that image analysis with an autocorrelation function could be applied equally to polished sections and to micro-CT X-ray images. This led to the observation that the waviness zones were distinctly longer in the prepreg samples than in the RTM samples.

It is now appropriate to build on the successes of these earlier studies by extending the scope to include pultruded GFRP bridge decks. This entails initial investigations into mathematically defining the fibre waviness at the FWJs of such decks, along with acquisition of experimental insight into the way in which this waviness can influence the failure behaviour of the joints when the decks are loaded. The remainder of this paper is dedicated to one such study.

In so doing it must be recognised that the above-described coupon fabrication approach and testing methods used to date cannot be applied to pultruded GFRP bridge decks, for the following reasons:

- The coupons have been flat, whereas the FWJs of pultruded decks are of complex geometries defined by combinations of flats, curves and steps.
- Simplified, specific waviness profiles have been built into these flat coupons. By contrast, the waviness profiles in pultruded FWJs are complex and random, due for example to the randomness of the vibrations within the fibre-pulling pultrusion machinery.
- Coupon fabrication has entailed room temperature curing of the resin, which very likely induces only minor residual stresses in the cured coupon. However, pultrusion entails cooling of the resin from over 100°C down to room temperature. Spatial temperature differentials develop through the resin volumes in the FWJs during this large temperature drop, inducing palpable residual stresses and microcracks within the FWJs. These initial stresses and cracks depend on the FWJ geometries and can significantly affect the load-carrying capabilities of these FWJs.
- In previous tests simple axial tension or compression has been applied to the specimens with embedded waviness. However, as shown in Fig. 1, concentrated tyre loading on pultruded bridge decks induces significant local biaxial flexing of the top flange and introduces high local flexure and shear forces at the nearby flange-joint boundaries. Hence the loading used to test FWJs in the bridge decks must differ significantly from those previously employed.
- Only one joint type (if any) has required consideration previously. For pultruded decks, however, both the original joints of a unit and the bonded joints must be considered, in the latter case with the added complexity of testing from both sides if the bonded joint is asymmetric.

For these reasons a novel testing approach has been developed in the present study. The key ideas which underpinned this study are stated in the next section.

2. AIMS AND OBJECTIVES OF THE PRESENT STUDY

The overall aim of the present study is to experimentally characterise fibre waviness at the joints of pultruded GFRP decking and to gain insight, via suitably designed tests, into the failure-inducing effects of this waviness when the joints are loaded. The ASSET deck system, a unit of which is shown in Fig. 2(a), has been chosen for the study. In order to maximise insight into the joint mechanics, each test was designed to satisfy the following criteria, namely :

- Loading to failure of only one joint.
- Development of generalised force patterns – local moments and shear forces – on the joint which are reflective of those induced by concentrated tyre loads applied to the flange of the deck.
- Full determinacy of these generalised forces acting at the entry to the joint from the applied load.
- Preservation of the natural continuity between the FWJ and its adjoining webs and flanges, to ensure that the natural stresses and crack propagations are induced within the joint under load on the deck.

In addition, it was important to test all joint configurations possible within an individual deck unit as well as between bonded deck units. To those ends, the objectives of the study were to :

- Illustrate an effective manual approach to documenting the fibre waviness at the deck joints.
- Show how select cuts in the deck enable determinate loading of single joints with web-flange continuity.
- Highlight the extent to which bonding the deck joints can influence joint failure loads and modes.
- Quantify any progressive local losses of stiffness due to crack propagation along the wavy interfaces.

In what follows the test specimens and procedures are described, then results are presented and discussed, after which conclusions are drawn and suggestions are made for further work.

3. TEST SETUP

3.1 Identification of Joint Types for Testing

Fig. 2(b) identifies the four flange-web joint (FWJ) types, henceforth termed JA, JB, JC and JD, that exist when two ASSET units are bonded together. Bonding of further ASSET units produces more of these (and no other) joint types. JA and JD are both fundamental joints within the individual ASSET unit. JA joins three members, namely the flange, diagonal web and an external web of the ASSET unit, with 60^o angular separations between these members and with a groove at the end of the flange. JD joins two members, namely the flange and the unit's other edge web, again with 60^o angular separation between them and with a lip protruding from the flange.

JB and JC both refer to the hybrid joint formed by bonding together adjacent deck units, whereby the lip of the "JD" joint from one deck unit fits into and is bonded into the groove of the "JA" joint from the adjacent unit. Since this hybrid joint is asymmetric, it is important to separately consider the effects on the joint of local loading on the flange both from the "JA-side" and the "JD-side". It is these considerations which have led to the double identification of this hybrid joint as either

JB, when it is loaded from the flange on the “JA-side”, or alternately as JC, when it is loaded from the flange on the “JD-side”. There is a loss of alphabetical order in naming the joints from left to right in Fig. 2(b), because the decision was taken that JA and JB should be paired, ditto JC and JD. This will facilitate comparisons between joints within each pair later in this paper.

3.2 Layout of Test Specimen and Loading Strategy

The specimen shown in both plan and elevation in Fig. 3 was fabricated to enable testing of each joint type defined above. As can be seen, the specimen comprised six ASSET units, each 200 mm wide, bonded to each other both along their FWJs (the lip of one deck unit fitted and bonded into the complementary groove of the adjoining unit) and along their inclined webs. In addition, the bottom flanges of all six deck units were bonded underneath to a 25 mm thick steel plate, which served as a translationally and rotationally rigid base.

JA and JD naturally occurred at the top left and right ends of the specimen. Hence, the local flange span connecting into each of these joints was cut across the 200 mm width, near the next joint inwards. This converted each such flange span into a cantilever, which was loaded near its tip during the test. Given that the cantilever is isostatic, the resulting local shear forces and moments induced at the cantilever’s entry into the joint were fully determinate. Note also, in Fig. 3, the cuts within the flanges on both sides of the middle top layer joint. Clearly, the roots of the resulting cantilevers connect into JB and JC to the left and right respectively of the middle top joint.

An important feature of this specimen layout is that, other than the essential flange cuts, the real load paths between adjacent deck units, through the bonded FWJs and webs, were strictly preserved. This is consistent with one of the requirements set out for the test setup as stated earlier. Also, as an aside, Fig. 3 shows that this distribution of flange cuts led to a sequencing of joints from left to right, which follows the alphabetical order JA, JB, JC and JD.

3.3 Characterisation of Joint Fibre Waviness

Fibre waviness was documented for each joint type by placing against the cut surface of the joint a transparent plastic strip on which was printed a grid of 10 mm squares. As Fig. 4(a) shows, this was done by making the top horizontal line of the grid flush with the top of the deck. A sharp-pointed red marker was used to highlight on the plastic strip a series of points along each wavy fibre layer of interest, the spacing of these points decreasing with any increased local gradient of the wavy layer under consideration. In Fig. 4(a) the first few such red points can be seen at the early stage of defining a crucial wavy fibre layer in the joint-flange transition zone, with the grid lines also palpable. The abscissae and ordinates of the points were then determined by first placing the 10 mm square grid with highlighted points against another, denser grid of 1 mm squares printed on paper which was used to determine the coordinates of the points to within ±0.25 mm. These coordinates were entered into Excel or Matlab, which was then used to provide spline fits through the points, resulting in plots of the wavy layers.

This approach was first trialled for the JA joints within the deck unit shown in Fig. 4(a). As can be seen in Fig. 4(b) this joint occurs as JA1 and JA2, at both ends of the diagonal web for this fundamental unit. It will be shown later that these flange-diagonal web joints include a top, intermediate and base fibre mat layer. This trial focused on the intermediate layer, since the tests (reported later) showed that layer to be quite involved in the local failures.

Fig. 4(c) compares this intermediate layer's wavy profiles for JA1 and JA2. The top left image of Fig. 4(c) shows the original marker points dotted on the transparent plastic for the JA1 plot. In developing the plots from these points the x-origin was taken as the flange-joint transition point, namely the location at which the flange suddenly narrowed into the joint to define the starts of the JA grooves which are clearly visible in Figs 2(a), 2(b) and 4(b). The y-origin was taken as the soffit of the flange. As Fig. 4(c) shows the JA1, JA2 wavy profiles are broadly consistent, but differences exist especially in the peak slope and on the flange side of the flange-joint transition. Note that the present paper focuses on the general features of these wavy profiles and their effects on local load response. In future, sinusoidal curve fitting may be attempted through these points.

By repeating this approach at one joint of each type, the wavy profiles within JA and JD were recorded more than once. This provided an opportunity to further check the consistency of the waviness profiles recorded for these joints. The results presented later will address this issue.

3.4 Testing - Loading Strategy and Instrumentation

Fig. 3(a) shows the load setup used for each test. Each cantilever was vertically loaded at a 95 mm lever arm from its connection into the joint. This use of a constant lever arm in all tests enabled useful comparisons to be made between the load responses of the different joints. A square section aluminium bar was used to apply the load uniformly across the 200 mm width of the flange, while a load cell placed between the bar and the loading actuator was used to measure the applied force. The load was applied by an hydraulic jack fed with oil from a reservoir by a hand pump. Potentiometers supported on stands with magnetic bases were used to measure the vertical deflections under the ends of the loading bar. By this means, the deflection at the loading point of the cantilever was measured. Fig. 3(b) shows a close-up of this test setup for joint JC.

Strains were recorded from 5 mm long electrical resistance gauges placed on the flange and web members very near the joints, to the layout shown in Fig. 3(a). All gauges were oriented to measure strains along the local spans of the members. For the tests at JA and JD, this included gauges at the roots of the cantilevers on both surfaces, to enable quantification of the effects of the maximum moments developed along the cantilevers. All gauge, potentiometer and load cell readings were recorded continuously during each test at 10 Hz by an electronic data acquisition system.

4. WAVINESS PROFILES

The first two parts of Fig. 5 show, for each of JA and JB, a photo of the joint in the deck's cross section with the wavy fibre layers evident, along with the fibre waviness profiles recorded for the joint. Note that the waviness profile is presented in the important context of the local joint geometry. Note from each photo the presence of three fibre mat layers through the flange thickness, namely one layer (labelled Top) near the top of the flange, another layer (labelled Int) at an intermediate level through the flange thickness and a final layer (labelled Base) travelling around the corner very near the base of the flange. Only the top and intermediate layers are here represented.

In the plots of Figs 5(a), (b), the marker points which form the basis of the waviness profiles are clearly shown. For the top and intermediate fibre layers the zones of peak waviness are identified as the fibre trajectories between the letters A and B, and C and D, respectively. In both cases, the top layer (A-B) zone displays the more pronounced waviness. Within the hybrid joint JB (Fig. 5(b)), this A-B zone on the "JA-side" of the joint generously exceeds the "JD-side" of the joint in waviness. This pronounced waviness is a direct result of the top layer fibres, which are very near the upper surface of the deck, needing to travel around the corner of tight radius created by the end of the groove where the flange meets the joint.

Clearly, these peak waviness zones are not representable by single sinusoidal curves. Indeed the Matlab spline-fits in these zones were found to be sixth order polynomials, which can be conveniently expressed in normalised (non-dimensional) form. Finally, Fig. 5(c) shows that the waviness profiles are broadly similar, although there are distinct differences in the peak waviness zones especially in maximum tangent angle to the horizontal. This can have important implications for the consistency of the deck's failure behaviour under a given load type and should be considered in more detail in further work.

Fig. 6 presents the corresponding results for JC and JD. It is seen that while the waviness in JD or on the JD side of the JC joint is palpable (Fig. 6(a), (b)) and shows a reasonable consistency between the two joints (Fig. 6(c)), it is far less pronounced than that for JA. Indeed, the profiles in Fig. 6(a) suggest that the wavelengths for the "JD-side" of the hybrid joint JC far exceed, and the amplitudes distinctly less than, those for the critical top fibre layer on the "JA-side" of the joint. It is interesting to note how these relative levels of waviness on the two sides of the bond in this hybrid joint translate into wavy interface fracture profiles as the load shifts from the JA side to the JD side of the joint. This issue will be addressed again in the ensuing sections while interpreting the load test results.

5. DISCUSSION OF TEST RESULTS

5.1 Failure Mode and Load Comparisons Between Joints

The test results show that failure never occurred in the adhesive bonds or along the webs common to adjacent deck units. Instead, failure was always confined to the FWJs, where the physical manifestation of such failure was fracture of the wavy fibre-resin interfaces. Fig. 7 shows these fracture profiles for the FWJs of all four joint types. An interesting observation is that the failure mode remained almost unchanged from JA to JB (Fig. 7(a)), but changed sharply from JC to JD (Fig. 7(b)). JA and JB both failed on the "JA-side" of the joint, largely by interface fracture for the intermediate fibre layer within the joint, along with some interface fracture for the intermediate and top layers extending just beyond the joint a short distance into the flange. The wavy interface fractures for JD were within the web side of the web-flange resin rich zone, and were broadly parallel to the inclined web. Fractures in JC were still on the "JD-side" of the joint, but with these fractures now near-horizontal for the top, intermediate and base layer fibres. The base layer fractures, located quite near the lip-adhesive bonded interface, were particularly pronounced.

The insensitivity of the JA-JB failure mode to joint make-up was very likely due to the stiff diagonal web support which, even on its own minimised local flexing of the joint and so, with the bond in place, ensured only moderate stress transfer through to the bonded lip of the adjacent deck unit. This might have resulted in similar stress states within and so similar failure modes for the JA, JB joints at ultimate.

Fig. 7(b) shows that JD experienced significant rotation of the unstressed lip extension, with considerable tensile stress transfer from the flange to the web clearly having occurred at the outer edge of the resin rich flange-web transition zone. However once the lip and web were bonded to the adjacent unit to give JC, the resulting restraint to lip rotation generated through-thickness tensile stresses in the lip and resin-rich zones that led to the multiple near-horizontal fractures seen for JC in Fig. 7(b). This explains the change in failure mode from JD to JC. Also, the JC failures within the parent GFRP material strongly suggest that the bonded interfaces between the GFRP and the externally applied adhesive enjoyed more favourable stress demand / strength ratios than did the fibre-resin interfaces within the GFRP itself.

Table 2 completes the picture on joint strength. It is seen that JA and JB were of nominally identical strengths, while the strength of JC was over four-fold that of JD. Importantly, the strongest joint was JC, over 2.5 times the capacity of JA. This is initially surprising because the lip extension in JC is quite thin and so the pronounced fractures within this lip (Fig. 7(b)) may have been expected to occur at fairly low loads. In this respect the one advantageous feature which puts JC ahead of JA and JB is the low waviness of the fibre mat layers alongside which the fractures occurred. The much more pronounced waviness in JA, JB might have significantly increased the wavy interface stress demand under load and by this means might have triggered the comparatively lower failure loads. This suggests a dominant effect of fibre waviness on local joint failure behaviour.

These failure crack patterns and loads show that, while the bonding adhesive layers allowed stress transfers across the hybrid joints, the failure-inducing activity remained on the side of the adhesive layer at which the external load was applied. The nature of this failure crack pattern was unchanged in proceeding from JA to JB, but morphed from JC to JD. This role of the adhesive layer as a buffer between the two sides of a hybrid joint should be explored in future work.

Figs 8 - 10 show the progression of fractures for each of joints JA, JB and JC. For JA (Fig. 8), fracture initiated alongside the intermediate wavy fibre mat layer within the joint, followed by further fractures alongside both the intermediate and top layers in the joint-flange transition zones. For JB (Fig. 9), fracture initiated alongside the intermediate layer where the tangent to the wavy profile was at its steepest in the joint-flange transition zone, followed by crack jumping through the resin across to the top fibre mat layer where the fracture continued to propagate along the steepest tangent to that layer. Subsequently, other fractures formed both above and below the top and intermediate layers largely within the joint zone, with short fracture extensions into the flange.

Fig. 10 shows that the first fracture in JC occurred alongside the top fibre mat layer in the main body of the flange-web transition zone and so just outside the lip extension, accompanied by crack jumping through the resin down to the intermediate way layer. This was later followed by extension of the fracture alongside the top wavy layer well into the lip extension zone, together with more fracture development alongside the intermediate layer in the resin-rich zone and, most importantly, the main fractures alongside the base fibre mat layer, just above the bonded interface of the lip with the externally applied adhesive. The thin “skin” of parent GFRP material under this main fracture remains fixed to the adhesive, suggesting good integrity of the GFRP-adhesive bond.

5.2 Stiffness and Ductility Comparisons Between Joints

Fig. 11(a) compares the load vs cantilever deflection (measured at the loading point) characteristics for the tests including JA and JB, while Fig. 11(b) does the same for JC and JD. It is immediately apparent that the move from the JA test to the JB test led to a significant increase in stiffness, while that from the JD test to the JC test led to a huge increase in stiffness. This is confirmed by Table 1, which shows a 3.14-fold and a 7.26-fold stiffness increase of the JB test over the JA test and of the JC test over the JD test respectively.

Hence in proceeding from the JA test to the JB test, the strength increase has been almost zero but the stiffness increase has been considerable. In fact strictly speaking, this stiffness increase was due not only to the bonded FWJ, but also to the entire bonded length of web to the adjacent unit which provided much additional restraint to the rotations and displacements of the cantilevering flange. Certainly this bonding to the adjacent deck unit along the entire length of the web would have accounted for a lot of the huge stiffness increase of the JC specimen above the JD specimen, as the JD specimen had only the one web leg to help restrain rotation and deflection at the root of the flange cantilever (while the JA specimen had two splayed web legs before the additional restraint appeared from the adjacent deck unit in the JB specimen).

Fig. 11(a) shows an ability to hold a significant proportion of the load capacity after stiffness drops due to fracture. This suggests ductile behaviour of JA and JB. Clearly, the post-peak load holding as a proportion of the peak load is palpably better for JB than for JA, probably due to the additional material available to help with stable stress redistribution. By contrast, JD and JC show precipitous drops in load-carrying capability beyond peak load, suggesting little ductility.

The left plot of Fig. 12(a) shows, for JA, the variations with load of strains recorded from the outermost locations of the flange and each web section at connection into the joint. The strain gauge locations are given in Fig. 3(a). The plots suggest linear behaviour up to failure, when strains of almost 2000 $\mu\varepsilon$ were recorded. In the right plot of Fig 12(a), these raw strains are then separated out into an axial effect (the average within each pair of strains) and the flexural effect (the difference within each pair). It is seen that the axial effect for the cantilever is almost zero, as required from equilibrium, while that for the two webs remains small. By contrast, the flexural effects are quite pronounced, confirming the bending-dominated behaviours of the members framing into this joint. The two plots of Fig. 12(b) do the same for the cantilever framing into JD. The nonlinear unloading curves may have been due to the pronounced and sudden cracking.

Now, recall the elementary beam theory expression $M = EI\kappa$, where M is the section moment, E is the assumed homogenous material modulus, I is the second moment of area of the section about its neutral axis and κ is the section curvature. Further, recall that if d and $\Delta\varepsilon$ are respectively the section depth and the difference in longitudinal strains between the outermost locations of (namely the gauge locations on) the section, then $\Delta\varepsilon / d$ is the section curvature. Finally, the moment at the gauged section is obtained from statics using the applied load and the lever arm from the load to the gauged section. Hence using these formulae along with the test data, it was possible to deduce the flexural stiffness EI of the cantilever section at the gauged locations.

Fig. 13 shows the resulting EI variations with load for the gauged flange cantilever sections framing into JA and JD. This Figure shows that each section flexural stiffness was roughly constant with load increase. The plots start at about 0.2 kN, to avoid the effects of errors in the strain recordings at lower loads. The 2.5 kNm^2 starting value for JD exceeds the corresponding 2 kNm^2 starting value for JA by 25%. This is probably due to the lesser waviness of the fibres and the associated further-out locations of the fibre layers on the section at JD than at JA. More importantly, the EI value at JD exceeds double that calculated using the manufacturer's E value (Table 3) for the flange along with an I value for the rectangular section of 200 mm width and

15.6 mm depth. This probably has to do with the fact that the *I* calculation assumes a homogenous section, while in fact the concentrated fibre layers which strongly influence section stiffness are at discrete levels which differ from those assumed when the equivalent homogenous section properties were produced. More work is needed into this effect of fibre waviness.

More generally, fibre waviness also occurs along the length of the flange between FWJs. This causes variation along the flange of the GFRP material's effective modulus. Use of strain gauges at regular intervals along the flange cantilever between the loading point and the joint would enable this modulus variation to be estimated.

6. SUMMARY AND CONCLUSIONS

Some key conclusions from this study are as follows :

- The use of a sharp-pointed marker to highlight dots on transparent plastic sheeting placed firmly against the cut face of a pultruded GFRP bridge deck unit enables reliable representation of the fibre waviness profiles in the flange-web joint zones of the deck. Then, using Matlab or Excel, it is possible to define equations which closely fit the particularly wavy profiles, for possible use in further analysis (beyond the scope of this specific study).
- It is crucial to identify both the fundamental joints within the deck units and the hybrid joints formed by bonding the originals together, taking care to distinguish between the two sides of asymmetric hybrid joints, since the tests can be used to establish the impact of bonding on joint behaviour.
- A novel experimental strategy was devised in which only one joint at a time was loaded by statically determined generalised forces from the root of the nearby loaded flange cantilever.
- Under load on the flange cantilever, failure always occurred by fracture of the wavy fibre-resin interfaces within the FWJs, even for the bonded joints, where no failures were observed in the adhesive or along the webs common to adjacent deck units.
- Fibre waviness also influences the effective section flexural stiffness and so the effective material modulus along the flange. These effective values may be deduced from knowledge of

the statically determined moments and the section curvature as deduced from strain gauge readings at regular intervals along the flange cantilever.

This study has focused on plotting fibre waviness and experimentally observing its effects on the quasi-static behaviour of the joints. Future work should focus on using statistical approaches (given the likely random nature of fibre waviness) tied to predictive modelling and experiments, to establish the effects of this waviness on local tyre load fatigue of the decks.

7. REFERENCES

[1] Ellingwood B. R. Toward load and resistance factor design for Fiber Reinforced Polymer composite structures. ASCE Journal of Structural Engineering, 2003, 129(4), 449-458.

[2] Coogler K., Harries K. A., Wan B., Rizos D. C., Petrou M. F. Critical evaluation of strain measurements in Glass Fiber-Reinforced Polymer bridge decks. ASCE Journal of Bridge Engineering, 2005, 10(6), 704-712.

[3] Keller T, Gurtler H. Quasi-static and fatigue performance of a cellular FRP bridge deck adhesively bonded to steel girders. Composite Structures, 2005, 70(4), 484-496.

[4] Sebastian W. M., Gegeshidze G., Luke S. Positive and negative moment behaviours of hybrid members comprising cellular GFRP bridge decking epoxy-bonded to reinforced concrete beams. Composites Part B: Engineering, 2013, 45(1), 486-496.

[5] Gabler M., Knippers J. Improving fail-safety of road bridges built with non-ductile fibre composites. Construction and Building Materials, 2013, 49, 1054-1063.

[6] Sebastian W. M., Keller T., Ross J. Influences of polymer concrete surfacing and localised load distribution on behaviour up to failure of an orthotropic FRP bridge deck. Composites Part B: Engineering, 2012, 45(1), 1234-1250.

[7] Sebastian W. M., Webster T., Kennedy C., Ross J. Profiled metal plate – cork mat loading systems on cellular FRP bridge decks to reproduce tyre-to-deck contact pressure distributions. Construction and Building Materials, 2013, 49, 1064-1082.

[8] Zi G, Kim B. M., Hwang Y. K., Lee Y. H. An experimental study on the static behavior of a GFRP bridge deck filled with a polyurethane foam. Composite Structures, 2008, 82(2), 257-268.

[9] Yanes-Armas S, de Castro J., Keller T. System transverse in-plane shear stiffness of pultruded GFRP bridge decks. Engineering Structures, 2016, 107, 34-46.

[10] Yanes-Armas S, de Castro J., Keller T. Energy dissipation and recovery in web-flange junctions of pultruded GFRP decks. Composite Structures, 2016, 148, 168-180.

[11] Turvey G. J., Zhang Y. Characterisation of the rotational stiffness and strength of web-flange junctions of pultruded GRP WF-sections via web bending tests. Composites Part A, 2006, 37(2), 152-164.

[12] Feo L., Mosallam A. S., Penna R. Mechanical behavior of web-flange junctions of thin-walled pultruded I-profiles: An experimental and numerical evaluation. Composites Part B: Engineering, 2013, 48, 18-39.

[13] Fascetti A., Feo L., Nisticò N., Penna R. Web-flange behavior of pultruded GFRP I-beams: a lattice model for the interpretation of experimental results. Composites Part B: Engineering 100, 257-269.

[14] Quadrino A., Penna R., Feo L., Nisticò N. Mechanical characterization of pultruded elements: Fiber orientation influence vs web-flange junction local problem. Experimental and numerical tests. Composites Part B: Engineering, 2018, 142, 68-84.

[15] Adams D. O., Hyer M. W. Effects of Layer Waviness on the Compression Strength of Thermoplastic Composite Laminates. Journal of Reinforced Plastics and Composites, 1993, 12(4), 411-429.

[16] Bloom L. D., Wang J., Potter K. D. Damage progression and defect sensitivity: An experimental study of representative wrinkles in tension. Composites Part B: Engineering, 2013, 45, 449-458.

[17] Sutcliffe M. P. F., Lemanski S. L., Scott A. E. Measurement of Fibre Waviness in Industrial Composite Components. Composites Science and Technology, 2012, 72, 2016-2023.