Bi-Axial Behaviours of Abraded and Rehabilitated FRP Decks as Anisotropic Plates Under Concentrated Wheel Loading

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ABSTRACT

For in-service GFRP (glass fibre-reinforced polymer) cellular bridge decks, wheel loads can induce damage of the anti-skid surfacing-to-deck bond, thereby loosening fragments of surfacing that then cause abrasion of the deck's top flange. Indeed, over the last 20 years, wheel load-induced damage to the top flanges of FRP decks on the road network has observed in different countries, after periods in service ranging from a few days to a few years, due to inadequate design. Bonding of uni-directional GFRP panels to the abraded flange constitutes a potentially effective rehabilitation strategy, but it also influences the deck's local wheel-load response by altering the anisotropy of the top flange. The present paper uses an experimental-numerical study to explore this role of anisotropy for both abraded and rehabilitated decks. The experiments captured the top flanges' peak biaxial strains, using gauges on the flange soffits to avoid damage by the wheels. The numerical model captures the morphology of the deck, the actual spread of the tyre load over the contact zone and spatial variations in anisotropicity of the abraded or built-up flanges and of the webs. The results show that the uni-axially dominated rehabilitation strategy strongly improves bi-axial response to static wheel loads. The numerical model encouragingly predicts the bi-axial strains for each of the abraded and rehabilitated decks, and reliably predicts the strain *reductions* due to rehabilitation. Refined meshes along the tyre-loaded local flange span, with coarser meshes in adjacent spans, enable these reasonable predictions of response. It is concluded that top flange gauges installed via ad-hoc tooling inserted through holes in the bottom flange, in tandem with numerical modelling, constitutes an effective two-pronged approach for elucidating wheel load effects.

KEYWORDS : GFRP bridge decks, bi-axial, anisotropy, wheel loads, rehabilitation, numerical model.

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1. INTRODUCTION

1.1 General Background

Glass fibre reinforced polymer (GFRP) bridge decks comprise lightweight, corrosion-resistant, cellular modules that enable rapid construction of durable road bridges on light foundations, in either a new-build or rehabilitation context. Many GFRP decks in use (including that of the present study) have been manufactured by pultrusion, others by resin infusion. In many applications FRP decks are used because, relative to reinforced concrete decks, they accelerate and economise construction while avoiding in-service deterioration from de-icing salts. In such cases the FRP decks are connected to steel [1], FRP [2] or prestressed concrete [3] beams underneath. In other cases, e.g. [4, 5], the alternative strategy has been used of FRP beams connected to overhead concrete slabs, so that the FRP and concrete carry tension and compression, respectively, from global bending, in alignment with the complementary stress resisting capabilities of the materials.

The ease with which the material can be moulded means that new forms of FRP cellular decking are routinely reported. A recent example [6] entails pultruded box sections sandwiched between pultruded flat panels, such that the box sections run either along or normal to the bridge's main span, to form a system in which all the cells are voided. In another recent example [7], a two-step manufacturing process of vacuum-assisted resin transfer moulding (VARTM), followed by bonding, was used to output a double-layer deck system in which vertical back-to-back trapezoidal cells filled with low-density polyurethane foam alternate horizontally with voided hexagonal cells.

FRP deck bridges are a relatively recent innovation, so research is needed to understand key facets of their global and local structural mechanics. To date global features such as dynamic performance, transverse load distribution and deck-beam composite action have been studied via analysis along with lab and field studies [9-20]. Even for more conventional (e.g. steel composite, prestressed concrete and steel orthotropic deck) bridges, field monitoring [21-26] based on use of various sensors including strain gauges is used to gain deeper understanding of structural action.

Now, a crucial facet of local behaviour is high cycle tyre load fatigue of the deck's top flange acting compositely with the deck's anti-skid surfacing. Fig. 1(a) shows that, under tyre loading, the top flange (seen without surfacing for clarity) exhibits significant dimpling as an anisotropic plate. The anisotropy stems from the in-plane directional dependency of the fibre layout in the flange. Within the dimpled zone onerous 3D stresses develop in the flange-surfacing system, triggering fatigue.

One manifestation of fatigue is fracture of the interfaces between the wavy glass fibres and the resin, within the deck's web-flange junctions (WFJs, see Fig. 1(a)) near the tyre loads and along the flange flats spanning locally between WFJs. These fractures propagate and eventually breach the deck's outer protective resin layer, allowing moisture ingress from the deck's surface which exacerbates degradation [27]. Good computational and experimental representation of the tyre load in 3D, so as to properly capture this effect, has been a subject of previous studies [27-33].

Another manifestation of local fatigue is fracture of the anti-skid surfacing and of the surfacing-to-deck bond, creating loose fragments of surfacing that abrade the top GFRP flange under further lorry tyres. This little-known effect (prior sightings of flaky surfacing were due to poor workmanship [34-36]) can strongly compromise the top flange's structural integrity if left unchecked. Bonding of FRP panels to the abraded flange is a potentially cost-effective, user-friendly means of rehabilitation. If the panels mimic the abraded top flange in fibre architecture, then the result is a built-up top flange of consistent fibre architecture. In practice, the top flanges contain multi-directional fibres while the available panels contain uni-directional fibres. This causes the anisotropy of the built-up top flange to differ from that of the abraded flange, which in turn influences the deck's tyre load response. The core mechanics of these influences are unknown.

The uni-directional fibres should be aligned with the local bending direction of the abraded flange, transverse to the deck's pultruded direction. Also, the panels should be as long as possible for continuity across several abraded flanges and to serve as part of an effective top flange to the bridge.

Now insight into the local stress field, and so into the local bi-axial strains, is fundamental to understanding the tyre load responses of abraded and rehabilitated decks. To that end it is prudent to locate strain gauges on the soffits of the tyre-loaded flange locations, to protect the gauges from damage by the tyres on the top surfaces. Fig. 1(c) shows that this is difficult due to the *fully* closed-cell nature of the deck. By contrast steel orthotropic decks are *partially* closed-cell, so that strain gauging of the critical zones from below is possible, e.g. Fig. 1(d) as achieved in a recent study [26]. Prior studies on GFRP decks have tackled this issue by using short lengths of deck which are easily gauged internally [1, 3, 28, 31, 33], or by carefully protecting gauges on the outer surfaces [3, 11, 27, 30], or by placing gauges on internal surfaces near the edges of the deck, where there is uninhibited access to those surfaces, and then applying the tyre loads also in those edge zones [32].

This paper presents an experimental-numerical study into the anisotropy influenced responses of an abraded and subsequently rehabilitated deck to tyre loading. Specifically, the paper seeks to :

- Use field evidence to show that abrasion of GFRP flanges by surfacing fragments is a problem.
- Present a rehabilitation scheme based on bonding of uni-directional plates to the abraded flange.
- Describe an ad-hoc strategy for capturing local wheel load induced bi-axial strains on the decks.
- Report local tyre load tests conducted on the abraded and rehabilitated decks.
- Highlight the importance of anisotropy in the numerical model used to predict response.
- Assess the rehabilitation scheme's effectiveness using the predicted and measured data.
- Discuss the role of this methodology in evaluating tyre load fatigue of GFRP deck systems.

1.2 History of Tyre Load Damage in FRP Decks

Wheel load-induced damage to FRP bridge decks on the road network has occasionally been observed in different countries. A UK example is Bonds Mill bridge, an 8 m long, single lane lifting bridge built over a canal in 1994, Fig. 2(a). It is the world's first all-FRP traffic bridge including the side rails. The deck comprises a foam-filled, pultruded cellular system. Within its first two years of use, the deck's top flange delaminated and the foam crushed due to wheel loads, Fig. 2(b). The issue became more pronounced over time and was eventually addressed by laying (not bonding) steel plates onto the deck, to carry the wheel loads on their own, Fig. 2(c). The plates increased self-weight such that the bridge no longer lifts, and they incur anti-corrosion maintenance costs. The damaged FRP remains under the steel plates.

In the USA, a sandwich-type deck with an integral foam cell core and manufactured by VARTM (vacuum assisted resin transfer moulding) developed top face sheet delaminations which propagated under wheel loads during its first two months in service [37]. The problem progressed until the FRP deck was replaced by a concrete deck [34]. It was concluded [34] that the small and frail face sheet-core junctions make these decks prone to such degradation.

In 2020, a pultruded cellular FRP bridge deck on the road network in Holland developed pronounced cracking within the top flange (Fig. 2(d)) immediately adjacent to, and parallel to the deck-deck joints after only a few days in service. This bridge is of only 4.5 m span, with the FRP deck units laid across longitudinal steel beams, and is near a major construction site serviced by heavy duty lorries. The problem became so severe that the FRP deck has been replaced by a timber deck, to keep the weight low as this is meant to be a lifting bridge.

The present paper shows that such wheel load effects were also observed on another UK FRP bridge deck, after a few years in service. These examples raise the following generic points :

- The cases cover a 20-year period, so this is a long-standing problem that needs to be resolved.
- It is not a weakness of the material, rather it is a result of inadequate design.
- It has occurred in VARTM decks and across generations of pultruded deck (Bonds Mill, West Mill, Dutch bridge), so the full spectrum of deck types should be evaluated for resistance to such damage.
- Damage occurred at between a few days and a few years in service, for decks at various sites in different countries, implying that no harmonised design method exists to address this.
- A range of tyre loads must be considered, given traffic variations between the affected bridges.
- The damage occurs well before the 120-year design life specified for road bridges in the UK, so new design methods are needed to protect FRP bridge decks against this problem.
- The use of steel plates, timber decks and concrete decks to replace damaged FRP decks is ironic, given that FRP decks are meant to be durable alternatives to these traditional options.
- Thermal stresses from temperature changes of the deck in service may be a contributing factor.

2. WEST MILL GFRP ROAD BRIDGE

The earlier stated objectives are achieved via a combined experimental and numerical study conducted on a GFRP cellular deck bridge on the road network in the UK. This bridge experienced significant abrasion of the top flange from surfacing fragments created by tyre load fatigue, and was subsequently rehabilitated using bonded panels. In what follows the bridge is described, evidence is presented of the important factors up to and including abrasion, the rehabilitation scheme is explained, the numerical modelling strategy defined and, finally, the wider significance of the results discussed.

2.1 Original Bridge

The 10 m span West Mill FRP bridge carries two lanes of contraflow traffic across the river Cole in Oxfordshire, UK. Fig. 3(a) show the cross section of the original bridge [20]. As can be seen, the bridge comprises a deck made from pultruded double-triangular GFRP ASSET deck units, one of which is shown in Fig. 1(b), laid transversely across four main longitudinal FRP beams. Each beam in turn comprises four square GFRP tubes and is completed with CFRP flanges at the top and base. The entire deck-and-beam system is bonded together.

Built in 2002, this was the first FRP deck-on-FRP beam traffic bridge on the public highway network in Europe [38]. The bridge is suited to vehicles up to 46 tonnes [39]. Between 2005 and 2011, the annual average daily traffic (AADT) was found to be approximately 2000 vehicles of which about 1.3% were heavy goods vehicles, placing the bridge within the Traffic Category 4 (local roads with low flow rate of lorries) in Table 4.5 of Eurocode 1 [38].

Each deck unit is continuous over the 6.8 m width of the bridge, including 3 x 1.75 m continuous spans across the main beams to support the carriageway and 0.775 m cantilever overhangs at both edges to support the walkways. A transversely sloping polymer concrete anti-skid surfacing layer was bonded to the deck's top flange in the original bridge. The construction process, which benefitted from low-power craning of the lightweight bridge into position, Fig. 3(b), is described in Hejll et al. [20].

2.2 Problems With Original Deck and Surfacing

From circa 10 years of service onwards, two key manifestations of deterioration were observed for the FRP deck of the West Mill bridge. Fig. 4(a), (b) show that one manifestation entailed fragmentation, sinking and flaking off of the surfacing. Fig. 4(c) shows the other manifestation, which occurred within two of the deck's triangular cells that were adjacent to each other along the direction of tyre roll. For contextualisation, the traffic (tyre roll) direction is also provided. It is seen that this latter manifestation entailed severance of failed portions of the top flange from the rest of the deck at the WFJs, leaving triangular voids in the original deck. Note that the length of failed flange in each cell was approximately 2 m.

The images of Fig. 4(b) have an additional significance. The left image shows that the surfacing fragments initially remained confined by the surrounding intact-bonded surfacing material. Hence, with each passage of a lorry tyre directly over the fragments, the vertical load from the tyre pushed the fragments firmly onto the top surface of the GFRP flange while friction from the tyre simultaneously dragged the fragments over short distances along the flange. Over time, the net result was abrasion of the flange by the loosened surfacing fragments. The right image of Fig. 4(b) shows an example of an abraded zone of flange (not for the same location of the deck as the left image). The "veins" evident on the flange surface in the right image represent the boundaries between the surfacing fragments. The flange thickness was reduced by an estimated 1 mm due to this abrasion.

Now it is normally held that surfacing is beneficial either because it disperses the tyre loads or because it acts compositely with the deck's top flange to more effectively resist the tyre loads.

However, the above abrasion means that the surfacing can also be detrimental to the health of the top flange. There are important implications here for reliably evaluating the tyre load fatigue life of the surfacing-to-flange bond, so that well-informed decisions can be made on timely replacement of the surfacing in practice, thereby avoiding this detrimental abrasion.

2.3 Repair Strategy

A two-pronged rehabilitation strategy was designed for the damaged deck, as described below.

- Recall from Fig. 4(c) that two adjacent cells of the deck suffered failed top flanges. This happened over approximately a 2 m length along each cell, in the transverse direction of the bridge. The rehabilitation scheme employed was to rebuild these lost lengths of top flange, using new lengths of GFRP plate bonded to the surrounding intact original deck material. In addition, lengths of structural foam were used to fill the cell voids underneath those new made-up flanges, and adhesive used to fill any foam-FRP gaps so enabling the foam to directly support the rebuilt flanges above. Fig. 5(a), (b) show the locations and dimensions of those foam-repaired zones. It is seen that this occurred in one lane, at about a third the span of the bridge from one end.
- Over the entire plan area of the deck (including the foam repaired zone), two layers of uni-directional GFRP panels, each 10 mm thick, were bonded to the top of the existing deck. Fig. 5(c) shows the detail of these two panel layers for two cells of the deck. The panel fibres ran in the left-right direction in the plane of the page, thus providing structural enhancement to the deck's original top flange mainly along its local span between the webs of the deck.

The first step in the staged implementation of this repair scheme, was removal of the original surfacing from the deck, followed by cleaning of the exposed original deck surface. Fig. 6(a) shows the cleaned out and trimmed back portions of cell ready for insertion of the foam blocks and re-building of the top flange, while one of the foam blocks just removed from its packaging is shown in Fig. 6(b). Fig. 6(c) shows laying of the panels in progress. Each panel was 0.5 m wide and 10 m (the entire length of the bridge) long. Several operatives (five in the image) were needed to carry the panel and offer it down to the deck's surface already smeared with the adhesive. Note the wobbles along the panel, owing to self-weight, the material's low elastic modulus longitudinally and its length between human supports. Finally, Fig. 6(d) shows the repair works completed after the new bituminous surfacing had been applied. These repair works consumed a six-week period.

3.0 INSTRUMENTATION AND TESTING STRATEGY

Fig. 5(c) schematically illustrates the ad hoc strategy used to strain gauge the soffit of the deck's original top flange. The aim was to install an electrical resistance (foil) 0-90 strain gauge, comprising one gauge along the local span of the flange between webs and the other in the perpendicular direction (along the direction of pultrusion), at each of two locations of the deck. Each foil gauge was 1 cm long while each location was at the local midspan of the flange, between adjacent webs of the deck. As Fig. 5(a), (b) show, two sets of these 0-90 gauges were installed onto the (transverse) deck cell located at midspan of the bridge, within one traffic lane.

It is seen that this was accomplished (Fig. 5(c)) by drilling a 30 mm diameter hole through the thickness of the bottom web-flange joint, which is vertically aligned with the local midspan of the top flange. Vertically through this hole was fitted a rotating drill shaft equipped with sandpaper (and later with a cleaning agent on small pads) on a disc at the end of the rotating shaft, to prepare the soffit of the top flange for gauging. Once the surface was prepared the already leaded 0-90 gauge, with adhesive applied to its bonding surface, was centred on a metal disc at the upper end of a 20 mm diameter tube. Perpendicular lines were inscribed on the disc's upper surface, and these lines were matched as near as circumstances allowed, to the longitudinal and transverse directions of the top flange, to ensure as far as possible correct alignment of the gauges during installation. This tube is shown in Fig. 5(c) as fitted through the hole drilled in the bottom flange and on its way up to the underside of the top flange where gentle upward pressure was exerted so that the disc at its top end was in bearing on the strain gauge against that top flange, to encourage bond of the gauge to the flange via the adhesive. For convenience, the strain gauge is shown already bonded to the underside of the top flange, to distinguish gauge from disc. Shining a torch up through the hole enabled checks by eye on the gauge alignments.

Now, the adhesive used to bond the gauge to the GFRP flange required a raised temperature of 60°C for full cure within a couple hours. This consideration was particularly important because the work was done outdoors in winter. To that end, some additional design features of the above tube are now described. Hot air guns were used to blow heated air up the tube from its lower end. This air heated up the tube's top end metal disc, which in turn conducted the heat to the strain gauge and adhesive bearing against the GFRP flange, thereby enabling proper cure of the adhesive. Near the top end of the tube, approximately 1 cm below the metal disc, small holes were drilled through the tube's thin wall to provide an exit route for the hot air coming up the tube. Fig. 5(c) illustrates this routing of the hot air and also shows metal handles near the lower end of the tube. Straps fixed to the soffit of the deck and wound around these handles were used to fix the tube in place during use.

Site implementation of the above can be seen in Fig. 7. Owing to the shallow river underneath the bridge, this installation was performed from a scaffolding platform mounted with feet on the riverbed. Fig. 7(a) shows one of the two tubes as fabricated. Note the threaded metal handles and, with more detail at the inset, the disc and holes at the top end. Fig. 7(b) shows the tubes vertically fitted through the holes at the base of the deck and held in place by the straps supported from the soffit of the deck. Fig. 7(c) shows the air guns in operation fitted at the bases of the tubes, including the in-situ supports used to hold the guns themselves in place. This tooling led to successful installation of the strain gauges, as evidenced from the data obtained during the lorry tyre load tests conducted afterwards on the deck and reported later in this paper.

4.0 TYRE LOAD TESTS

A lorry with a (measured) 8.5 kN load coming through a single tyre on the front axle was used to load the deck, centred directly above each of the two 0-90 gauge locations. This tyre load was applied first to the exposed original deck surface after the original surfacing had been removed, and then a second time after the double layer of GFRP panels had been bonded onto the original deck. In both cases the length and width of the tyre-deck contact patch was measured at 190 mm x 160 mm. Fig. 8 shows the tyre being driven into position on the rehabilitated deck.

During each tyre load application, the strain gauges readings were recorded by an electronic data acquisition unit at 10 Hz. The unit was powered by a site generator. All gauges were zeroed and recording began before the lorry was driven onto the bridge. The centre and boundaries of the tyre-deck contact patch were marked onto the flange’s top surface beforehand, to help with final locating of the tyre. Note the size and shape of the contact patch were already known by loading another independent specimen of the same decking with the tyre, near the end of the bridge, and this contact patch geometry was reconfirmed during the tests. In order to check consistency, the tyre was repeatedly driven onto and off each 0-90 gauge location. This exercise revealed that the deck’s response was indeed consistent.

An important observation from the tyre loading exercise is that the strain changes as recorded from the gauges were negligible until the tyre was almost very near, say within 300 mm of, the gauges. This means that the longitudinal bridge (global) bending strains induced by the lorry overall were tremendously dwarfed by the plate component bending strains induced locally by the tyre load. This mimics an observation made in a previous experimental study [3], where the local bending strains from a concentrated load applied to the same deck of another FRP deck bridge were over 20 times the global bending strains.

In the next section of the present paper, the above measured local load-strain behaviour is used to verify a FE model of the deck, in an attempt to establish the level of predictability of the strain reductions achieved by the panel bonding rehabilitation scheme.

5.0 FE – TEST COMPARISONS

Given the experimental observation that the recorded strains were almost totally dominated by local, not global response, a decision was made to predict these strains using a local model of the deck. This model including the bonded double panel layer is shown in Fig. 9(a). Five bonded together deck modules in total were considered, with the central module subjected in its mid-length zone to the tyre load, and hence with two deck modules either side to provide representative restraint. Given the highly localised nature of the response, this layout of material around the tyre load was considered reasonable.

The software package ANSYS was used to conduct the analyses. Eight-noded solid (3D) elements were used to model the deck. Fig. 9(a) shows that, for the original top flange of the deck, a refined mesh was used along the middle module where the concentrated tyre load was applied. It is seen that, for the original deck, the mesh then becomes less refined in the adjoining webs and flanges. Fig. 9(b) shows a close-up view of the gradation of the FE mesh from the middle module to its immediate surroundings. Note also the fine mesh used for the overhead adhesive and panel layers, at a level of refinement somewhere between that of the original top flange and that of the adjoining webs. A zero thickness adhesive layer was assumed between the sloping webs of adjacent deck modules, leading to common nodes in the FE model for neighbouring modules along their common interfaces. The edge nodes at the underside of the deck were restrained against movements in all directions, all other nodes were free to move.

Note that, in order to represent the 1 mm attrition of the top flange by abrasion from the surfacing as described in section 2.2 of the present paper, the top flange thickness of the FE model was reduced to 1 mm below that of the deck module as presented in Fig. 1(b). A core feature of the modelling entails representation of the anisotropic GFRP material properties, for both the abraded and rehabilitated flanges, as well as for each of the webs and lower flanges of the deck. To those ends, Table 1 gives the 3D orthotropic material properties used for the deck's flanges and webs, also for the bonding adhesive and the panels. Note how the rehabilitated top flange has been built up in the FE model by representing each of the abraded flange, the adhesive and the two uni-directional plate layers discretely. This enabled reliable representation of the change in anisotropy between these two flanges, by use of the relevant orthotropic properties in the discrete layers depending on whether the pre- or post-rehabilitated flange was under consideration.

Fig. 9(c) shows the manner in which the 8.5 kN tyre load was distributed over the measured 190 mm x 160 mm rectangular patch. Previous experimental research [32] shows that the tyre load may be closely approximated as a trapezoidal distribution which varies as a function of the load level. This approximation was applied to the present loading, using formulae presented in [32]. The peak pressure zone (red strip) along with the zones of linearly tapering pressure (down to the minimum pressure blue zone) can be seen in Fig. 9(c).

Fig. 10(a) shows the variation, with normalised time, of strain recorded in the top flange's local span direction at the gauge locations shown in Fig. 5, for this top flange both in the original state and after bonding of the double-panel layers. Fig. 10(b) does the same for the recorded strains in the direction along the (pultruded) length of the deck module. On both sets of plots, the strain reduction and subsequent increase during the test on the original abraded flange were due to movement of the tyre load away from and back to the gauged flange. In each case, the tyre load was held for at least 30 seconds with the strains at their peak levels.

Fig 10(a), (b) illustrate two key points, as follows :

- For each test, the strain developed by the top flange in the local span direction exceeded that developed by the same flange in the deck's pultrusion direction, by a factor of at least 2.5. This confirms that the top flange's local tyre load response is strongly dominated by flexing along its local span direction.
- Bonding of the panels led to almost six-fold reduction in strains along the local span, from 620 με to 110 με. Hence the panels had a highly beneficial effect on tyre load response, with beneficial implications for tyre load fatigue life given this significant strain reduction.

Fig. 10(c) shows, for the top flange both before and after rehabilitation, the FE-predicted strain profiles in the local span direction, from one end to the other of that local top flange span through the experimentally strain gauged location. For comparison, the strains recorded (Fig 10(a)) from the tyre load tests at the middle of that local span are provided. It is seen that in the crucially important local span direction the FE analysis predicts a reduction of 630 με , from 890 με to 260 με, while the tests revealed a measured reduction of 510 με , from 620 με to 110 με. Hence the analysis overestimates the local strain, by 44% for the original flange, but predicts the strain reduction reasonably, at 81% of the experimentally obtained value. This points to the value of FE analysis incorporating anisotropic properties as a tool for providing insight into the effectiveness of bonded panel schemes.

Note that the compressive strain in the top flange due to (global) longitudinal bending of the bridge was estimated, based on beam theory and assuming rigid bond between the beams and deck. This compressive strain was found to have been (in absolute value) approximately an order of magnitude below the corresponding strains in the same direction due to the local tyre load effect as predicted by the above FE analysis. This is important, because the FE analysis covers only the local effects, while the site test measurements included both local and global effects. It may be that this global compressive strain accounts for some of the disparity between the predicted and test results in Fig. 10(c).

6.0 Discussion

In reality, the tyre load fatigue life of the surfacing-to-deck bond would be generously exceeded by that of the deck itself. Hence the surfacing will typically need to be replaced multiple times during the service life of the deck. To that end, an estimate of the intervals required between re-surfacing events will be best obtained from tyre load fatigue tests of surfaced deck specimens. Even then, these estimates will be subject to some tolerance, and in practice some abrasion of the top flange might well occur beforehand.

This is where the approach presented in this paper can be useful. If it is accepted that abrasion will occur to some extent, and given that it has in the present example (and possibly in others not yet recognised as such), then evaluation of the replenishing effect of the bonded panel scheme is important. This must be done without the surfacing present, as in the present approach, because different bridge owners may opt for different thicknesses and types of surfacing. The tyre load fatigue life of the deck, with or without the bonded panels must be evaluated for the design life of the bridge or deck, and that entails a study of the type presented here.

Note that fibre optic sensors installed on the West Mill bridge, when it was first built, were not available for the testing reported in this paper. In future tests, the promising digital image correlation (DIC) technique can be employed to provide full-field strains over the zone of interest.

It is hoped that, if they exist, any further examples of abrasion and rehabilitation of FRP bridge decks may be published to enable development of a meaningful body of work on this important issue. Further studies on the influence of other anisotropic layouts of the decks should be at the core of these developments.

7.0 CONCLUSIONS

The key conclusions to be drawn from this study are that :

- Wheel loading of multi-cellular GFRP bridge decks in service can lead to fatigue of the anti-skid surfacing and of the surfacing-to-deck bond, thereby loosening fragments of surfacing which then abrade the top GFRP flange when pressed into and rubbed against that flange by subsequent lorry tyres. This is a little-known, but important effect. A more widely known local tyre load fatigue effect is fracture within the top GFRP flange material, leading to severance of the deck's top flange from the rest of the deck in isolated zones. Over the last 20 years on road networks in the UK, Holland and the USA, FRP decks manufactured by different methods have exhibited such fractures after periods in service ranging from a few days to a few years.
- For decks which have suffered such damage, a site-friendly rehabilitation strategy entails bonding uni-directional panels onto the deck's abraded flange, with the panel fibres oriented parallel to the local span of the abraded top flange across the GFRP webs. The resulting change in anisotropy of the top flange due to the panels should be accounted for in assessing the benefits of this rehabilitation strategy. Where the flange has been severed, structural foam inserts and rebuilding of the severed portions is appropriate.
- Strain gauges bonded to the soffit of the abraded top flange provide an excellent route to understanding the local tyre load responses of both the abraded and rehabilitated flanges. Due to the fully closed cell nature of the deck, this soffit of the top flange was prepared and gauges successfully installed via ad hoc tooling inserted through small holes cut out of the deck's bottom flange.

- For the present example, up to six-fold reductions of the static tyre load-induced bi-axial strains were recorded from the soffit of the abraded flange, due to the bonded panel rehabilitation strategy.
- In the crucial local span direction of the top flange, a 3D FE analysis over-predicted the tyre load induced strains, by 44% (partly due to global bending effects deliberately ignored in the FE analysis) for the abraded flange, but produced a reasonable estimate of the strain reduction brought about by the bonded panelling, at 81% of the experimentally obtained value. Fundamental to the FE model was discrete representation of each layer of the built-up top flange, so that the anisotropic properties of each such layer could be entered into the model.
- It is likely that abrasion of the top flange from loosened fragments of surfacing will occur in practice, so the present approach to understanding abraded and rehabilitated decks, founded on the material anisotropies and without the surfacing present, is advisable.

Future work should consider extended use of the gauges, or of digital image correlation (DIC, to provide full-field strains over the zone of interest), to record the spectrum of strains due to passing overhead lorry tyres over time. This will help assess the true value of the bonded panel strategy in a tyre load fatigue performance context.

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