Modular FRP-Steel bridges for the UK road network

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Synopsis

In response to the UK's ageing bridge stock, fibre reinforced polymer (FRP) bridge decks are increasingly considered as a lightweight, prefabricated and low-maintenance alternative to steel or reinforced concrete bridges. However, concerns over costs, carbon, fatigue and end-of-life have hindered their wider uptake. Through a National Highways-funded project, researchers from University College London (UCL), with support from COWI, have developed a design package for a modular FRP-steel hybrid road bridge that aims to address these concerns. The proposed bridge facilitates rapid construction, replacement/reuse of the FRP deck panels and future automation of the design process. This article summarises the lessons learned from previous FRP bridges and how they underpinned the project requirements for the modular FRP-steel bridge. The article also presents a novel approach to quantifying the carbon savings associated with the rapid construction of the modular FRP bridge due to reduced traffic disruption, which can be applied to other highway structures.

1. Introduction

In the UK, over 3100 traffic bridges are classed as substandard [1]. Replacement schemes using reinforced concrete (RC) or steel bridges often entail lengthy construction times and traffic disruption, and the replacement structures may suffer from recurring maintenance issues, for example corrosion due to de-icing salts. Furthermore, designs that facilitate replacement and reuse of structural components are essential in the transition to a circular economy in construction.

FRP road bridge decks can help alleviate these problems by offering a prefabricated, modular alternative that ensures high quality control during manufacture and minimal on-site activity. The lightweight FRP deck panels (20% - 40% of an equivalent RC deck) are prefabricated, ensuring high quality control, and easily transported to site and lifted in place using low-capacity cranes, minimising local disruption and noise during construction. For bridge rehabilitation schemes, the low weight of FRP decks relative to concrete decks allows existing abutments to be reused while increasing the live load capacity of the bridge. FRP decks are also corrosion resistant with minimal maintenance requirements (e.g. no painting), helping to achieve the targeted design life of 120 years.

The UK is at the forefront of FRP bridge technology, boasting Western Europe's first all-FRP pedestrian (Aberfeldy, 1992) and highway (West Mill, 2002) bridges [2]. Data from these and other pioneering projects fed into state-of-the-art design standards (CD 368 [3]) and guidance (CIRIA C779 [4]) for FRP bridges. This knowledge has now been synthesized with that from the rest of Europe with the recent publication of CEN/TS 19101 *Design of fibre-polymer composite structures* [5], the Technical Specification that precedes a full structural Eurocode.

FRP decks comprise mostly glass fibres embedded in a thermoset resin formed into a sandwich structure with two stiff and strong FRP face sheets connected via FRP webs and/or a low-density core material (e.g. balsa wood). Of the two dominant manufacturing processes for FRP decks, pultrusion facilitates high-volume and relatively low-cost production of standard sections that can be factory bonded into larger deck panels, whereas resin-infusion enables large, bespoke FRP decks panels with integrated kerbs and connection details to be produced. For road bridges, the FRP deck can span either longitudinally between abutments or transversely between longitudinal FRP, steel or RC girders. An example of the hybrid FRP-steel option is the UK's Mount Pleasant bridge, constructed in 2005, which features two 26 m spans carrying a single lane of traffic over the M6 motorway, see Figure 1. Each span was fabricated in the hard shoulder and lifted onto the supports in a single night closure.

National Highways aim to develop the FRP-steel hybrid concept into a truly modular, standardised and low-carbon bridge. To that end, funding was awarded to Professor Wendel Sebastian and Dr Matthew Poulton from UCL, who worked with COWI UK’s bridge team to develop a Design Package for the bridge concept. The Package targets replacement of low-trafficked bridges within the 15-25 m span range (single or multi-spans) and adaptable to different widths. This article presents the development of the brief, conceptual design and carbon assessment for the modular bridge.

Figure 1: Mount Pleasant FRP-steel hybrid bridge during construction.

2. Turning lessons learned into project requirements

During Phase 1 of the project, UCL produced a feasibility study which identified several lessons learned from previous FRP bridge projects worldwide, dating back over 30 years. The output, namely a set of considerations and risks associated with FRP bridge design, construction and maintenance, underpinned the initial project requirements and early conceptual design, as summarised in Table 1.

Table 1: Summary of key risks/considerations for FRP deck road bridges and the associated project requirements

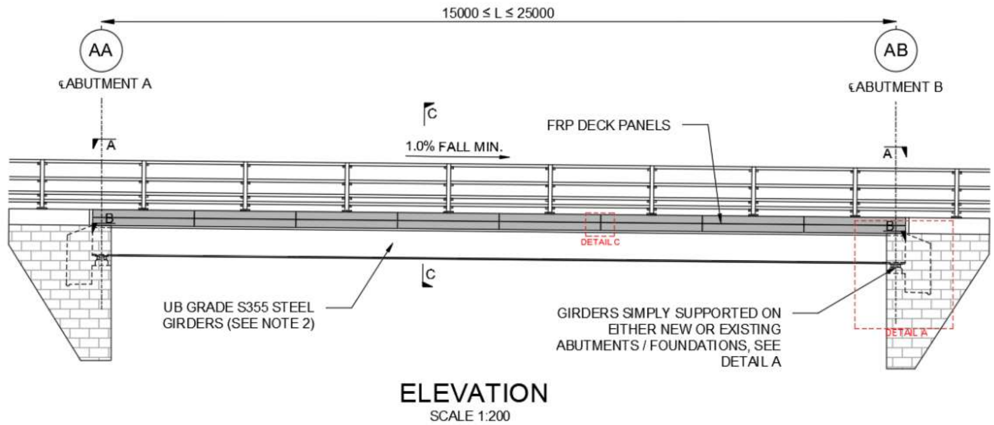
Consideration/Risk	Discussion	Project requirement
Commercial availability and high cost of FRP decks	Previous FRP bridge projects have suffered from high initial costs due to a nascent supply chain and the one-off, bespoke nature of schemes that inhibit market competition and growth.	Ensure the proposed bridge deck is **modular**, facilitating mass production (and hence lower cost), and that the design is compatible with different manufacturing techniques, including the option of building-up the FRP deck panels from existing pultruded profiles. This is achieved by producing an **FRP Deck Specification**, with early involvement from key suppliers and manufacturers.
FRP design standards and technical approval process	Design, installation and maintenance of FRP decks requires specialist knowledge of FRP as a construction material and the relevant design standards including CD 368 and CEN/TS 19101. This can be a barrier to adoption and technical approval.	Produce a draft **Approval In Principle (AIP)** with early feedback from the technical approval authority. The AIP should provide general arrangement and key connection drawings and guide the engineer on design methods, standards, good detailing and key risks to be mitigated for the individual structure.
Structural connections to FRP deck	Previous FRP deck bridges in Europe have used adhesively bonded connections between the FRP deck units and to the steel girders. Whilst this method gives good mechanical properties and durability, it is not consistent with a modular, rapidly constructed bridge.	Specify **mechanical connections** (e.g. bolted) into and between the FRP deck panels and **no on-site bonding**. The connections should facilitate rapid installation, reversibility (for replacement of individual panels), easy inspection and straightforward maintenance. Some examples of possible connection details are discussed in Section 3.
Local tyre-load fatigue of FRP decks	Some previous FRP road decks have suffered local fatigue damage due to repeated and highly concentrated tyre patch loading from vehicles, especially heavy lorries [6]. This has been driven in part by inadequate representation of the tyre load in local fatigue tests, and poor in-service performance of the road surfacing.	To limit the risk of tyre load fatigue of the FRP deck, the proposed bridge shall be limited to **50,000 HGVs per year** (the lowest traffic category in the Eurocodes). Furthermore, the mechanical connections should enable replacement of individual panels if local repair is not feasible. A parallel study of improved test methods for local fatigue verification of FRP decks shall also be conducted.
Integral vs. simply supported abutments	Integral abutments, while a requirement of CD 350 for reduced maintenance, entail a more complex design process	Assume **simply supported abutments** in the preliminary design and propose suitable

	and do not facilitate a modular design, wherein the behaviour of the bridge superstructure is independent of the substructure. Furthermore, retrofitting an existing abutment from simply supported into integral is challenging.	details to enable bearing replacement and water management around the joint.
Carbon footprint	Previous studies have showed that, relative to a steel or RC bridge, an FRP option has a higher 'upfront' carbon that is typically offset over the whole life of the structure due to reduced maintenance and a longer design life [7]. However, the reality is that bridge owners often prioritise the upfront carbon when evaluating different bridge options. This may lead to erroneous rejection of an FRP deck option on the grounds of sustainability.	Perform a desk study to obtain up-to-date values of FRP deck embodied carbon. Also, estimate the carbon savings due to the reduced traffic disruption associated with rapid construction. This includes emissions due to both traffic diversions over the bridge (similar to a previous study of the Clifton Suspension Bridge [8]) and queuing/congestion on the underlying motorway due to temporary traffic management. The latter is often neglected in the upfront carbon assessment due to a lack of guidance. A novel approach was developed in this project and presented in a **Carbon Assessment Report,** which is summarised in Section 6 of this article.

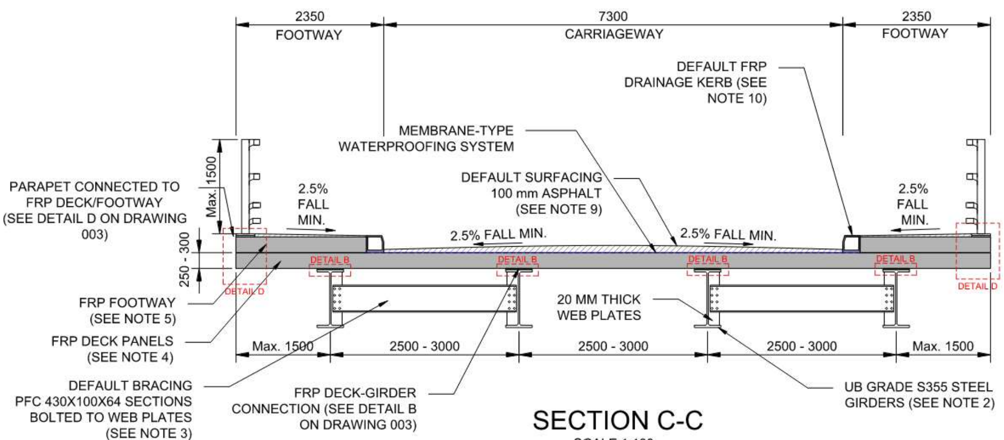
3. Proposed design

General arrangement and key details

Figure 2(a) and (b) show an elevation and section drawing, respectively, of the proposed modular FRP deck-steel girder bridge in a single span, 12 m wide configuration, which accommodates two carriageways and pedestrian footpaths. The bridge features modular, transversely spanning FRP deck panels supported by longitudinal simply supported UB steel girders (either weathering steel or painted) in braced pairs with full transverse bracing at the supports. The use of UB rolled sections is consistent with the standardised, modular design philosophy and enables girder sizes to be quickly specified for each span/width (e.g. using a app-based tool). The spacing of the girders is between 2.5 m and 3.0 m, which is adjusted along with the total number of girders to accommodate different total bridge widths. This spacing optimised the design of the FRP deck, striking a balance between transverse spanning capacity and resistance to local tyre load. This girder spacing is also approximately equal to the width of a traffic lane, which facilitates future widening. The FRP deck panels can be manufactured to accommodate large skews, although the associated structural assessment was beyond the scope of the initial study.



(a)



(b)

Figure 2: (a) Elevation and (b) section drawings of single-span, 12 m wide configuration of modular FRP deck bridge.

Figure 3 shows a 3D illustration of a single FRP deck panel and the key geometric limits. The deck spans the full width of the bridge to obviate longitudinal joints. The length of each panel is between 2.5 m and 3.5 m, the width up to 18.7 m wide (for easy transportation), with a depth of between 0.25 m and 0.30 m. The FRP deck, including the FRP kerb, may be resin-infused as a single piece or built up from factory-bonded pultruded profiles (either stock or purpose-built). The parapet posts are connected to the edge of the FRP deck at its mid-length, which avoids clashes with the panel-panel connection whilst maintaining a unform post spacing along the bridge.

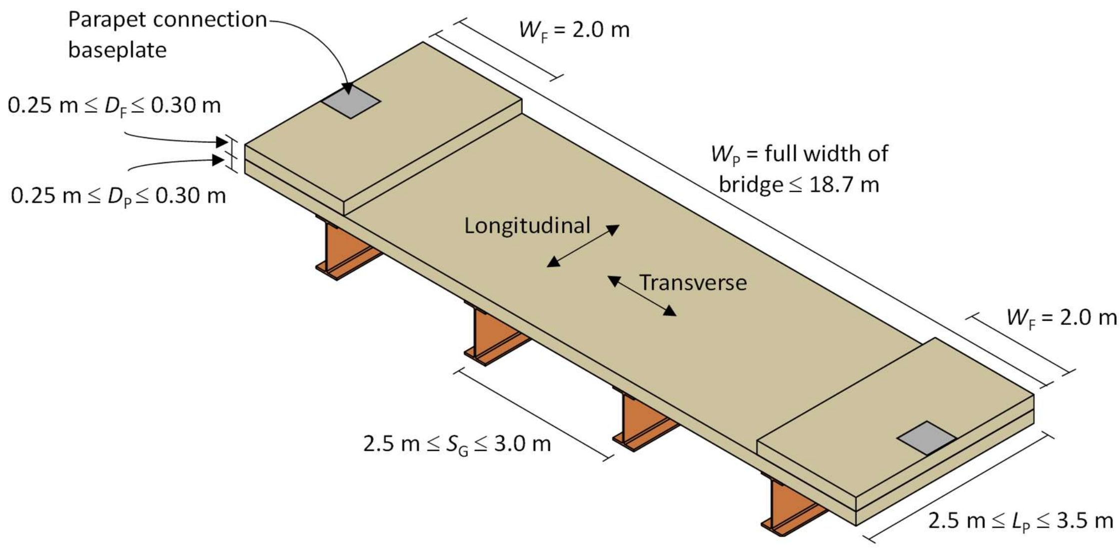


Figure 3: Illustration of modular FRP panel with allowable dimensions.

The key connections to the FRP panels – namely the transverse panel-panel, longitudinal panel-to-girder and parapet post connections – are *bolted* to facilitate rapid construction and replacement of individual panels upon damage, whilst also allowing access for inspection and maintenance in-service. The design and performance criteria for these connections are given in an FRP Deck Specification, whilst allowing for different solutions appropriate to the FRP deck type (e.g. pultruded or resin-infused). Through engagement with FRP manufacturers in Europe and the US, Figures 4 to 6 show some suggested connection details. Notably, the FRP panel-to-girder connection (Figure 5) features steel plates with downward-facing, high-strength friction grip (HSFG) countersunk bolts that are factory-bonded to the underside of the FRP deck. The plates are then bolted to the top flange of the UB girder on site through predrilled, oversized holes (allowing for manufacturing tolerance) and are designed to be slip-resistant at SLS, thus mitigating fatigue issues. The parapet connections (Figure 6) can be prefabricated and the posts connected on site. Their design – based on recommendations in [5] – must ensure that at containment level N2 the connection resistance is 25% higher than that of the steel post, thus preventing damage to the FRP and allowing easy replacement.

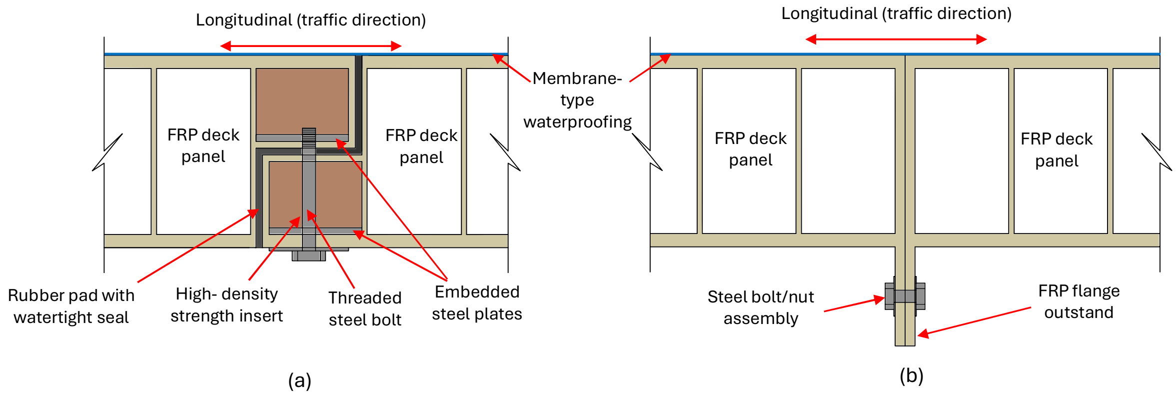


Figure 4: Transverse FRP panel-panel connection options.

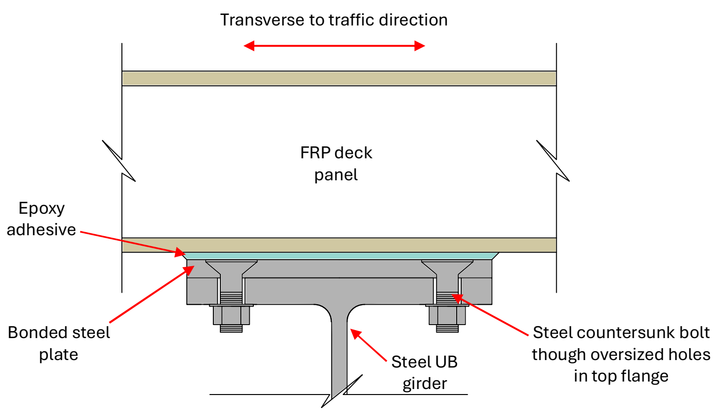


Figure 5: Longitudinal FRP panel-girder connection option.

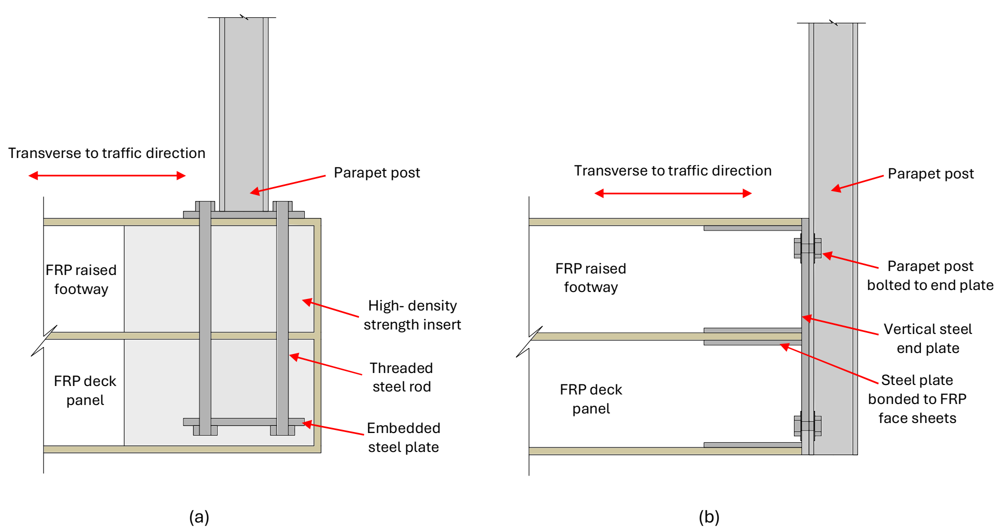


Figure 6: Parapet to FRP panel connection options.

4. Preliminary design and analysis

A preliminary structural analysis of the modular FRP-steel bridge was performed to determine both the UB girder sizes at different spans and the critical design actions in the FRP deck and connections. Using a finite element (FE) model in ANSYS, the deck was modelled as 2D shell elements and the steel girders as beam elements, see Figure 7. The 12 m wide bridge with a 3 m girder spacing produced the greatest load effects in both the FRP deck panels and connections, and hence their design was based on this configuration.

Eurocode traffic (LM1, LM2, braking), pedestrian and thermal loading and their combinations (Group 1a, 1b and 2) were considered, with the vehicle wheel loads represented via a uniform pressure acting over a 0.4 m by 0.4 m square patch, as specified in BS EN 1991-2. Note that this wheel contact patch is only used for assessment of *global* load effects in the FRP deck. For *local* effects, where the realistic non-uniform tyre-deck contact pressure distribution (CPD) is more onerous than that specified in the codes [9], testing using a suitable tyre loading device that mimics the actual tyre CPD is required in CEN/TS 19101. For thermal loads, there are currently no temperature profiles for FRP-steel decks given in the Eurocodes or CEN/TS 19101. Hence, a conservative approach was taken that was based on the temperature profiles for steel decks, but which accounted for potentially high thermal gradients through the FRP deck due to an insulating core material (structural foam or timber).

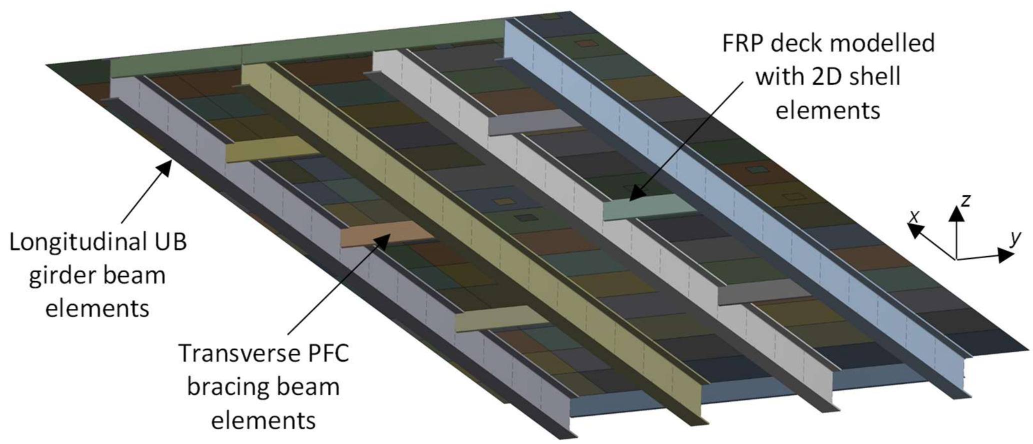


Figure 7: 3D view of FE model geometry.

One important aspect of the FE model is the assumed coupling restrains between the FRP panels and steel girders – i.e. the degree of composite action. While the proposed FRP panel-girder connection shown in Figure 5 provides a rigid connection at SLS, the design had to cater for alternative connection details and spacings that may allow some slip between the FRP deck and girders. Hence, in the analysis, depending on the structural member and/or limit state under consideration, one of three coupling constraint conditions were assumed, as illustrated in Figure 8, namely:

1. No composite action - Figure 8(a). This enabled frictionless sliding and separation between the FRP deck and girders. This was achieved by inserting additional contact elements between those of the beam and shell

elements that prevented penetration in the *z*-direction. This assumption gives the highest *transverse* stress resultants in the FRP deck and the UB girders.

2. Full composite action - Figure 8(b). This comprised rigid joints connecting every node of the girder beam elements to the adjacent FRP deck nodes. FCA gives the highest *longitudinal* stress resultants in the FRP deck.
3. Partial composite action - Figure 8(c). This comprised rigid joints at discrete longitudinal spacings along each UB girder. This enabled more reliable prediction of the forces in the deck-girder connection.

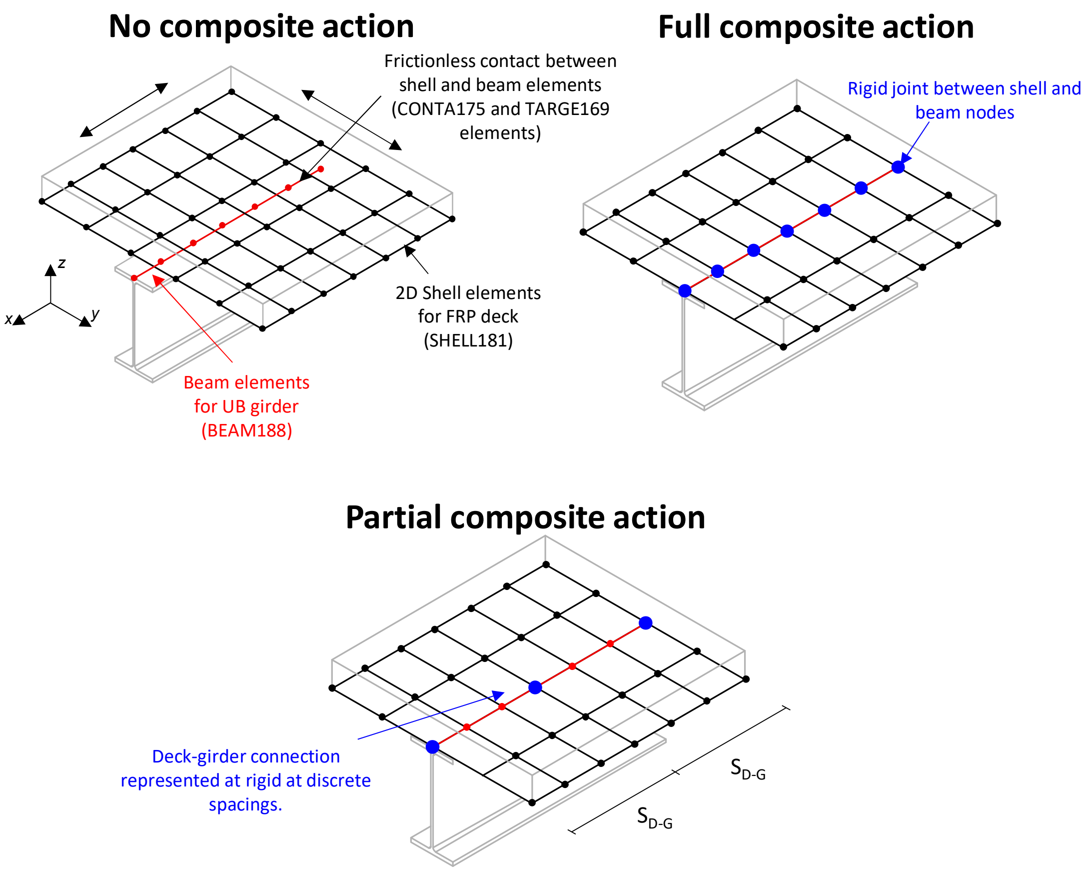


Figure 8: Specified coupling constraints between steel girders and FRP deck for (a) no composite action, (b) full composite action and (c) partial composite action.

By assuming the worst-case deck-girder coupling constraints and the critical traffic load locations on the deck, the governing stress resultants in the FRP deck and connections were determined. These, along with the geometric limits shown in Figure 3 and additional global stiffness limits in both transverse and longitudinal directions, form the basis of the Specification to which the FRP deck must be designed. The analysis also enabled specification of suitable steel UB girder sizes at different span ranges between 15 m and 25 m.

5. Construction sequence

Figure 9 shows the proposed construction sequence for a single span modular bridge, although the approach can be mirrored for a two-span motorway overbridge with a central pier. First the girders are lifted onto the abutments in braced pairs, then the FRP deck panels are sequentially lifted in place using a single crane located on one side of the bridge and mechanically connected. Finally, the waterproofing, surfacing and parapets are installed. This rapid construction method may be completed in 1-2 days on site with minimal traffic disruption. For single lane bridges (e.g. Mount Pleasant, see Figure 1), the bridge may be fabricated off-site and lifted in a single piece to further reduce traffic disruption. As shown in the following section, reduced traffic disruption during construction can lead to significant savings in upfront carbon for the structure.

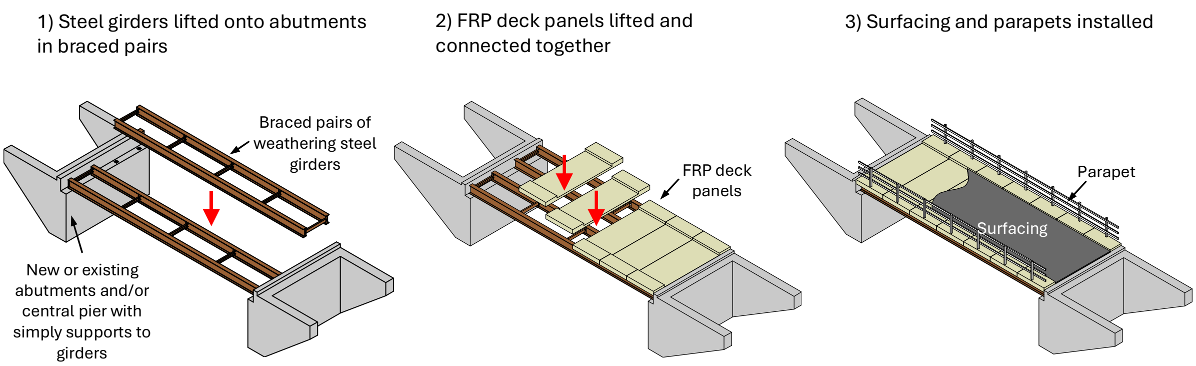


Figure 9: Proposed construction sequence for modular FRP deck bridge.

6. Carbon assessment

The carbon assessment focussed on the 'upfront' carbon, i.e. modules A1-A5 according to PAS 2080 [10], as this is widely considered a weakness for FRP bridges compared to other materials. The analysis assumed a 50 m, two-span, single lane (4.6 m wide) overbridge carrying farm traffic over a live motorway, as this is a primary target for the NH modular FRP bridge. The results are compared to an equivalent in-situ RC deck bridge with steel beams. Only the carbon associated with the bridge superstructure was considered, all other operations are assumed equal between the two options (e.g. demolition of existing structure and construction of foundations/abutments). The assessment was performed using guidance and recommended carbon factors from the IStructE's *How to calculate embodied carbon* (2nd Edition) [11] and the *Carbon calculation guide for bridges* [12].

FRP deck embodied carbon

To provide a reliable estimate of the embodied carbon of the FRP deck, a desk study was performed that collated manufacturer's published data for several commercially available FRP decks, both from Environmental Product Declarations (EPDs) and using the EuCIA Eco Impact calculator [13]. Table 2 gives the cradle-to-gate (Modules A1-A3) embodied carbon values for five glass-FRP decks, both pultruded and resin-infused, giving an average of 3.1 kgCO_2e/kg. However, later feedback from European manufacturers indicated that these values may still be outdated, and values closer to 2.0 kgCO_2e/kg would be achieved for FRP decks produced at scale today.

Considering these findings, in the present study an embodied carbon of 300 $kgCO_2e/m^2$ was assumed for the FRP deck (equal to 2.5 $kgCO_2e/kg$ multiplied by the deck weight of 120 kg/m^2). This value is still conservative as it does not account for future reductions, for example due to the increased use of renewable energy in raw material production, recycled PET or balsa wood as core materials, or flax fibres and plant-based resins. The latter, known as bio-composites, are increasingly used in footbridges and the world's first traffic bridge made entirely from flax fibres was recently installed in Ulm, Germany.[12]

For comparison, an equivalent 250 mm deep C40/50 in-situ concrete deck reinforced with 250 kg/m^3 rebar was assumed. Using the recommended values in [12], a total embodied carbon of 220 $kgCO_2e/m^2$ was calculated (see Table 2), which is only 27% less than the assumed value for the FRP deck. Similar to the FRP deck, this value is conservative in not assuming cement replacements or recycled rebar, which are not always used in practice.

Table 2: Assumed values of FRP deck and RC deck embodied carbon (Modules A1-A3)

Material / Component	Source / Explanation	Embodied carbon	Unit
Pultruded GFRP	Krafton van Bilj, Netherlands, 400.80 deck (EPD)	2.29	[$kgCO_2e/kg$]
	Fiberline, Denmark, UD Plank (EuCIA)	2.78	
	DuraComposites, UK, pultruded plank (EPD)	3.97	
Resin-Infused GFRP	FiberCore, Netherlands, bridge deck (EuCIA)	2.67	
	DuraComposites, UK, moulded product (EuCIA)	3.80	
Assumed baseline value for FRP deck	Assumed value of 2.5 $kgCO_2e/kg$ and FRP deck weight of 120 kg/m^2	300	[$kgCO_2e/m^2$]
Total for FRP deck + shear connections	Total deck area = 230 m^2	69.0	[tCO_2e]
	25 mm by 430 mm bonded steel plate connection (see Figure 5)	25.0	
Concrete	C40/50 average UK mix from ICE v3.0 database	0.16	[$kgCO_2e/kg$]
Steel reinforcement	World average from ICE v3.0 database	1.99	
Assumed value for equivalent RC deck	0.25 m deep slab with 250 kg/m^3 rebar	220	[$kgCO_2e/m^2$]
Total for RC deck + shear connection	Total deck area = 230 m^2	51.0	[tCO_2e]
	Steel shear studs	1.00	

Carbon emissions due to traffic disruption

Construction of the modular bridge will likely require two types of temporary traffic management (TTM), namely lane closures with speed restrictions to provide a safe working area and night possessions for lifting operations. The former causes queuing of vehicles through the TTM zone and the latter causes vehicles to travel further and slower along a diversion route. This section aims to quantify the carbon emissions associated with both TTM types for the FRP an RC deck options. The assumptions made for the TTM plan for an example construction site on the M6 (near the Mount Pleasant FRP bridge) are given in Table 3. The analysis included only the durations of TTM that are attributable to the bridge *superstructure* installation. In practice TTM would be in place for much longer for the other construction activities (demolition, earthworks and foundations/abutments) and potentially as part of other road upgrade schemes. However, these activities are beyond the present scope.

Table 3: Assumptions for TTM during construction of FRP and RC deck overbridges

		FRP deck	In-situ RC deck	Reference/remarks
Motorway traffic details		AADT = 70,000 vehicles/day Cars: 69%, LGV: 18%, OGV1: 2%, OGV2: 11%, PSV: 0%		From UK DfT Road Traffic Statistics. Example site used: M6 J33 [14]
TTM for general works	**Speed limits**	Normal 70 mph (113 kph) reduced to 50 mph (80 kph) over a 2 km total distance		Assumptions based on [15]
	No. of lanes closed	From 3 to 2 lanes in both directions		-
	Duration of TTM	2 days	10 days	Additional time for RC concreting/curing and finishing works
TTM for night possession	**Night closure details**	Complete closure of 10 km in both directions between 22:00 – 06:00		Typical distance between motorway junctions
	No. of diverted vehicles	0.011 × AADT vehicles/hour = 6160 vehicles total		From CD368 [3]
	Diversion details	13 km diversion with average speed of 30 mph (48 kph)		Modest increase in distance along rural roads
	Duration of TTM	1 night	3 nights	Additional possessions for RC option for deck concreting and finishing works

Data on the CO_2 emissions of different vehicle types as a function of speed were obtained from the Department for Transport (DfT) Transport Analysis Guidance [16], as shown in Figure 10(a). The red curve shows the weighted average derived from DfT count point data from the M6 site. For the night possessions, Figure 10(b) shows the sensitivity of the total change in carbon emissions to the average vehicle speed and extra distance travelled along the diversion route. Using the assumed values in Table 3 gives **4.3 tCO_2/possession**.

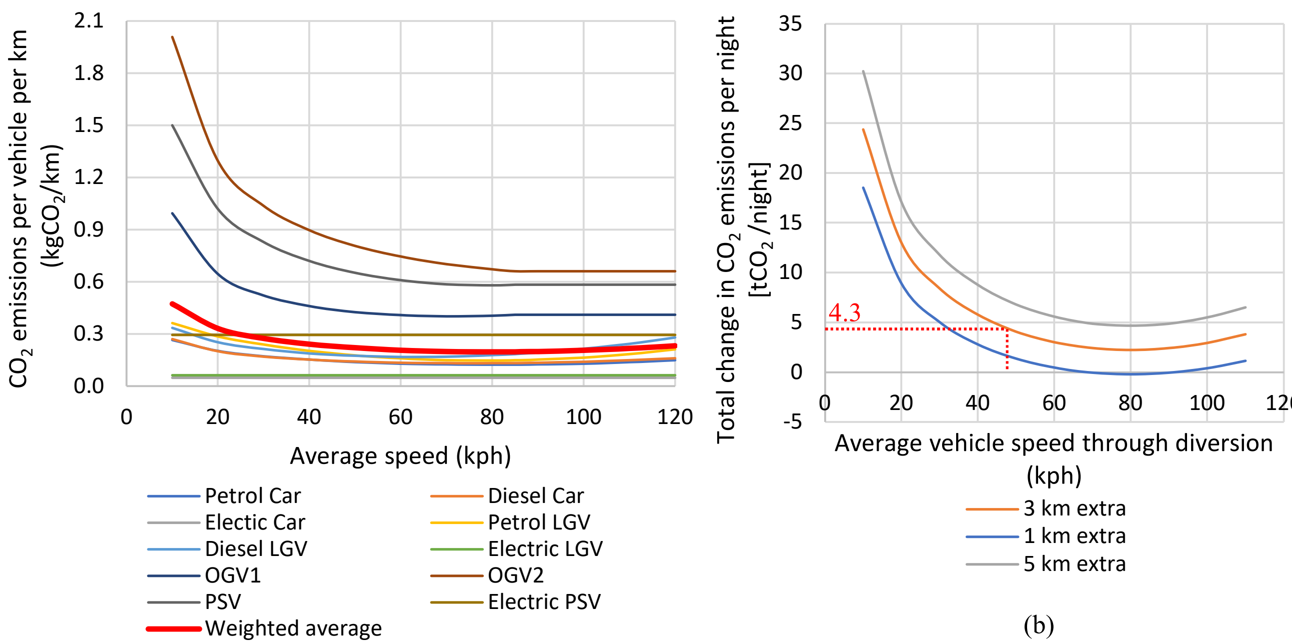


Figure 10: (a) CO_2 emissions for different vehicle types as a function of travel speed [16], and (b) change in CO_2 emissions for different diversion distances and average speeds during night possessions.

For queuing on the motorway, Figure 11(a) shows the change in average vehicle speed for different TTM scenarios as a function of average annual daily traffic (AADT). These curves were derived from simulated traffic flow data published in CD 355 [17], which provides the capacity-related time delay as a function of AADT for different lane numbers. This data is intended for whole-life *cost* assessment of highway structures but was deemed suitable for this preliminary carbon assessment. By taking the difference in average speed between normal and TTM conditions, Figure 11(b) gives the total change in vehicle CO_2 emissions per day per km of TTM as a function of AADT. The curves show that, if only two lanes remain open within the TTM zone, the increase in emissions is significant and highly sensitive to the AADT. Using the values in Table 3 gives **10.9 tCO_2/day**.

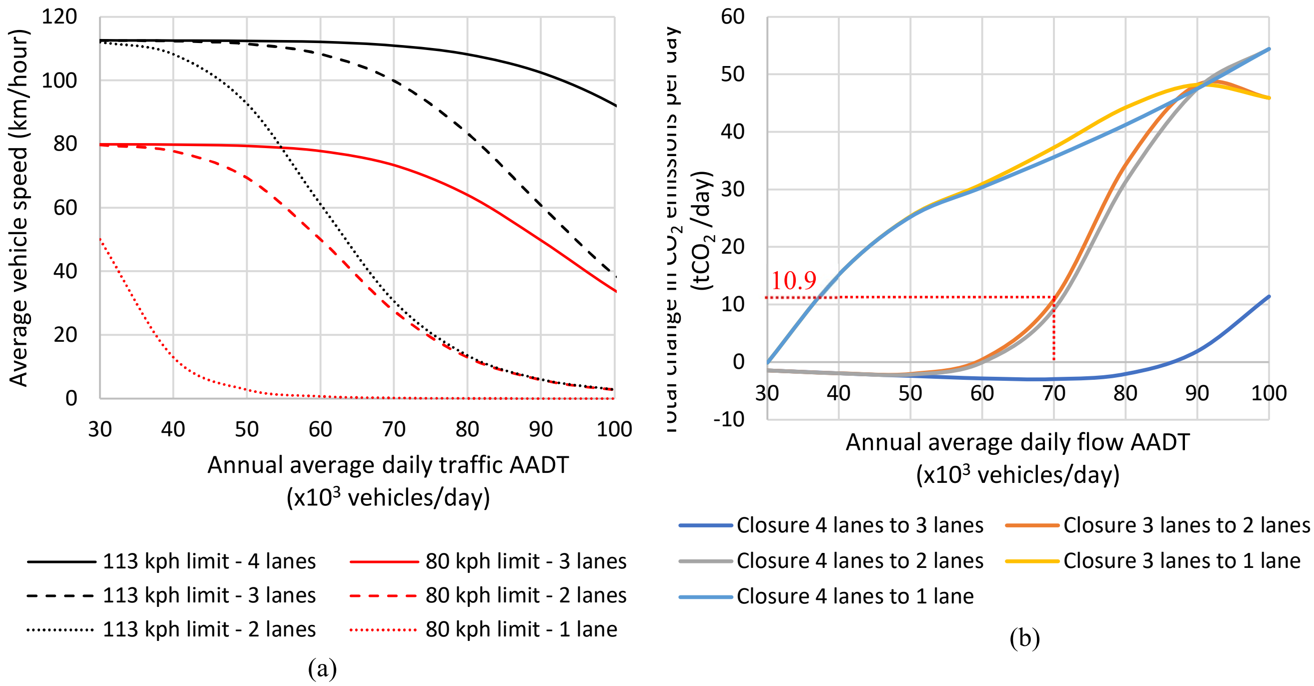


Figure 11: (a) Average vehicle speed and (b) change in CO_2 emissions as a function of AADT for different TTM scenarios for 2 km total distance [16] [17] .

Results and discussion

Figure 12 shows bar charts comparing the upfront carbon of the modular FRP deck bridge with the RC deck option. The higher embodied carbon of the FRP deck and footway is offset by the reduced traffic delay during construction, leading to a net saving of 7%. This saving increases to 41% for AADT = 80,000 vehicles/day, which highlights the sensitivity of emissions to traffic flow. The results also show that night possessions have a relatively small carbon impact, which favours off-site construction. Two further potential upfront carbon savings were ignored from the present study, namely reduced diversion of traffic *on* the bridge and reuse of the existing abutments. The latter may only be achievable with a lightweight FRP deck, thereby offering significant time and material savings and a reduced TTM duration, possibly on the order of months.

This section highlights the importance of optimising the construction sequence and TTM for motorway overbridges for achieving a low-carbon solution. The methodology outlined in this section gives bridge Engineers a simple approach for evaluating these important effects at the concept phase for a more reliable carbon assessment of different bridge designs. The method applies equally to whole-life carbon assessment, where traffic delay emissions due to maintenance activities (e.g. steel painting, bearing and surfacing replacement) can also be estimated.

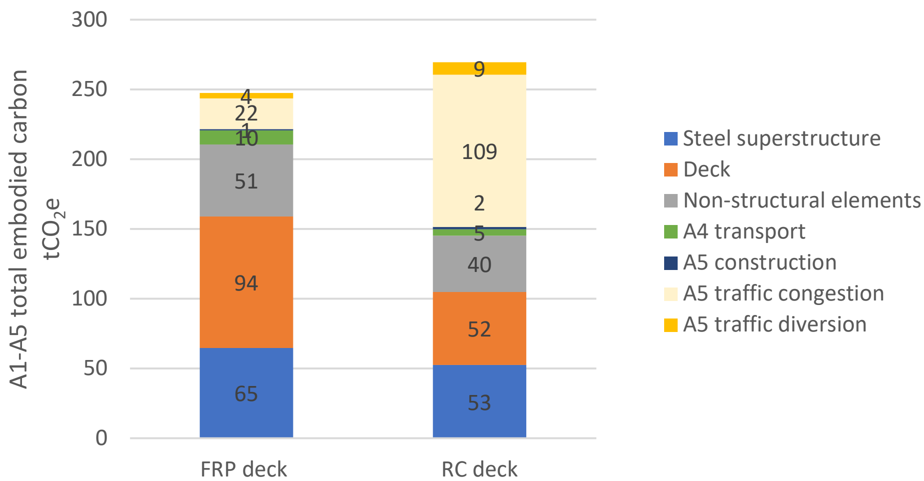


Figure 12: Comparison of upfront carbon for a 50 m two-span, 4.6 m wide bridge superstructure.

7. Conclusions and future use of the design package

The modular FRP-steel bridge aims to provide a simple, robust and sustainable structure that minimises traffic disruption during construction, requires minimal maintenance and considers replacement and reuse of the deck panels at end-of-life. The simple structural form with modular, standardised components and connections facilitates future automation of the design process. Figure 13 shows the different components which together form the Design Package for the modular FRP-steel bridge. All documents, reports and drawings can be accessed by contacting the authors, who welcome feedback from key stakeholders regarding the proposal.

Figure 13: Components of the Design Package for the modular FRP-steel bridge.

8. References

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