Structural Design of a Fibre Reinforced Composite Bridge Deck for Offshore Applications

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SUMMARY: An all-composite bridge deck was designed to facilitate the maintenance of an offshore conveyor gantry. Preliminary designs used both manufacturers and published materials data to give initial geometry. Further detailed designs were carried out using finite element analysis; utilising material properties derived from in-house testing. A modular construction approach was developed to give excellent design and manufacturing flexibility. The bridge deck geometry was optimised to provide exceptional structural performance within the given design constraints and objectives. A one-half scale prototype was manufactured to validate the proposed manufacturing technique and design.

KEYWORDS: Offshore, Bridge Deck, Corrosion Resistance, Civil Engineering.

INTRODUCTION

Offshore conveyor gantries are used for the transportation of bulk substances, such as coal, to and from awaiting ships. They operate in a variety of coastal conditions and are subjected to very corrosive and arduous environments. Subsequently, structural materials such as steel and reinforced concrete require careful detailing and constant preventative maintenance to ensure their longevity.

A fibre reinforced composite bridge deck was developed in a collaborative project between Connell Wagner Pty Ltd and the University of Southern Queensland. The fibre composite bridge deck provides vehicular access to the gantry and offers an alternative solution to the steel or reinforced concrete bridge decks currently used.

This project forms the initial research of the primary author towards the award of Doctor of Philosophy.

DESIGN OBJECTIVES

The conveyor gantry supports the bridge deck at four metre intervals upon headstocks. The deck is of single carriageway width, with no restrictions placed on the decking depth by existing structures. Dynamic load effects limit the live load deck deflection to span/500, which subsequently became the primary design criteria. Design live loads of 75kN/axle result from specialist maintenance vehicles used by the gantry owners. Consequently the bridge deck does not conform nor follow the AASHTO or AUSTROADS bridge design code loading. Due to the lack of

longitudinal supports the bridge deck essentially performs the function of a bridge, (although of considerably short span) and hence must possess both longitudinal and transverse stiffness. Bridge decks commonly span transversely between girders, only requiring adequate stiffness and strength to effectively transfer loads to the bridge girders. Due to the relatively short span and physical dimensions of the bridge deck the design presented is quite economical. That is, the entire bridge "function" is condensed into a homogeneous compact structure rather than employing separate structural elements. However, it would be quite uneconomical to extrapolate this design to much larger spanning structures.

The following objectives form the boundaries used in the optimisation of the bridge deck geometry.

- Meet the global live load deflection limit of span/500.
- Provide comparative local deflection performance to steel decking under the application of wheel loading.
- Possess high transverse stiffness to ensure excellent load spreading capability.
- Have the ability to be manufactured by a variety of manufacturing techniques as required by production quantity, availability etc.

BRIDGE DECK GEOMETRY

The civil engineer is generally confined to the geometric sections available from the manufacturer (structural steel), or, in the case of reinforced concrete, those sections that are generally accepted. Fibre reinforced composite materials offer the potential for the development of new structural shapes and systems that don't mimic their more conventional counterparts.
The engineer working with composites is faced with the decision of what geometric configuration offers the best balance and compromise between economics, manufacturing flexibility and simplicity, and structural efficiency. Optimisation is the term used to describe the process of iteration needed to converge to this design and is common in the development of new structural forms for composite materials (Ref 1).

The *top* and *bottom* laminates, the composite material that forms the bridge deck running surface and bottom face respectively, are predominantly responsible for the overall longitudinal bending stiffness of the bridge deck. It must be noted that the structural depth has been fixed at approximately 0.25 metres (ie. Distance between *top* & *bottom* laminates) to induce sufficiently high laminate strains. The respective laminates are analogous to the top & bottom flanges of an I-beam. The *bridge deck core* (the material and geometric configuration used to separate the *top* and *bottom* laminates) does contribute to the overall bending stiffness depending on the chosen fibre architecture however it's primary job is to separate the two "flanges" while providing transverse stiffness far beyond what can be achieved by varying the degree of orthotropicy used in the *top* and *bottom* laminates alone. This introduces the importance of fibre architecture, which is essential in the efficient use of fibre composite materials. By varying the "lay-up" of the structure its stiffness and strength can be tailored to suit the loading. When combined with geometric optimisation as presented here the designer has total control over structural response under loading.

The first bridge deck design was deliberately simplistic in an effort to minimise manufacturing complexity and associated cost (refer fig.1), but unfortunately had poor transverse load carrying capacity (refer fig.2).

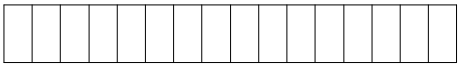

Fig. 1: *First bridge deck design in cross-section (Vierendeel girder).*

The design consists of composite box beams to form the *bridge deck core*. To provide adequate local deflection performance under the wheel loads, the box beams must either be produced with a very strong core, or, the width of individual beams must be reduced to subsequently reduce the span between the vertical webs, or, relatively thick *top* and *bottom* laminates must be used. In all cases the limit of these changes is a flat plate structure which can be shown to be a highly inefficient form of composite construction.

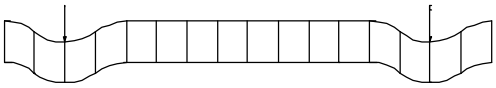

Fig. 2: *Poor transverse load spreading capability of bridge deck with Vierendeel girder cross-section.*

A further four bridge deck designs were investigated, as represented in the diagrams below, before converging to the final bridge cross-section (refer Fig. 7).

Fig. 3: *45-Degree truss style cross-section.*

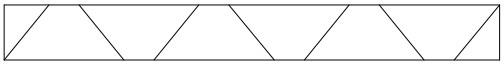

Fig. 4: *Trapezoidal style cross-section.*

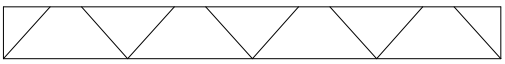

Fig. 5: *Hybrid Trapezoidal-45Degree truss style cross-section.*

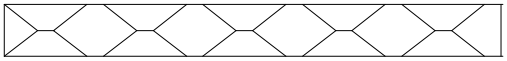

Fig. 6: *Honeycomb style cross-section.*
(Ref 1.)

The final bridge design shares its cross-sectional geometry with a *Warman* truss and offers the best compromise between structural and manufacturing objectives.

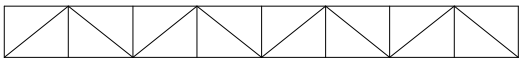

Fig. 7: *Warman style cross-section of final design.*

From inspection it can be seen that the *Warman* style geometry halves the *top* laminate span between adjacent web members when compared to the 45-degree truss alone, but retains the excellent transverse load spreading capability of the 45-degree truss.

DESIGN

To this point the process of preliminary design and manufacture has largely been separated, however it is now necessary to carefully consider the implications of manufacture and its feedback to the detailed design stage. It was decided that a modular solution to the construction of the bridge deck was desirable since this technique would allow for complete design and manufacturing flexibility. This design approach also provides the maximum number of bonding surfaces, which although increasing the risk of bond imperfections, reduces the risk of failure by providing substantially greater bond area compared to a standard core configuration.

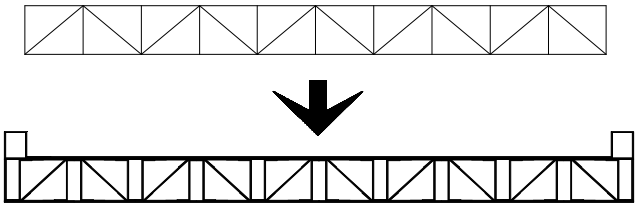

Fig. 8: *Transition from theoretical to final bridge deck cross-section.*

The adoption of a sandwich style vertical web member over a single web improves the buckling performance significantly. The sandwich web also provides a significantly greater bond area compared to the single web thus improving the bond between top and bottom laminates.
The final design also incorporates the addition of gutters. The gutters were utilised to both reduce the bridge decks global deflection by increasing sectional properties, and the amount of in-situ construction effort.

COMPOSITE DESIGN CONSIDERATIONS

During the design phase a number of pertinent issues became apparent that are specific to the design of civil engineering structures:

1. Commonly available core materials used in sandwich construction are inadequate for civil engineering structures due to poor mechanical performance and high cost.
2. “Wet” laminates outperform the “dry” aerospace style of composite construction when used in civil engineering structures. Durability, buckling performance and other concerns are priorities over weight reduction for civil engineering structures. Consequently wet lay-up results in superior economic and structural performance.
3. Thin laminate sandwich style construction is often redundant when assessed in terms of durability. For eg, a thin *top* laminate cannot be used due to the risk of puncture from road debris. This is especially critical for civil engineering structures where there is often a lack of inspection and maintenance.

4. Structural depth is an efficient means of developing high laminate strains while ensuring serviceability deflection limits are met.

PRODUCTION STRATEGY

Since the bridge deck design possesses repeating geometry in the form of triangles it was the obvious candidate for a modular style of construction. One possible scenario to construct the theoretical truss geometry could be to manufacture right-angle triangles and place them back to back. Difficulties in providing the optimal fibre architecture arise, as does the issue of vertical shear connection between adjacent modules. Such a design produces a comparatively heavy deck with pertinent issues relating to the manufacture of the triangles, their stacking and susceptibility to fibre kinking on tight radii.

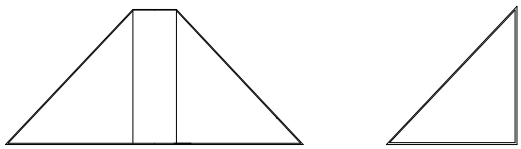

Fig 9: *Comparison between two possible design solutions. Left: Two part double vertical web module as used in the design presented. Right: Right angle triangle which requires generous radii for acute angle to prevent fibre kinking and general ease of manufacture.*

Many potential solutions were investigated before the final manufacturing technique and detailed design was selected. The final triangular module consists of a vertical member of sandwich construction, which provides exceptional buckling performance. The plateau that exists atop of the module also prevents the fibres from bending through an acute angle, as would be the case with a right angle triangle. Subsequently the potential delamination sites are reduced and the amount of filler needed to occupy voids is reduced thus reducing the weight of the structure.

The *bridge deck core* is constructed from an assembly of triangular modules. There are nine full modules and two half modules per bridge deck. The modules can potentially be manufactured by a variety of techniques providing excellent flexibility in terms of manufacturing costs and process availability.

The manufacture of individual modules using hand lay-up is a two step process utilising two matched steel moulds.

The first step results in the production of the *top hat* section, which consists of a box beam (of sandwich construction) with a discontinuous flange along the bottom.

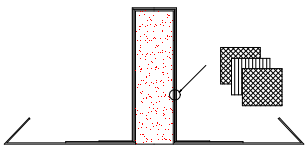

Fig. 10: *Top hat section showing fibre architecture ($^{+}$45/0/$^{+}$45)*

This section is then placed in a female mould whereby it is wrapped with further fibre reinforcement to form the section illustrated in figure 11. Each module has unsymmetrical laminates until combined with a continuous reinforcement layer and

adjacent modules (refer fig. 12).

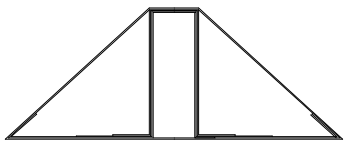

Fig. 11: *Cross Section of Module Assembly*

The individual modules are assembled to form the bridge deck core. The core is constructed such that it has continuous reinforcement transversely in the form of a unidirectional layer that effectively ties the modules together.

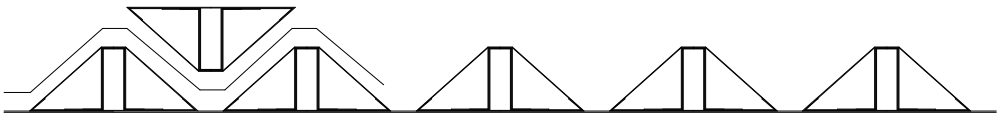

Fig. 12: *Assembly of bottom modules showing section of continuous reinforcement and top module.*

Once the bottom modules are placed into position the continuous reinforcement is added prior to the introduction of the top modules. The core of the deck is complete once the top modules are in place. The top and bottom laminates are subsequently formed on the deck core and the gutters added.

MATERIAL PROPERTIES

The following abbreviated material mechanical properties were derived from in-house testing. These properties were evaluated using the relevant ASTM standards and are specific to the materials and fabrication techniques used in this particular application.

Table 1: *Principal material mechanical properties.*

Property	**Unidirectional E-glass / Epoxy**
E_{11T}	30 Gpa
E_{11C}	42 Gpa
ε_{11T}	2 %
ν_{12T}	0.25
G_{xy}	3.2 Gpa
σ_{11C}	350 Mpa
σ_{11T}	615 Mpa

Under tensile loading the material displays linear elastic behaviour up to failure. For the majority of finite element modelling this allows for the use of linear elastic analysis to be used. Another common property with fibre reinforced composite materials is the differing compressive and tensile moduli. The lower bound tensile modulus was used throughout the design phase and is considered a reasonable assumption. This assumption does however neglect the shifting of the neutral axis that

will occur due to the differing moduli. This effect however is expected to be minimal and should not adversely affect the structures performance.

FINITE ELEMENT MODELLING

The ANSYS finite element program was used to model the bridge deck. Layered eight node quadratic shell elements were used to provide a prediction of global deflection performance. Primary stresses within the structure are small in magnitude due to the relatively shallow structural depth and imposed deflection limit of span/500. As a result the main design focus was to reduce the presence of secondary stresses such as interlaminar shear and stress induced through stress concentrations. The combinations of stresses that result under the wheel load were also relatively small.

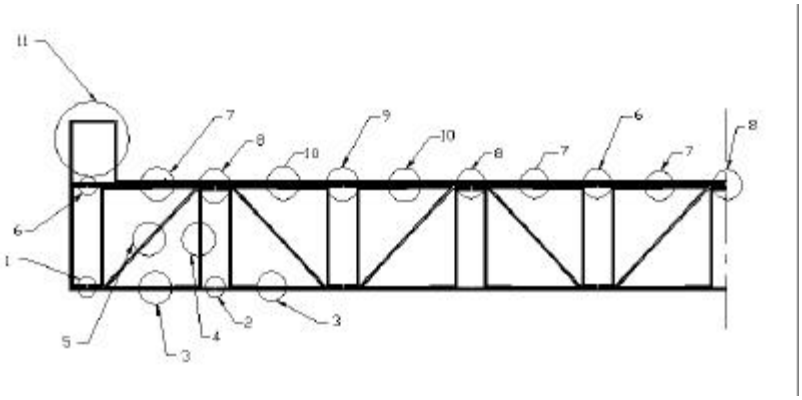

Fig. 13: *Half cross-section showing the element designations.*

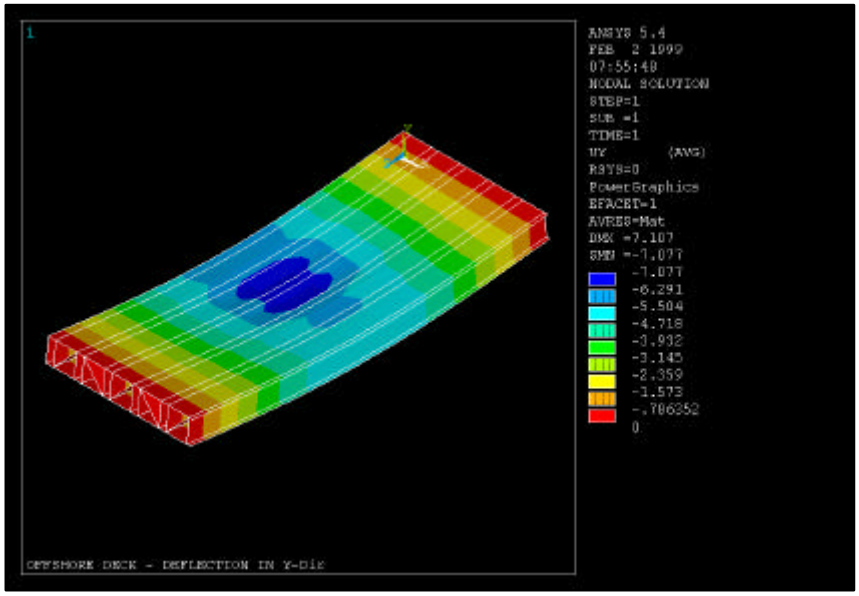

Fig. 14: *ANSYS deflection results.*

In addition to deflection and stress analysis, the finite element program was used to investigate the buckling performance of the bridge deck over supports. The effect of the sandwich core was investigated. A safety factor of four against buckling was adopted, buckling being the primary failure mode of the structure. Difficulties arise when determining the interaction between the laminate and core, and in turn how this

influences the bulking performance. Ranges of safety factors are presented in the following table.

Table 2: *Buckling performance results.*

Tyre Pressure	Core Included	Safety Factor
0.4Mpa	Yes	11.4
0.4Mpa	No	2.7

The buckling performance was considered reasonable in terms of the predicted upper and lower bounds of the finite element results. Experimental verification has not yet been carried out.

PROTOTYPE CONSTRUCTION

A half scale prototype was constructed using the hand lay-up process primarily to validate proposed manufacturing techniques and secondly to allow for mechanical testing. The prototype consists of E-glass reinforcement combined with an epoxy resin. The ½ scale deck weighs approximately ninety kilograms or slightly more than 1/8th the weight of the full size bridge deck. The increase in weight can be attributed to the difficulty in scaling parts of the bridge deck. One example is fillet radii, which is identical to the radii that would be used on a full-scale structure.

Fig. 15: *Half-scale prototype bridge deck.*

There are a number of problems associated with the manufacture of such a design. Although a modular design provides flexibility in both manufacturing technique and final structure it does introduce a number of equally challenging problems. As outlined in preceding sections, the modules are constructed in a two step process, which utilise two moulds. For the manufacture of a single module to be successful these two moulds must be accurately *matched* since geometric tolerances are critical. This becomes important when the designs successful manufacture relies heavily on the control of reasonably tight geometric tolerances. For the design presented this is critical since the design uses a repeating geometry, which is easily disturbed by

geometric mismatch. Such mismatches tend to propagate through the structure resulting in substantial deviations from the intended geometry. A design should be robust enough to tolerate such problems without compromising the overall integrity of the structure. Many teething problems were encountered when constructing the prototype bridge deck due to difficulties in maintaining consistent laminate thickness and geometry. These problems can be mainly attributed to the inexpensive moulds used and inexperience on behalf of the designer. Slight deviations between modules resulted in some assembly difficulties, however the use of a tie-layer between modules reduced the extent of the problem but nevertheless does result in potential sites for delamination. “Out-of-flatness” was another problem that troubled the modules resulting in voids being present between the top laminate and the bridge deck core. The bottom laminate was formed on the bottom of the bridge deck core and thus conformed to any irregularities that existed. A final production step of *drill and fill* was necessary to remove the voids between the top deck and core. This process consists of drilling small holes in the structure then using a resin filled syringe to fill the void. Such a process in very time consuming has very questionable results and produces an irregular structure.

The advantages of manufacturing a bridge deck using a modular approach can be summarised as follows:

- The size and complexity of tooling can be minimised.
- More manageable parts can be produced in terms of both transport and manufacture.
- Manufacture of modules can be accomplished by a variety of means without major re-engineering.
- Decks of varying width can be produced from the same tooling.
- More complex geometry can be accommodated.

Disadvantages include:

- Quality control is paramount.
- Tight geometric tolerances are required to ensure successful assembly.
- Tooling must be extremely robust and accurate due to the greater number of parts produced.

MECHANICAL TESTING

To validate both analytical and numerical models the ½ scale bridge deck was tested. It was necessary to scale the applied load and areas to provide equivalent stress states on the scaled bridge deck that would appear in the full sized version. The deck has been tested to a safety factor of 2, without any indication of imminent failure, while under design loading displaying a deflection equivalent to span/520. Subsequently the deck has comfortably met the design deflection criteria of span/500 and correlation between finite element results so far has been promising.

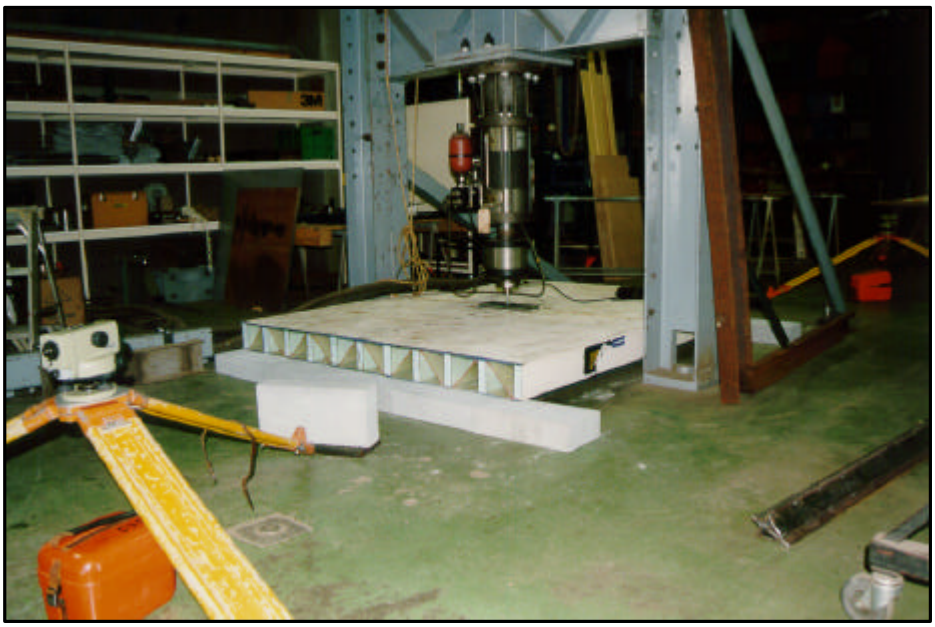

Fig. 16: *½ scale bridge deck under the test rig.*

CONCLUSIONS

The bridge deck exhibits exceptional structural performance by utilising highly optimised geometry and fibre architecture. The deck conforms to the global deflection limits at serviceability and displays superior transverse stiffness. The triangular modules with a vertical sandwich structure provide a reduction in local deck span between adjacent modules and offer greater performance than triangular elements alone. The modular solution while providing a number of advantages also suffers from some critical disadvantages. Modular bridge decking should be robust in design to accommodate geometric mismatches in modules that may result in significant deviations from intended geometry. The bridge deck design presented cannot accommodate such mismatches and requires strict adherence to geometric tolerances to be successfully manufactured. Under the application of a 45kN point load at deck midspan and centre, the difference in deflection across the deck was approximately 0.7mm.

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1. Roberto Lopez-Anid, PhD, P.E. Department of Civil & Environmental Engineering.
http://www.umeciv.maine.edu/rla/frp

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