The Use Of Geopolymer Concrete and GFRP Materials For An Innovative Wharf Structure

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Abstract

The design and construction of a new Wharf facility at the Wagners cement site in Brisbane Queensland features an innovative approach to building materials that delivers significant advancements in both environmental and engineering performance.

The wharf deck superstructure is comprised of 191 no. prefabricated panels that span between 8 and 12 metres over steel headstock beams. The panels are a unique hybrid structural system developed over many years by Wagners R&D division initially for use in pedestrian and road bridges. The system has been adapted and further developed for the challenging conditions of a marine wharf structure.

Each of the panels consist of:

- pultruded composite fibre girders that provide the tensile beam spanning capacity,
- geopolymer concrete engaged deck that acts as a compression flange while locking the girders together,
- glass fibre reinforced polymer (GFRP) reinforcing bar in the concrete deck to form a completely non-metallic structure that is risk free for marine exposure borne corrosion,
- vastly reduced embodied carbon emission compared to conventional materials.

The hybrid deck superstructure described above represents a new approach using high technology building materials to deliver efficient, low maintenance and low CO_2 emission engineering structures. This paper describes the design and manufacture of the prefabricated deck units and the necessary testing and material properties validation that were undertaken on this structural system and its component materials over many years.

Keywords: CFT, EFC, Glass Fibre Reinforced Polymer, GFRP, Geopolymer Concrete, U-girders, Wharf

1.0 Introduction

A new Wharf facility constructed at Wagners cement site on the Brisbane River, Queensland will enable the direct berthing of cement clinker ships that carry up to 35,000 tonnes cargo. This facility will replace the current arrangement of berthing clinker ships at the Port of Brisbane and road freighting clinker to the cement site. Figure 1 shows the location and overall layout.

The subject of this paper is the Wharf's deck which features a new and innovative approach to building materials and delivers significant advancements in both environmental and engineering performance.

The Wharf's deck is comprised of 191 no. prefabricated panels that span between 8 and 12 metres over steel headstock beams. The panels are a unique hybrid structural system developed over many years by Wagners R&D division initially for use in pedestrian and road bridges. The system has been adapted and further developed for the challenging conditions of a marine wharf structure. The wharf deck layout is shown in Figure 1.

Each of the panels consist of:

- pultruded composite fibre U-girders that provide the tensile beam spanning capacity,
- geopolymer concrete engaged deck that acts as a compression flange while locking the U-girders together,
- glass fibre reinforced polymer (GFRP) reinforcing bar in the concrete deck to form a completely non-metallic structure that is risk free for marine exposure,
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The hybrid deck superstructure described above represents a new approach using high technology building materials to deliver efficient, low maintenance and low CO_2 emission engineering structures. This paper describes the design and manufacture of the prefabricated deck units and the necessary testing and material properties validation that were undertaken on this structural system and its component materials.

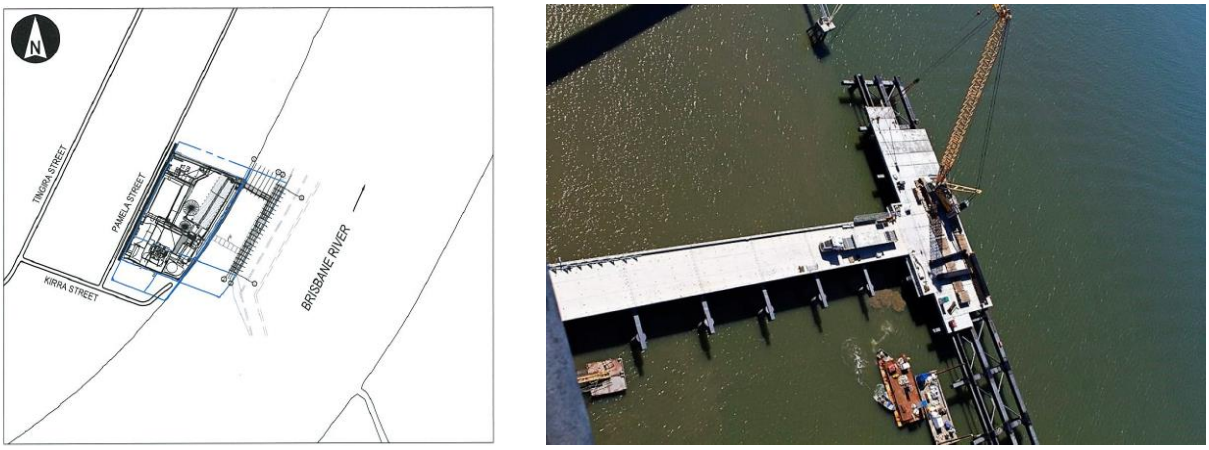

Fig. 1 Locality plan and aerial photograph while under construction – Wagners cement wharf

2.0 Use of novel engineered materials

Three novel engineered materials have been used in the design of the prefabricated deck units – geopolymer concrete, glass fibre reinforced polymer (GFRP) reinforcement and glass fibre reinforced polymer U-girders (CFT). The arrangement is shown in figure 2.

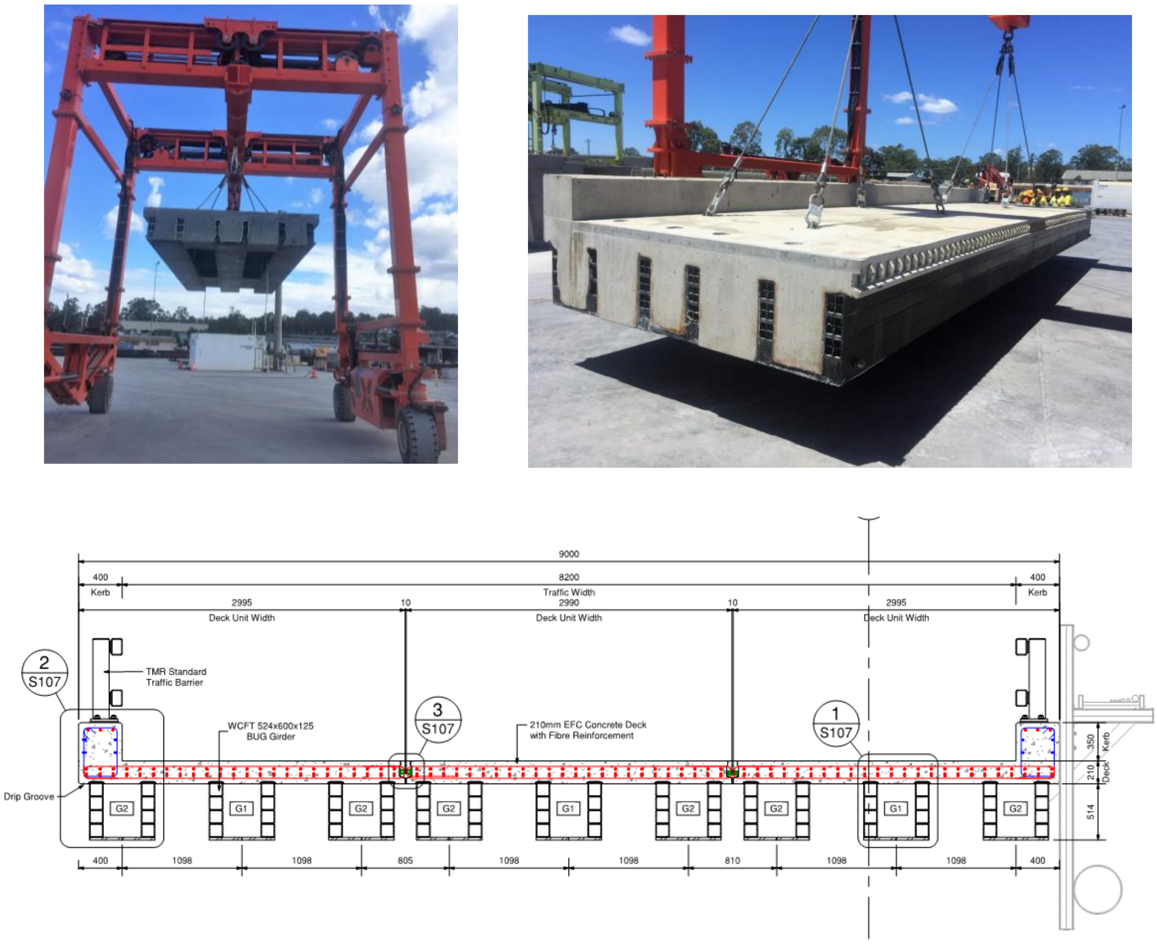

Fig. 2 Typical deck unit cross section and images of completed deck units

2.1 Geopolymer concrete

While alkali activated slag concrete has a history dating back to the 1930's in Eastern Europe (Roy 1999), geopolymer concrete is still deemed a relatively new technology in modern concrete construction. The proprietary geopolymer concrete mix (Wagners Earth Friendly Concrete® - EFC) used in this project follows over 10 years of work by Wagners developing a commercial product that is produced and handled in a similar manner to conventional concrete. It contains absolutely no Portland cement. The binder consists of ground granulated blast furnace slag (GGBS) complying to AS 3582.2 (2016), fly ash complying to AS 3582.1 (2016) and a proprietary geopolymer hardener solution. Comprehensive testing and independent R&D studies have shown EFC to possess many significant performance and durability benefits over conventional cement based concrete, including 30% higher flexural strength, low drying shrinkage, low heat of reaction and very high resistance to chemical attack.

Previous significant project examples of this proprietary geopolymer concrete include load bearing precast reinforced floor beams in a multi storey building (Bligh & Glasby 2013) and heavy duty aircraft pavements in Australia's newest public airport (Glasby et al 2015).

The project mix was developed to suit placement through heavily congested reinforcing layers and achieve the design strength requirements:

- Minimum flexural strength of 6.0 MPa at 28 days, tested to AS 1012.11
- Characteristic compressive strength of 50 MPa at 28 days, tested to AS 1012.9

The demanding strength criteria and rheological (flow) properties were able to be achieved using a 10 mm maximum aggregate size EFC that still achieved over 6.0 MPa flexural strength and 50 MPa characteristic compressive strength in 28 days. High flexural strength in comparison to conventional concrete is a benefit of the EFC geopolymer that was able to be used in the FE design of the prefabricated hybrid deck elements. The mix also satisfied the demand of high production precast by attaining the minimum 20 MPa lift strength in typically 15 hours without any artificial heating. An image of a deck unit being cast with EFC using a kibble is shown in Table 1.

2.2 Glass fibre reinforced polymer (GFRP) reinforcing bars

GFRP has a very important role to play as reinforcement in concrete structures that will be exposed to harsh environmental conditions where traditional steel reinforcement could corrode, especially in marine and other salt laden environments. GFRP reinforcing bars are gradually finding wider acceptance as a replacement for conventional steel reinforcement as it offers a number of advantages. Detailed laboratory studies of samples taken from reinforced concrete structures, aged from five to eight years old, have confirmed that GFRP has performed extremely well when exposed to highly corrosive marine field conditions (Kemp and Blowes 2011).

The GFRP reinforcing bars used in this project are made of E-Glass and a polymer resin matrix in a pultrusion manufacturing process. The GFRP bars are post-cured to set the thermosetting polymer matrix to prevent remoulding of the material at elevated temperatures. GFRP bar can come in a number of sizes with some standard and non-standard varieties. The prefabricated deck units' design and construction utilised 16mm, 19mm and 22mm diameter bars.

GFRP bars have a high tensile modulus and low modulus of elasticity compared to standard G500 reinforcing steel. They are also characterised by their light-weight and inherently brittle nature meaning that bars cannot be manually bent on site and do not yield like a typical steel bar. Instead, GFRP bars are designed with large factors of safety on their ultimate design to prevent brittle failure mechanisms developing. An overloaded under-reinforced steel reinforced slab will show warning signs of approaching failure, such as large deformations and crack widths. A well designed GFRP beam at overload will undergo an over-reinforced failure mechanism with the concrete failing in compression and exhibiting warning signs of oncoming structural collapse.

The GFRP reinforced geopolymer concrete slabs for the wharf deck units were designed in accordance with Canadian Standard CSA S806 (2012). This standard outlines methods for manufacturing requirements, designing beams and slabs for ultimate and service loads, testing of reinforcing bars and testing the bar and slab interactions. Three of the general governing concepts of this code include:

1. Ensuring the governing failure mode is from crushing failure of the concrete and not GFRP bar rupture failure.
2. Limiting GFRP bar strains to 0.002 and stresses to 25% of characteristic tensile strength for serviceability loading criteria, and

3. Including additional safety reduction factors and rules regarding the ultimate limit state moment resistance of the slabs to prevent sudden collapse mechanisms.

A comparison of typical properties of GFRP rebar and standard G500 rebar is shown in Table 1 below, along with images of the GFRP during manufacture of the deck units.

Material Type	Modulus of Elasticity	Tensile Modulus	Shear Modulus	Material Density
G500 Steel Rebar	200 GPa	500 MPa	80 MPa	7850 kg/m3
GFRP Rebar	~46 GPa	752 MPa	150 MPa	2030 kg/m3

Table 1 Comparison of standard mild steel vs. GFRP reinforcing bar

2.3 Glass fibre reinforced polymer (GFRP) U-girders

Fibre reinforced polymers have proven themselves as the material of choice in high performance applications such as the Aerospace and Marine industries. As the use of Fibre reinforced polymers have become more common their benefits have been realised by other industries and their use and acceptance by civil engineers has greatly increased in recent years (Benmokrane and Ali 2018).

Fibre reinforced polymers offer high strength, low weight, and long service lives as they are not prone to corrosion, rot or shrinkage unlike other materials more traditionally used by the construction industry. The product used for the U-girders in the prefabricated deck units was a proprietary GFRP material manufactured and supplied by Toowoomba Queensland based company, Wagners Composite Fibre Technology (WCFT). This company has been instrumental in expanding the use of fibre reinforced polymers in Australia and throughout the World, exporting products to locations such as the USA, New Zealand, Russia, and Malaysia.

WCFT use the 'Pultrusion Process' to manufacture proprietary GFRP sections branded CFT, figure 3. Electrical-Corrosion Resistant (ECR) Type Glass is used because it is a high-grade material with excellent strength performance, workability and chemical resistance (Ely et al 2001). The ECR fibres are bound in a vinyl ester resin which provides the best structural solution at an economical cost. WCFT supported by icubed consulting have been producing CFT sections for use in a multitude of applications for 14 years.

Table 2 shows the comparison between the CFT material properties and concrete, timber and steel.

Mechanical Properties of Typical Construction Materials							
Material	Young's Modulus	Shear Modulus	Density	Ultimate Tensile Strength	Ultimate Compressive Strength	Nominal Shear Strength	Poisson's Ratio
	GPa	GPa	kg/m^3	MPa	MPa	MPa	
CFT	36.3	8	2030	610	485	84	0.28
Steel	200	80	7600	300	~170	~180	0.30
Concrete	~30	12	2400	3-5	25-60	6-17	0.2
Timber	7-21	13	500-700	10-40	20-50	4-20	0.2-0.5

Table 2 Mechanical properties comparison of GFRP with typical construction materials compiled by icubed consulting

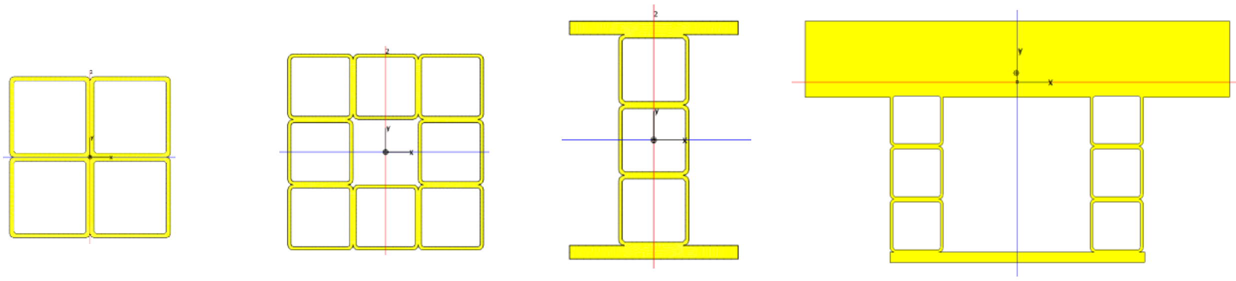

Fig. 3 Typical CFT section profiles
(bonded square section, bonded box section, bonded I-beam, bonded U-Girder)

A 24mm thick GFRP flange can be bonded to the square sections which greatly increases member stiffness and ultimate performance. All structural members subject to repetitive heavy loading are triaxially wrapped with a stitched fibreglass mat for a specified length to further reduce risk of delamination of glue lines and fatigue effects.

3.0 Wharf deck structural system

3.1 Interaction of CFT girders and EFC geopolymer concrete

The Wharf project and a number of AS5100 rated road bridges around Australia currently use the technology of CFT U-Girders integrated with a reinforced concrete slab wearing surface. These two technologies coupled together provide a 'composite' beam section. The modules act in the following manner:

1. The concrete slab acts as the top flange for the section by transferring compression stresses (under downward loads).
2. The CFT U-Girder acts as the webs transferring shear and longitudinal stresses, and,
3. The 24mm thick GFRP flange acts as the bottom flange to distribute longitudinal / extreme fibre stresses.

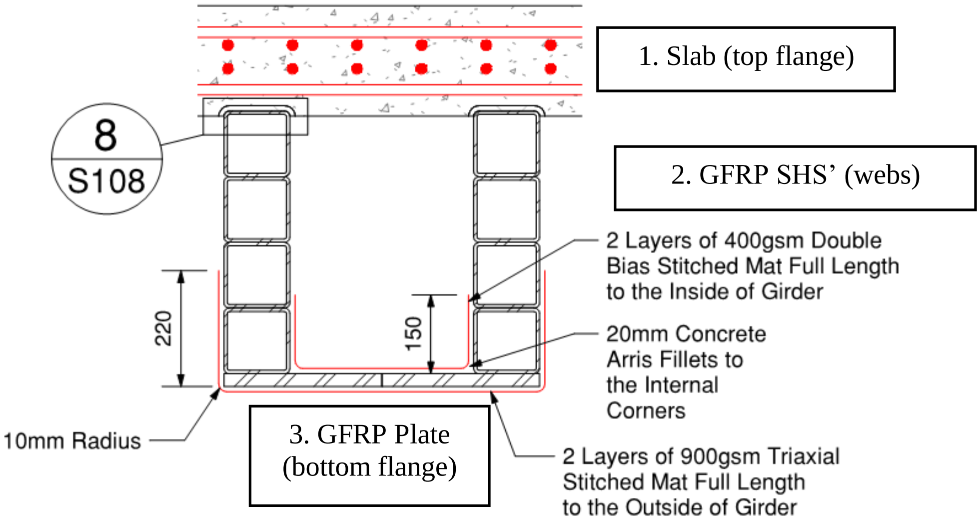

Fig. 4 Typical CFT U-Girder Cross Section

These actions can be seen in the cross-sectional stress graphs for a specific load case on the Wharf deck units, figure 5. The graph on the left shows the longitudinal shear stress values under maximum bending moment, while the graph on the right shows shear stresses across the section under maximum shear force.

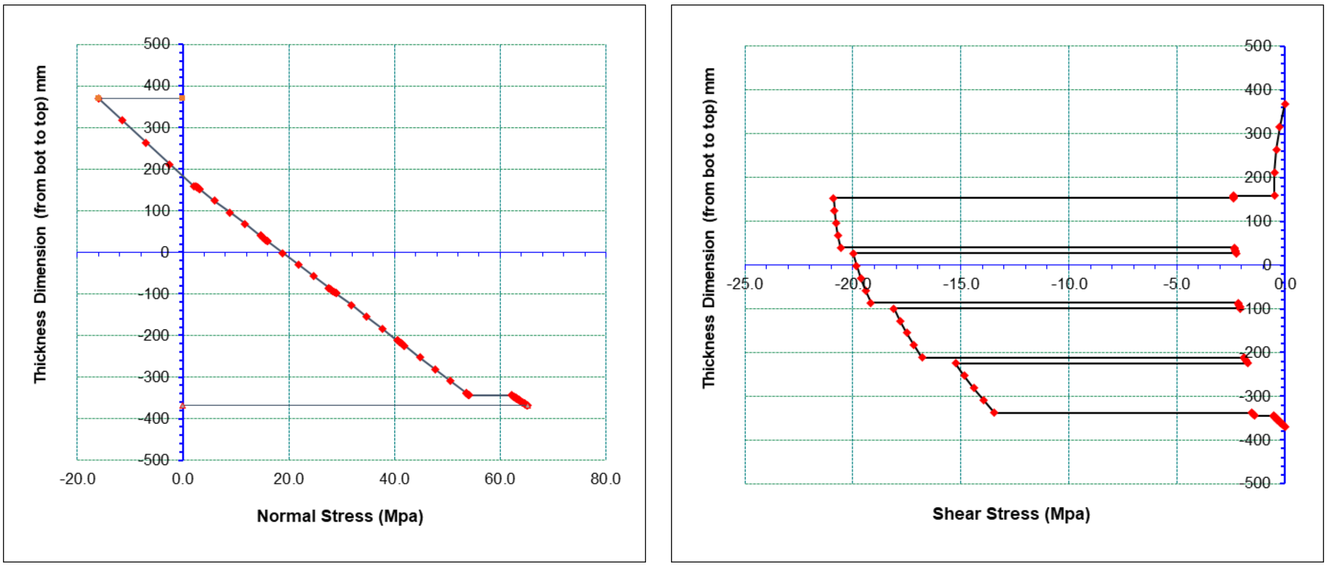

Fig. 5 Visual representation of longitudinal and shear stresses in the CFT U-Girder

The composite action of this member acts in the same manner as a typical reinforced concrete slab and Universal Beam (UB) floor system and can be seen in thousands of building projects across Australia. The use of composite floor slabs can be found in multistorey residential and commercial buildings, shopping centres, industrial warehouses, car parks and road and pedestrian bridges.

3.2 Neutral axis location

A critical design component of the CFT U-girders was the derivation of the neutral axis location. The neutral axis is the point at where longitudinal stresses change from compression to tension, or vice versa, under bending. It is characterised by a point of zero longitudinal stress. The below diagram from icubed's software shows the neutral axis sitting above the soffit of the concrete.

Longitudinal tensile stresses may form in the concrete from the position of the neutral axis to the soffit of the concrete. These bending induced tensile stresses are required to be limited to the concrete's tensile stress capacity. This longitudinal tensile force will transfer through the tension zone of the concrete soffit, to the aggregate shear key located between the concrete slab and the top two rows of CFT U-girders. The aggregate shear key is made up of 10-12mm coarse aggregate that is washed, dried and adhesively bonded to the pultrusion top flange using a vinyl-ester resin. Best practice is to size the neutral axis to be positioned as close to the aggregate shear key as possible. This will ensure that tensile stresses in the unreinforced section of the concrete soffit are kept to a minimum.

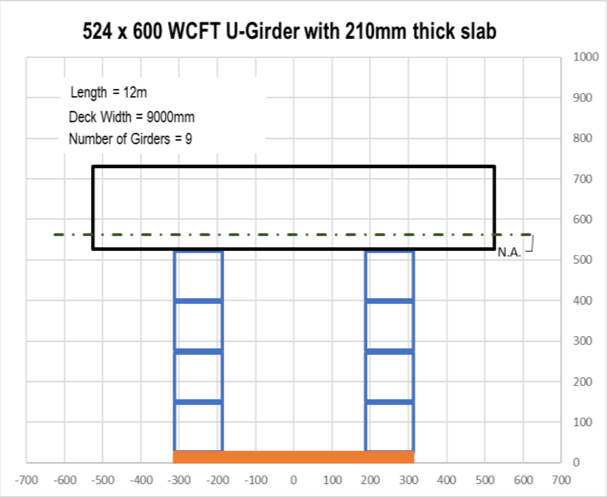

Fig. 6 neutral axis calculation by icubed consulting and image showing aggregate shear key surface on U-girders

3.3 Prying of U-girders and concrete infill

During the detailed design of the Wharf, icubed consulting undertook a finite element (FE) model of the interaction between the U-girders and the EFC geopolymer infill blocks between each U-girder at their support location. This analysis was undertaken using ANSYS and specifically looked into the surface contact between the walls of the U-girders and the wall of the concrete infill blocks.

The model showed that under high vertical loads the U-girders and the concrete infill panels may separate (delaminate) without a vertical shear key. In lieu of the shear key, due to added cost and manufacturing time, icubed and WCFT adopted a simple bolted stainless-steel rod that would act as a tension tie to prevent the U-girders and concrete infill blocks from prying under high loads.

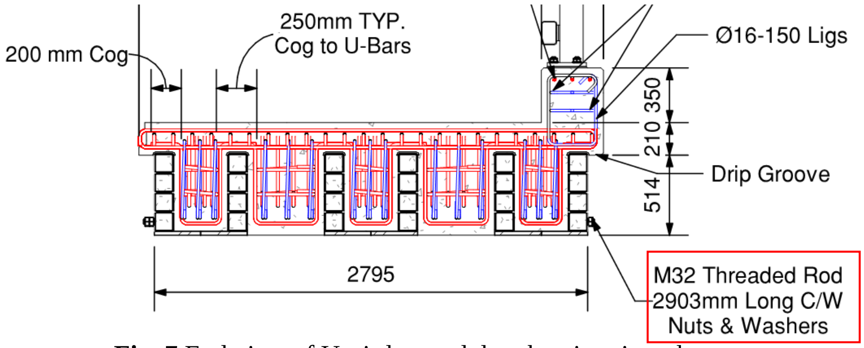

Fig. 7 End view of U-girder modules showing tie rod

3.4 Design Forces on Wharf structure

The Wharf structure has been designed to withstand some significant vertical and horizontal loads. The loads applied to the Wharf have been derived from detailed meetings with the Wharf operator focusing on their requirements over the design life of the structure.

The main deck was designed to AS 4997 'Guidelines for the design of maritime structures' (2005) with a deck load classification of Class 25. The Wharf was also designed to AS 5100 'Bridge design code' (2004) and allowance was made for specific client requested structures and vehicles, summarised in table 3:

AS 4997	AS 5100	Client Requested
25 kPa UDL	W80 wheel load	40t moxy
500kN PL over 1200x1200mm sq.	A160 axle load	80t fully loaded hopper
SM1600	SM1600 design vehicle	35t straddle carrier
HLP	HLP design vehicle	forklifts
50t SWL mobile crane		Conveyors and transfer towers
		Liebherr LR1280 tracked crane for construction

Table 3 Vertical loading criteria for Pinkenba Wharf

One of the largest vehicle loads on the Wharf would be the 300t capacity crawler crane used exclusively for construction processes. The crane allowed the wharf to be constructed in sequence as each time a set of decks was installed, the crane was able to move forward and prepare the next bent, figure 8.

All crane movements on the Wharf were accompanied by bog matts, which are large timber pads bolted together, to prevent the treads from damaging the wearing surface. Once the crane reached the jetty / wharf transition zone, large steel plates, as well as the bog matts, were laid to prevent damaging the wearing surface.

Fig. 8 Mobile crane tracking on the wharf deck during construction

3.5 Horizontal loading on the Wharf

In addition to the vertical loads outlined above, the Wharf structure is also required to resist a number of significant horizontal actions. These include:

1. 1 in 500-year flood and wave loading, including large debris mats.
   a. Uplift loads
   b. Downward loads
   c. Lateral loads
   d. Log/object impact loads
2. 40,000t moored vessel
   a. 80t bollard mooring loads (in multiple directions) from vessel
   b. 92t fender pile reactions from vessel

To accurately model and understand the horizontal actions imposed on the wharf, icubed consulting undertook a number of detailed finite element models in Strand7. The Strand7 models included developing the super-structure (EFC deck and CFT U-girders) as plate and brick elements and the sub-structure (structural steel transfer beams, headstocks, piles and bolts) as beam elements. A 3D screenshot of one of these models can be found below in Fig. 9 Strand7 FEA model the Wharf.

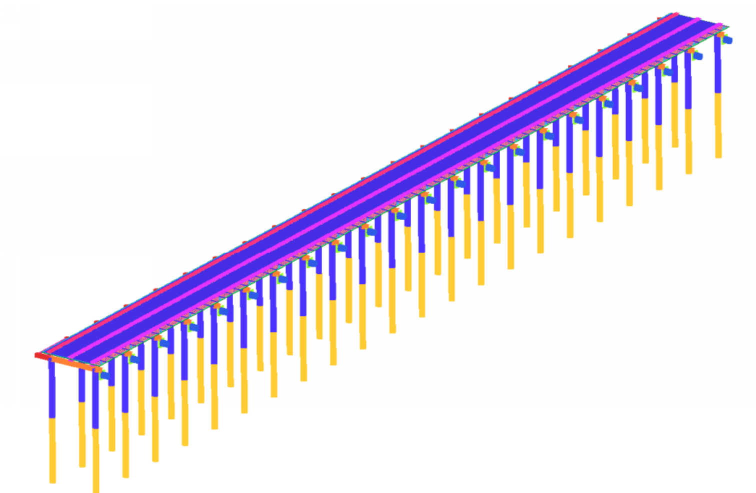

Fig. 9 Strand7 FEA model the Wharf

The horizontal load-response mechanism of the Wharf is complicated and required detailed analysis of both transverse and longitudinal actions through the deck. The EFC deck acts as a large diaphragm to share these loads across multiple bents. The results of the modelling indicated that longitudinal forces along the Wharf showed high tension and compression forces at joint locations while transverse forces across the Wharf showed high shear at joint locations. One of these graphical results can be seen below, figure 10:

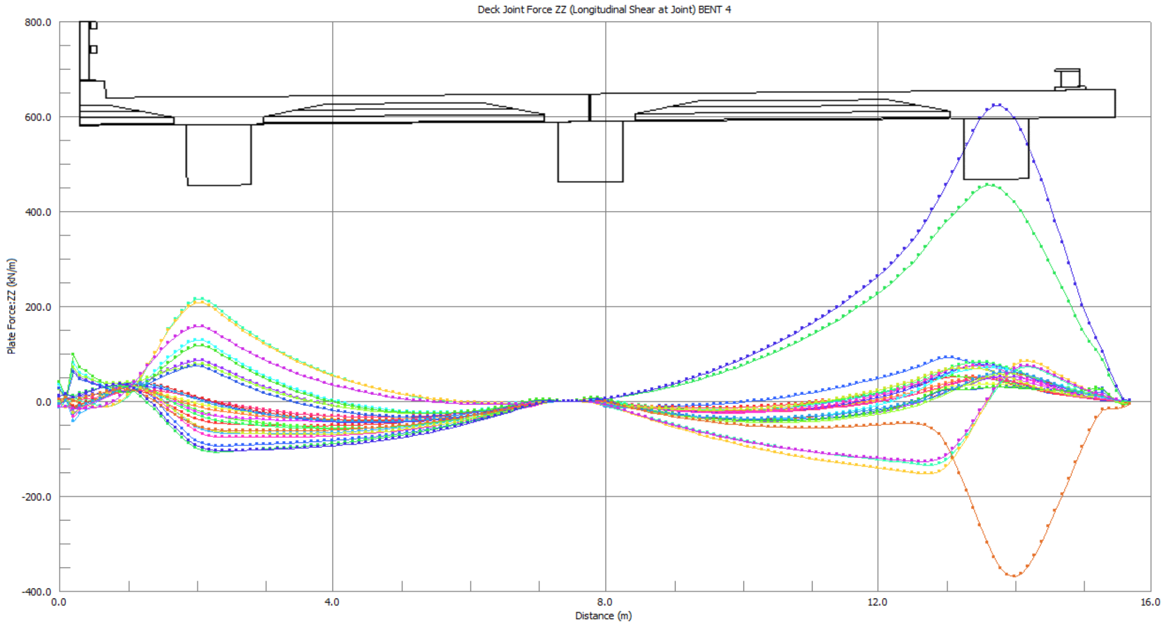

Fig. 10 Longitudinal shear at joint. LHS shows land side of wharf, RHS shows quay side (high forces from bollard loads)

3.6 Other environmental loads

In addition to the loading outlined above, the Wharf was also designed for 1-in-500-year wind event and 1-in-500-year earthquake event. Due to the magnitude of the horizontal actions from flooding, waves, debris and mooring of the vessels, the wind and earthquake load cases did not govern the design.

The strand7 models also assessed thermal expansion and contraction of the varying materials on the wharf (steel, GFRP and geopolymer concrete) and estimated time dependant movement of the concrete over a 30-year period.

3.7 Creep and fatigue loads

Creep and fatigue were assessed for both GFRP reinforced EFC geopolymer concrete and for the CFT U-girders. Creep and fatigue calculations were undertaken for the concrete slab to AS 3600 (AS 2009) and for the GFRP materials to Eurocomp ‘Structural design of polymer composites’(Clarke 1996).

3.8 Full-Scale Testing Program

Due to the relatively new-age technology used in the design and construction of the Wharf, icubed consulting requested a detailed testing program be undertaken to validate the theoretical design. The testing program was broken up into five key tests:

- Test 1: aggregate shear key tension test
  - To test tensile capacity of concrete

- Ultimate tensile capacity of shear key from direct tension (wave uplift) loads
- Test 2: GFRP reinforcing and concrete deck capacity
  - Test ultimate moment capacity
  - Test ultimate shear capacity
  - Test ultimate punching shear capacity
  - Test ultimate bending capacity of slab
  - Test fatigue performance of slab over 2e6 cycles
  - Test long-term creep performance
  - Test longitudinal shear key capacity
  - Measure crack widths
- Test 3: full scale U-girder and concrete deck test
  - Test ultimate moment capacity
  - Test ultimate shear capacity
  - Test ultimate bending capacity of slab
  - Test fatigue performance of slab over 2e6 cycles
  - Test long-term creep performance
  - Test longitudinal shear key capacity
- Test 4: GFRP reinforcing bar tests
  - Test tensile modulus
  - Test elastic modulus
  - Test shear strength
  - Test ultimate tensile strength
  - Deriving GFRP bond coefficient
- Test 5: U-Clip joint capacity
  - Test shear and tension across U-clips in construction joints between each deck module.

Selected modelling and testing images, figures 11 - 13, show the good alignment achieved through this process.

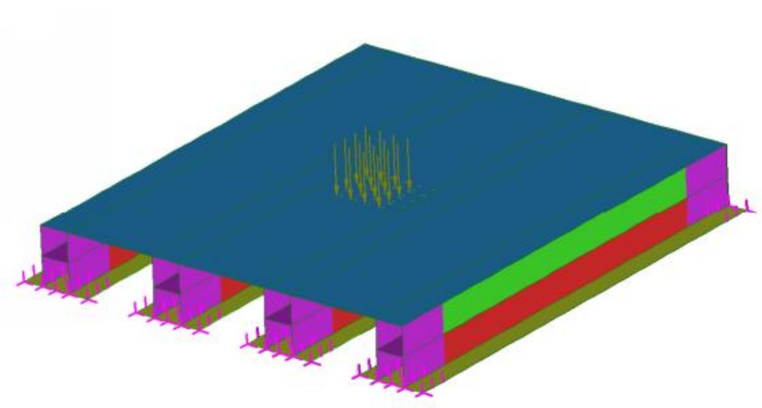

Fig. 11 Test 2: Strand7 FEA Model – GFRP rebar/concrete capacity and associated test rig

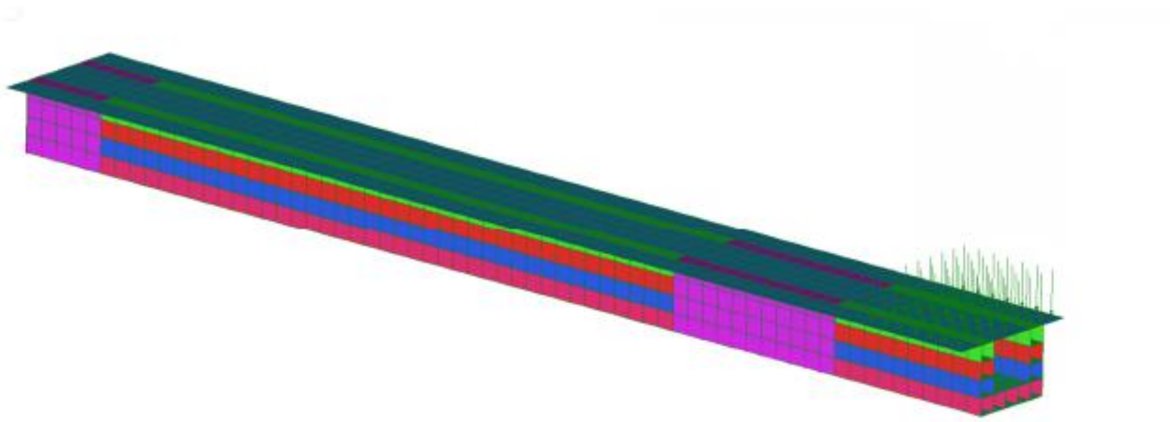

Fig. 12 Test 3: Strand7 FEA model – U-Girder cantilever performance

Fig. 13 Test 3: Actual cantilever testing being undertaken on full scale prototype

3.9 Cambering / serviceability description

The 12m long deck units forming the jetty section of the Wharf were designed with a 50 mm pre-camber in them while the 6m span modules that formed the long ship berthing section were designed as flat with no pre-camber. Cambering of the pre-cast modules for longer spans allows for imposed and environmental factors to occur without permanent sag in the U-girders. The calculation of pre-camber required is based on a consideration of the following items: dead load, live load, creep, fatigue, shrinkage, and thermal movement.

The above load cases were calculated manually and then input into Strand7 FE analysis. The vertical deflection reading at mid-span of the modules were then extracted into Microsoft Excel and summed to provide an overall required pre-camber for each module. The 6m span modules experienced zero pre-camber requirements due to the shorter span. This also assisted construction and pre-casting of the most labour-intensive portion of the Wharf.

3.10 Design life of the Wharf

The wharf facility has been designed for a 50 year design life in accordance with AS 4997 (2005).

WCFT have had three significant U-girder bridge designs installed in the USA and Australia for over 13 years. These three bridges to date have had no maintenance or remedial works undertaken.

- Wellcamp quarry access bridge, Toowoomba, Australia – installed 2003
- New Oregon Road Bridge, Erie County, USA – installed 2004
- Taromeo Creek Bridge, D'Aguilar Highway, Australia – installed 2005

3.11 Interaction of Wharf deck and the sub-structure

The prefabricated deck elements also required an appropriate load path to transfer vertical and horizontal actions into the steel sub-structure, and then into the river bed. The simplest solution for this issue was to install stainless steel hold down bolts across the entire wharf. Each bolt was installed in the webs of the U-girder and were full-strength butt welded to the sub-structure hot-rolled steel elements and treated accordingly. This configuration is shown below in figure 14.

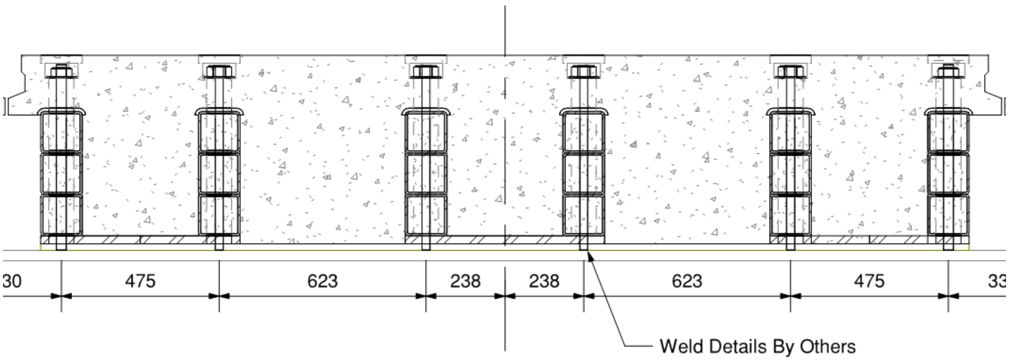

Fig.14 Positioning of a typical set of stainless steel hold down bolts

In the preliminary design phase of the project, icubed consulting undertook detailed hand calculations and simple beam structure models in Microstran to estimate the required bolt actions on the wharf. This proved to be too conservative so the hold down bolts were included as part of the greater FE modelling of the Wharf. Modelling the bolts in Strand7 allowed for accurate bolt force distributions across the deck modules which aided in providing a highly refined design outcome.

The bolt groups with the highest loads on the Wharf were located at the 80t deck bollards and would be required to shed the large uplift and shear loads to the sub-structure portal frame. Outside of the wharf bolting arrangement, large bolts were also required on the 84m long jetty, which acts as a large cantilevered structure for flood and debris loads. The extremely large bending moments at the abutment resulted in large force couples on the bolts. An extracted graph of the bolt shear forces at the abutment can be found below in figure 15:

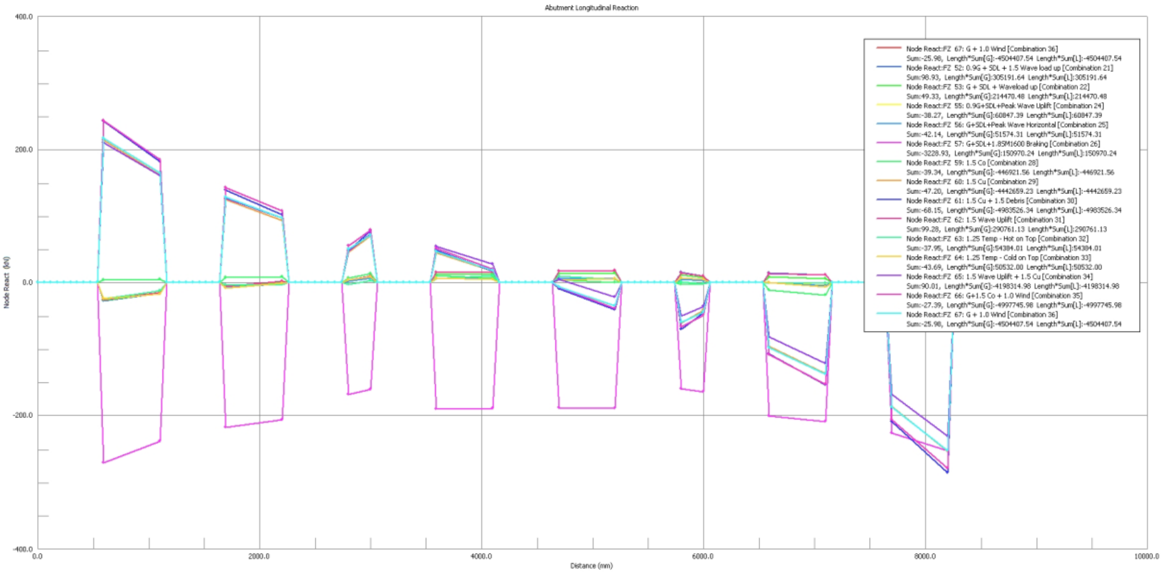

Fig. 15 Strand7 abutment bolt reactions visualised in a graph

3.12 Flexible filler end treatment

Another major design consideration for the hold down bolts was their fixity conditions at each end. The deck modules made allowance for a 75mm diameter grout hole for the hold down bolts to sit in. Grouting each hole with a high-strength, low-shrinkage grout would essentially result in a pinned-pinned end connection on a simply supported beam. To avoid the excessively high shear forces associated with this indeterminate model, icubed consulting undertook a localised FE model in ANSYS. This model looked at the stiffness requirements of a fully grouted end connection and also the stiffness of a flexible filler end connection. The results of the ANSYS model provided two key parameters to proceed with the design of the Wharf in Strand7:

1) The stiffness values for grouted and flexible filler end conditions were input into icubed's Strand7 FEA models to complete the hold down bolt design forces.
2) The ANSYS model looked at fatigue performance of the stainless steel over the working life of the Wharf. The predicted fatigue life of the bolts provided an upper-bound number of cycles for a fully loaded Moxy vehicle. The outcome of this analysis also drove the minimum bolt size requirements.

3.13 Post-Tension cables

Also discussed in Section 3.11 was the interaction of the super-structure deck with the steel sub-structure frame. Part of this design process also looked at the long-term performance of the deck construction joints to reliably transfer shear and tension loads from vessel and flood forces. The tension arching loads at both the quay-side and land-side of the wharf were in excess of 80t each. To help prevent unravelling and cracking of the high-strength grouted construction joint, icubed opted to install 4 no. 15.2mm dia. post-tension cables on each side of the Wharf. These cables would be greased and sheathed, non-grouted, and post-tensioned. Once the cables are in tension, the deck diaphragm would continuously act in compression and will be prevented from opening up due to adverse berthing impacts for its design life. Visual representation of this arching action in the deck diaphragm can be seen below in figure 16.

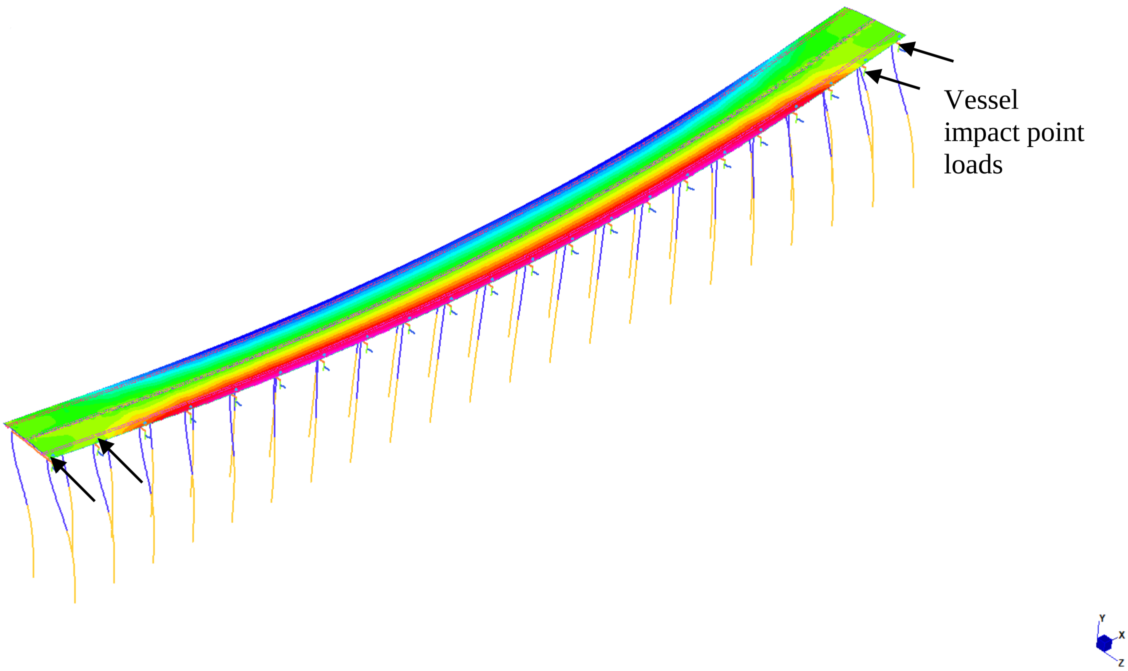

Fig. 16 Strand7 view of wharf deck arching actions – fender impact load case

4.0 Environmental benefits

The three novel engineered materials chosen for this project produce a significant improvement in environmental performance. In summary these include:

- The proprietary geopolymer concrete, EFC, contains no ordinary Portland cement and as a result achieves vastly reduced carbon emissions compared to conventional cement based concrete (Davidovits 2013). It contains a binder which also uses two common recycled wastes from other industries – GGBS and fly ash.
- Geopolymer concrete has a range of performance and durability benefits compared to conventional concrete that extend the life of concrete structures and reduces unplanned maintenance.
- GFRP reinforcing bars eliminate the risk of degradation of reinforced concrete via steel corrosion. This extends the life of concrete structures and reduces unplanned maintenance.
- CFT U-girders are high tensile strength, light weight and non-metallic / non-corrodable. These properties can deliver an efficient structure with long life and reduced unplanned maintenance.
- A life cycle assessment study by UNSW found that an I-Beam that is made from pultruded fibre composite has an environmental impact which is 76% less than that of a cold-formed stainless steel (316) I-Beam. This equates to a lessening on the effects towards human health, the ecosystem quality and resource use during its life cycle (Kara and Manmek 2009)

4.1 Carbon Emission (reduction) for the prefabricated deck units

An internal company report by the author (Glasby 2017) analysed this new technology wharf deck structure for the reduction in carbon emissions compared to a conventional ‘business as usual’ design in structural supporting steel with an in situ cast reinforced concrete deck.

A reference conventional design is provided by Sullivan (2017) in his thesis titled “Assessment of the Benefits of GFRP in Wharf Construction” which used this cement wharf as its subject matter.

Sullivan developed an alternative conventional design using code compliant concrete deck with steel reinforcing bar supported on structural steel beams. The deck design consisted of structural steel I-beams with steel shear studs welded to the top flange with an engaged in situ poured 50 MPa concrete slab that forms the deck surface. Steel member sizes to suit the two different spans of the wharf and jetty structure are:

- Jetty sections: 12 m spans. 6 no. steel girders, 700WB173, with 65mm long studs spaced at 145 mm along the girder. The concrete slab was 220mm thick, reinforced with SL102 structural steel mesh top and bottom (50 mm cover), and N16 steel reinforcing bars central spaced 200mm along the deck.
- Wharf sections: 8 m spans. 6 no. steel girders, 610UB125, with 65mm long studs spaced at 130mm along the girder. The concrete slab was 220mm thick, reinforced with SL102 structural steel mesh top and bottom (50 mm cover), and N16 steel reinforcing bars central spaced 200mm along the deck.

The emission reduction is shown below in Table 3 which is an extract from the internal report (Glasby 2017). These calculations show that there is an enormous CO_{2eq} greenhouse gas emission saving of 1,329 tonnes compared to the reference conventional design.

ITEM - Conventional Deck Design	CO_{2eq} (t)	Alternative - Wagners	CO_{2eq} (t)
Jetty steel girder - 700WB173	174.4	Jetty prefabricated panel - CFT girders	52.3
Jetty steel girder - 15.9 mm shear studs	2.9	N/A	
Jetty - 50 MPa grade concrete in deck (cement only)	54.6	Jetty prefabricated panel - EFC geopolymer concrete (binder only)	10.9
Jetty - N16 reinforcing bar in concrete deck	12.0	Jetty prefabricated panel - GFRP rebar in EFC geopolymer concrete	3.6
Jetty - SL 102 reinforcing mesh in concrete deck	17.6	Jetty prefabricated panel - GFRP rebar in EFC geopolymer concrete	5.3
Wharf steel girder - 610UB125	676.0	Wharf prefabricated panel - CFT girders	202.8
Wharf steel girder - 15.9 mm shear studs	17.3	N/A	
Wharf - 50 MPa grade concrete in deck	667.8	Wharf prefabricated panel - EFC geopolymer concrete (binder only)	133.6
Wharf - N16 reinforcing bar in concrete deck	66.9	Jetty prefabricated panel - GFRP rebar in EFC geopolymer concrete	20.1
Wharf - SL 102 reinforcing mesh in concrete deck	97.0	Jetty prefabricated panel - GFRP rebar in EFC geopolymer concrete	29.1
TOTAL	**1786.4**		**457.6**
Reduction from conventional deck			**1328.7**

Table 3 CO_{2eq} emissions reduction – Wharf deck structure

5.0 Conclusion

The Wharf deck structure described in this paper represents the next generation in high technology building materials and will serve as a demonstration case for long life, low maintenance and extremely low CO_2 emission engineering structures. The materials combination of geopolymer concrete, GFRP reinforcing bar and CFT U-bar girders have been successfully applied to the challenges of a heavily load wharf structure.

The application of these materials in an innovative engineering design has delivered a wharf structure that has performed well against the client's key criteria of – economy, fit for purpose, speed of construction and reducing the environmental impact.

This paper has shown how new engineered materials that may not be covered by design codes can be designed using manufacturing test data supported by appropriate R&D studies and full scale prototype models to provide the necessary level of confidence and reliability. The innovation displayed in this project is the result of many years of collaboration between engineering consultant and product developer / manufacturer and may be a useful example for others.

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