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Sustainable corrosion protection of steel bulkhead wall by installation of pultruded GFRP panels

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Abstract: In marine environments, particularly in wharf structures, the corrosion of steel bulkhead walls poses a significant threat to structural integrity and safety, resulting in substantial economic and environmental burdens due to frequent maintenance and potential structural failures. Traditional corrosion protection methods, such as coatings and cathodic protection, offer temporary solutions but are hindered by their limited lifespan, high maintenance costs, and potential environmental impacts due to the use of hazardous materials. This study proposes a solution utilizing pultruded Glass Fiber Reinforced Polymer (GFRP) panels in conjunction with concrete fill to provide sustainable and effective corrosion protection for steel bulkhead walls in wharfs. The pultrusion process ensures the production of high-quality GFRP panels with consistent properties, making them an ideal material for marine applications. These panels act as a waterproof membrane, preventing direct contact between the steel structure and corrosive seawater. The concrete fill not only provides structural support but also acts as a corrosion inhibitor by maintaining a high pH environment, which passivates the steel surface, forming a protective oxide layer that suppresses corrosion reactions. A corrosion protection project was completed using this technique at ATCL marina in Lebanon, offering a promising alternative to traditional methods, such as painting. This case study contributes to the advancement of corrosion protection technologies, addressing the critical need for durable, environmentally friendly solutions in marine infrastructure and paving the way for future innovations in marine structural protection.
Keywords: *Bulkhead, Corrosion protection, GFRP, Marine, Pultrusion, Wharf.*

1. Introduction

Corrosion of steel bulkhead walls in marine environments, particularly in wharf structures, is a pervasive issue that compromises structural integrity, safety, and economic viability. Steel-sheet piles are the most widely used sheet walls, thanks to the highly adaptable profiles offered by industrial production, the slenderness of the profiles calls for care to be taken in aggressive environments [1]. Steel bulkheads are constantly exposed to aggressive seawater, which accelerates corrosion and leads to material degradation, frequent maintenance, and, in severe cases, structural failure [2]. The economic impact of corrosion is staggering, with global costs estimated at over $2.5 trillion annually, representing 3-4% of the gross domestic product (GDP) of industrialized nations [3]. In addition to economic burdens, traditional corrosion protection methods, such as organic coatings and cathodic protection, often involve the use of hazardous materials and generate environmental concerns.

Traditional methods, while widely used, have significant limitations. Organic coatings, for instance, degrade over time due to UV exposure, abrasion, and chemical attack, necessitating frequent reapplication [4] and the need to use a cofferdam to enable paint application. Cathodic protection, on

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the other hand, requires continuous monitoring and energy input, making it costly and less sustainable [5]. These challenges highlight the need for innovative, durable, and environmentally friendly solutions to address corrosion in marine infrastructure.

In recent years, Fiber Reinforced Polymer (FRP) composites, particularly Glass Fiber Reinforced Polymer (GFRP), have emerged as promising materials for corrosion protection due to their high strength-to-weight ratio, chemical resistance, and durability in harsh environments [6]. Pultruded GFRP panels offer consistent mechanical properties and are inherently waterproof, making them an ideal barrier against seawater ingress [7]. When combined with a thick concrete fill (in our case a min of 40mm), the system provides a dual mechanism for corrosion protection: the GFRP panels act as a waterproof membrane, preventing direct contact between seawater and the steel structure, while the concrete fill not only provides structural support but also maintains a high pH environment that passivates the steel surface, effectively halting existing corrosion [8].

The effectiveness of this system can be explained through Fick's laws of diffusion, which is used to describe the movement of corrosive agents (e.g., chloride ions) through materials. According to Fick's first law, the diffusion rate of chloride ions is proportional to the concentration gradient across the material. Nevertheless, the GFRP panels significantly reduce this gradient by acting as an impermeable barrier, while the concrete fill further inhibits chloride ion penetration due to its low permeability and alkaline nature [9]. This combined approach ensures long-term protection against corrosion, even in aggressive marine environments. The use of GFRP panels can have a significant impact of CO_2 and reduction in construction surfaces and the usage of heavy cranes due to their light weight compared to steel [10].

In this project "ATCL-Lebanon: Steel Bulkheads corrosion protection" a novel approach to corrosion protection for steel bulkhead walls using pultruded GFRP panels in conjunction with a minimum of 40 mm concrete fill was proposed. The integration of these materials offers a sustainable and long-term solution that addresses the limitations of traditional methods. By leveraging the waterproof properties of GFRP, the passivating effect of concrete, and the theoretical principles of Fick's laws, this system aims to reduce maintenance costs, extend the service life of marine structures, and minimize environmental impact. The potential for widespread application in wharf structures is significant, offering a pathway to more resilient and sustainable marine infrastructure.

2. Project Description

2.1. Description

The purpose of this paper is to demonstrate the adequacy of using a combination of pultruded GFRP panels and a concrete section to protect existing steel bulkheads. This approach is evaluated in terms of structural capacity and the ability to sustainably prevent future degradation. The proposed solution, referred to as the CPS (Corrosion Protection System)**,** is a durable external protective barrier. It consists of composite panels installed on the water side of the sheet piles, with the space between the panels and the sheet piles filled with concrete.

2.2. Design Requirements and Assumptions

The foremost design requirement is to provide adequate protection to the existing steel bulkhead for 15 years against corrosive agents that will otherwise cause further degradation and steel section loss at the outer side of the structure (Waterside)

The proposed system will provide a durable external protective barrier in front of the existing bulkhead from the lowest astronomical tide to its full height above water and will prevent any contact between the bulkhead and the sea water at the splash zone. Furthermore, the installation of the system (GFRP panels + concrete) will significantly decrease the level of oxygen at the outer side of the bulkhead leading to complete halt of the corrosive reaction.

The main structural design requirement is related to the adequacy of the structural connection of the GFRP panels to the existing sheet piles against in-plane actions generated by the self-weight of the

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Vol. 9, No. 4: 984-1007, 2025
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system. Moreover, the capacity of the composite panels and their supporting system need to be designed in order to adequately perform as a formwork for the concrete at the construction phase.

For this design, it is assumed that the bulkhead wall at its existing state can safely withstand the imposed loads and can safely retain the soil. Therefore, it is further assumed that the GFRP panels will safely be fully suspended from the existing structure, that is the existing bulkhead wall can carry the additional overall weight of the system (GFRP panels + concrete). Finally, it is assumed that no corrosion or section loss will take place at the inner landside face of the bulkhead wall in the future since it is totally embedded in the soil.

3. Pultruted GFRP Panels Description and Properties

3.1. Methodology of Works

GFRP panels comprises flat composite panels that are positioned at a distance from the sheet pile with the in-between space filled with special-mix concrete reinforced with a grid of composite bars. Detailing includes composite supporting profiles as well as steel connectors and dowels that are pre-welded on the sheet pile [Fig-1]. The application height for the panels extends from lowest astronomical tide (+0.0mCD) up to the top of the bulkheads thus covering the sloshing wave height.

The panels are flat at their waterside face and have longitudinal fins at their landside face. They are comprised of high strength pultruded Fiber Reinforced Polymer (FRP) profiles that are reinforced by glass fibers using vinyl-ester resin as matrix [Fig-2&14]. The panels are vertically positioned in array, extending up to the bulkheads top and accommodating a spacing between them and the clutch of the sheet piles equal to approximately 4cm [Fig-1&8].

The composite panels are supported at their top and bottom by steel angle beams and at two intermediary levels by composite channel beams that externally link adjacent panels together [Fig-9&14].

All beams are connected through spacers to steel channel columns installed at every king pile location [Fig-3,4 & 5]. The steel columns extend along the installation height of the panels and are fixed to the seaside flanges of the king piles at the levels of the beams by use of hollo-bolts. The top and bottom steel angle beams are welded to the steel columns while the composite channel beams are fixed through the composite panels by use of hollow bolts. The vertical joint between adjacent composite panels has a male-female configuration that is sealed by application of epoxy resin along its height during panel installation.

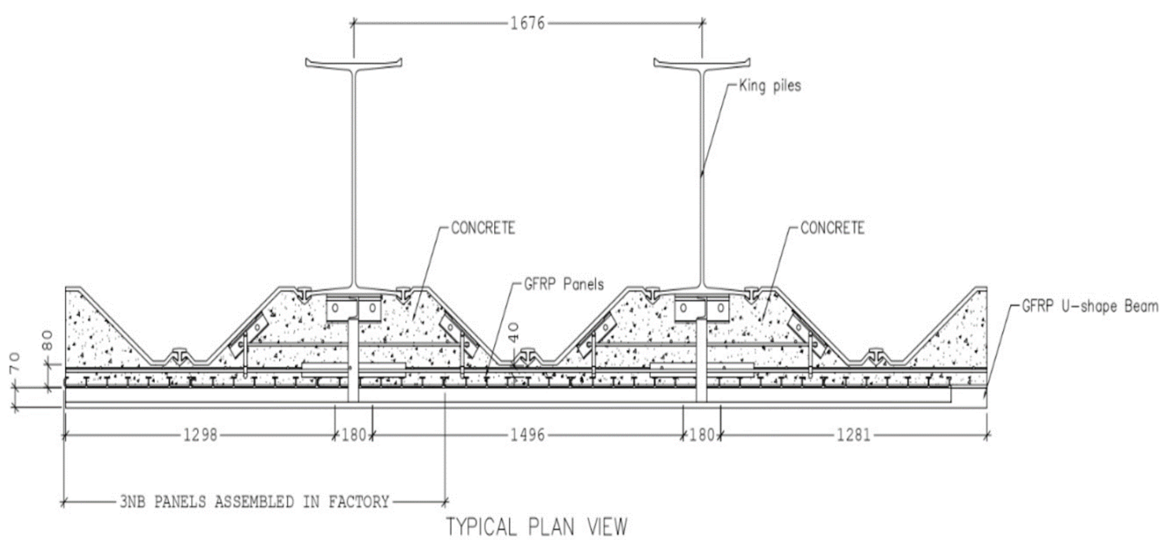

Figure 1.
Plan View.

Edelweiss Applied Science and Technology
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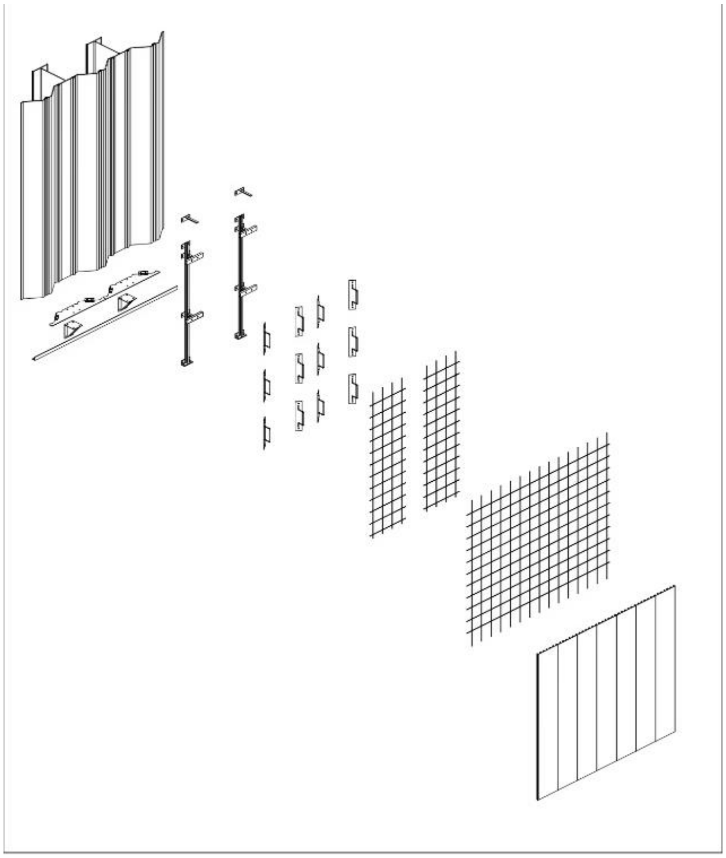

Figure 2.
Erection procedure

ISSN: 2576-8484
Vol. 9, No. 4: 984-1007, 2025
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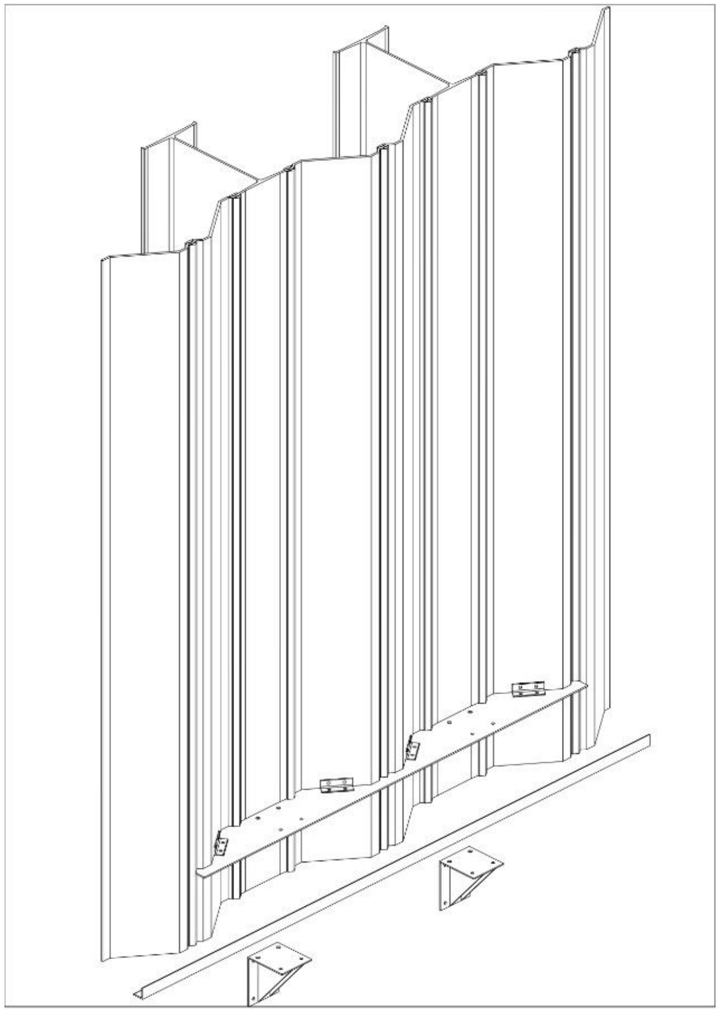

Figure 3.
Installation of steel support.

ISSN: 2576-8484
Vol. 9, No. 4: 984-1007, 2025
DOI: 10.55214/25768484.v9i4.6146

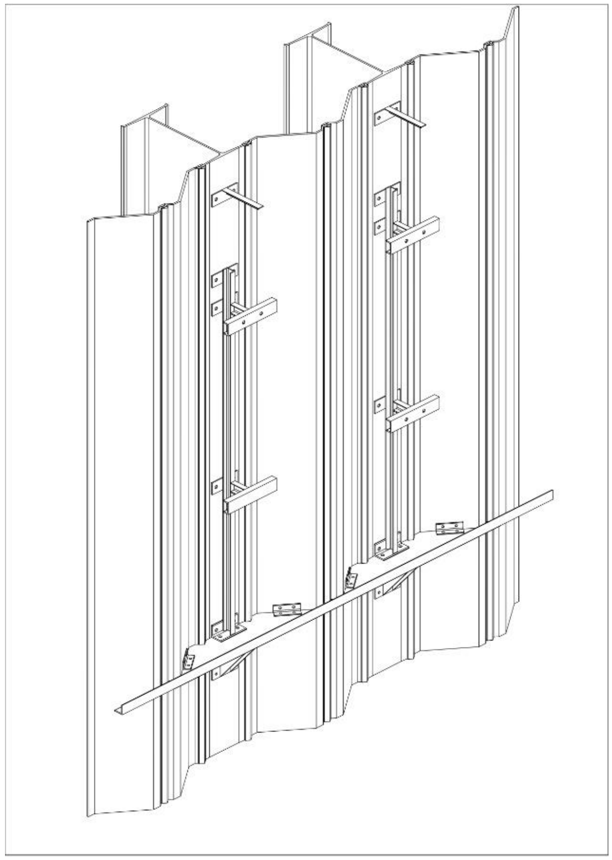

Figure 4.
Hot dip galvanized steel supports fixed to King piles.

DOI: 10.55214/25768484.v9i4.6146

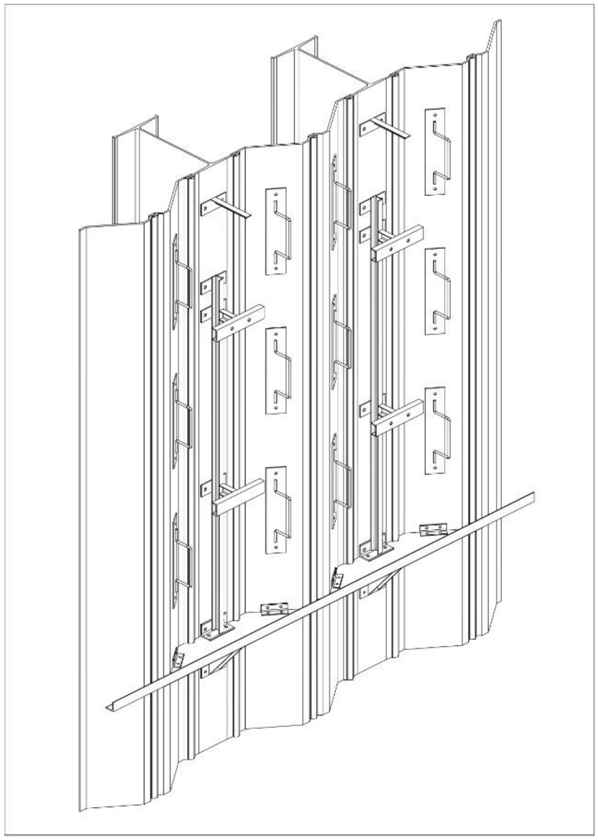

Figure 5.
Fixation of Hooks to sheet piles using Hollo Bolts.

ISSN: 2576-8484
Vol. 9, No. 4: 984-1007, 2025
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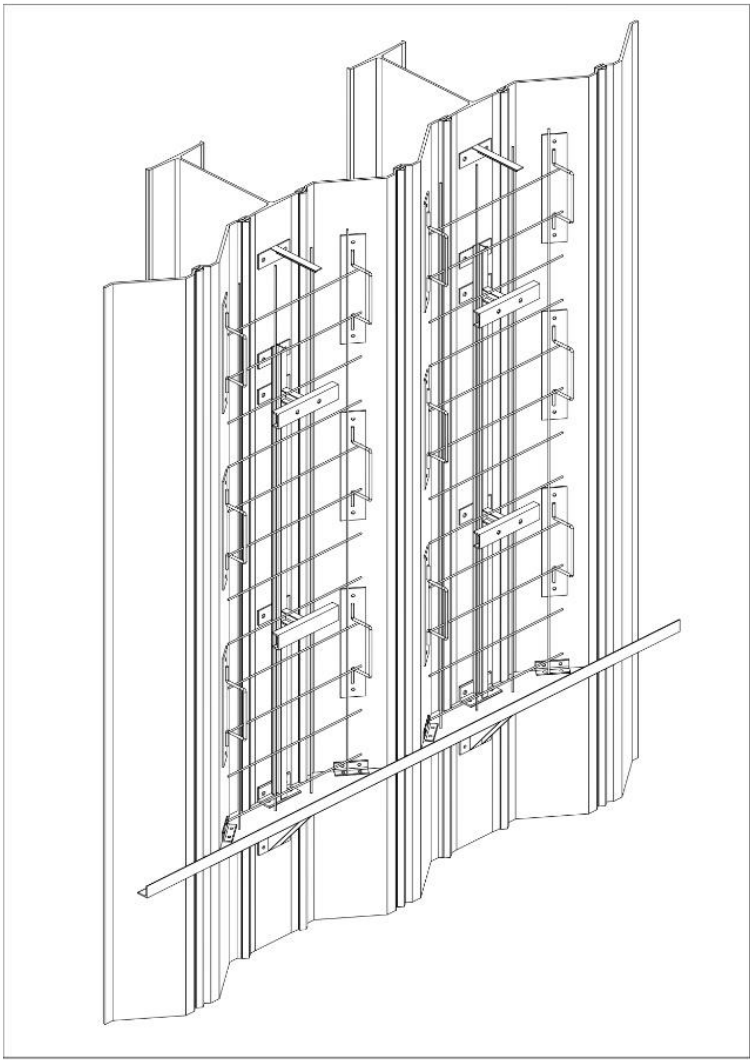

Figure 6.
Installation of GFRP rebars (max spacing 30cm).

ISSN: 2576-8484
Vol. 9, No. 4: 984-1007, 2025
DOI: 10.55214/25768484.v9i4.6146

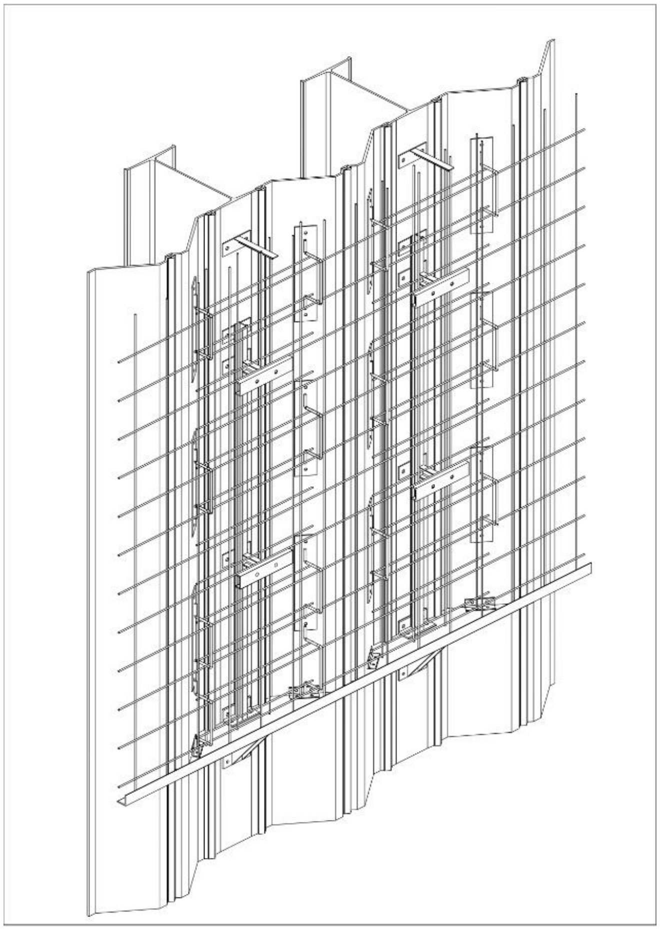

Figure 7.
Placement of GFRP rebars (Vertical and Horizontal).

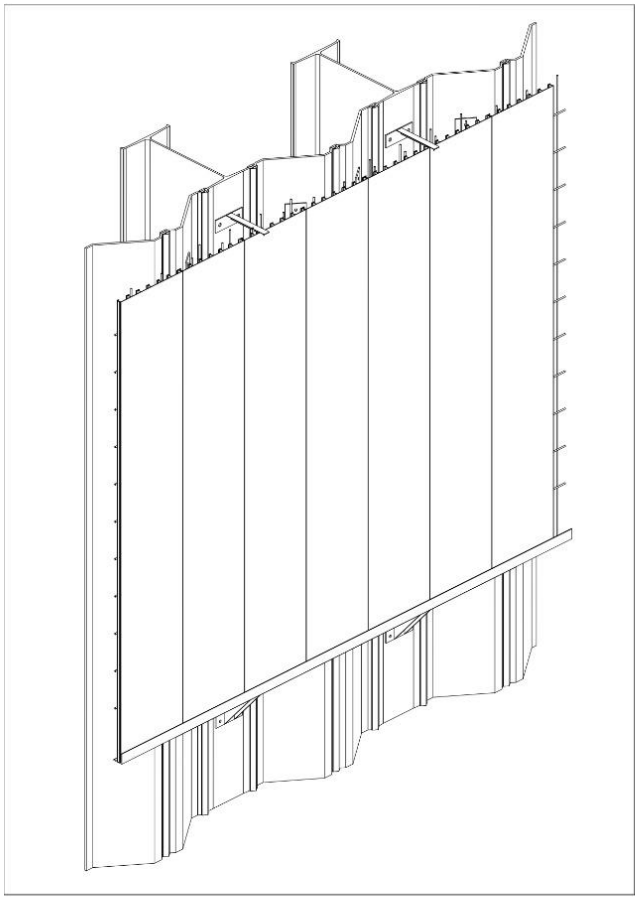

Figure 8.
Putting in place the “CPS” panels.

ISSN: 2576-8484
Vol. 9, No. 4: 984-1007, 2025
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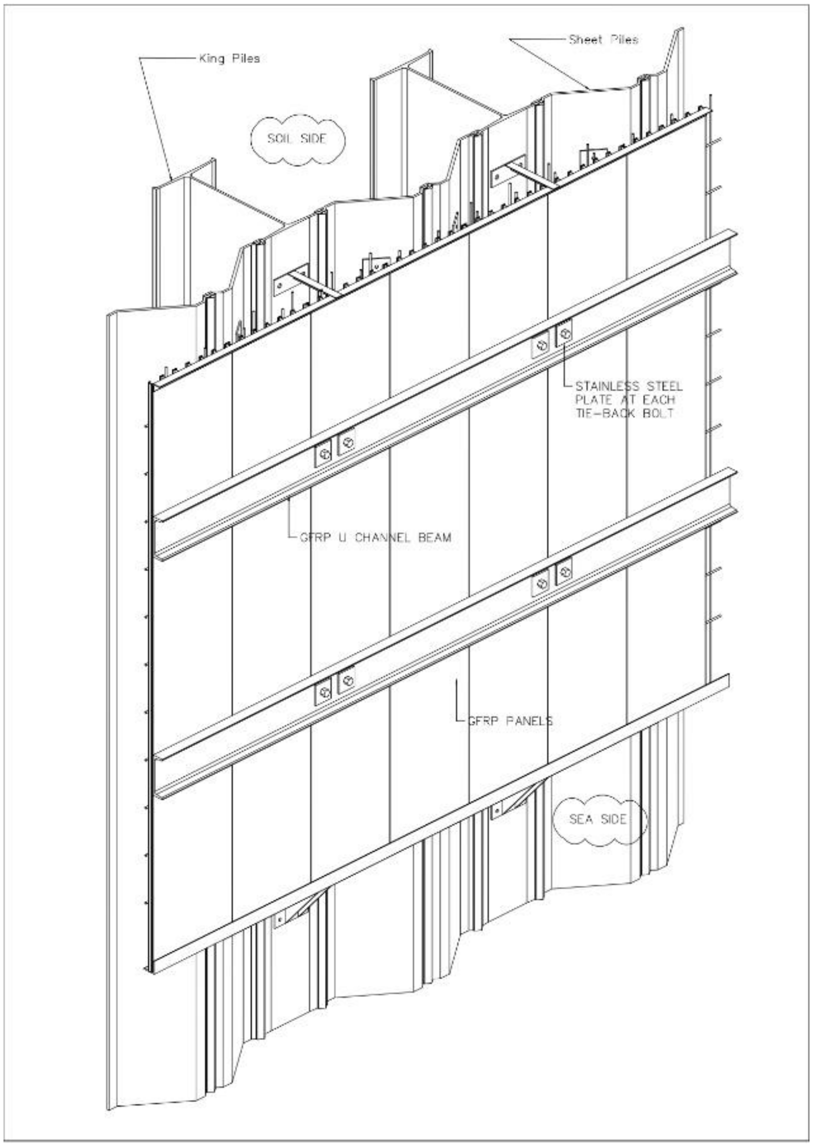

Figure 9.
Putting in place the U channel.

Edelweiss Applied Science and Technology
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Vol. 9, No. 4: 984-1007, 2025
DOI: 10.55214/25768484.v9i4.6146

Figure 20.
Placement of steel supports Hot dip Galvanized) bolted to King piles.

Figure 31.
Placment of GFRP rebars (max spacing 30cm).

3.2. Concrete

The space between the composite panels and the sheet piles is filled with C50 grout that is placed from bottom to top to avoid segregation. C50 grout has a maximum aggregate size of 5mm and is based on a mix of Ordinary Portland Cement (OPC) cement 42.5 with the addition of Micro Silica for enhanced performance. Plasticizers and superplasticizers are used to keep the water/cement ratio at the level of 0.28 [Fig-12]. The concreting hose is entered through on-site performed openings at the top of the composite panels and lowered down to the bottom of the composite panels. At the bottom, the space between the steel angle beams and the sheet-piles is sealed watertight to act as the bottom part of the concrete formwork. Any seawater trapped between the panels and the sheet piles will be extracted from the top during concreting.

ISSN: 2576-8484
Vol. 9, No. 4: 984-1007, 2025
DOI: 10.55214/25768484.v9i4.6146

Figure 12.
Concrete between Sheet Piles and GFRP Panels.

The concreting is performed in two phases. The first phase includes concreting up to level +2.0m CD (total concreting height: 2.0 m). Trapped water is released through holes drilled at the panels on site just above concreting termination level. Concrete is cured for 5 days before the second phase of concreting is performed. The second phase includes concreting up to the top of the sheet pile. The concreting openings at the panels are sealed by use of the cut-outs pieces and epoxy resin [Fig-13].

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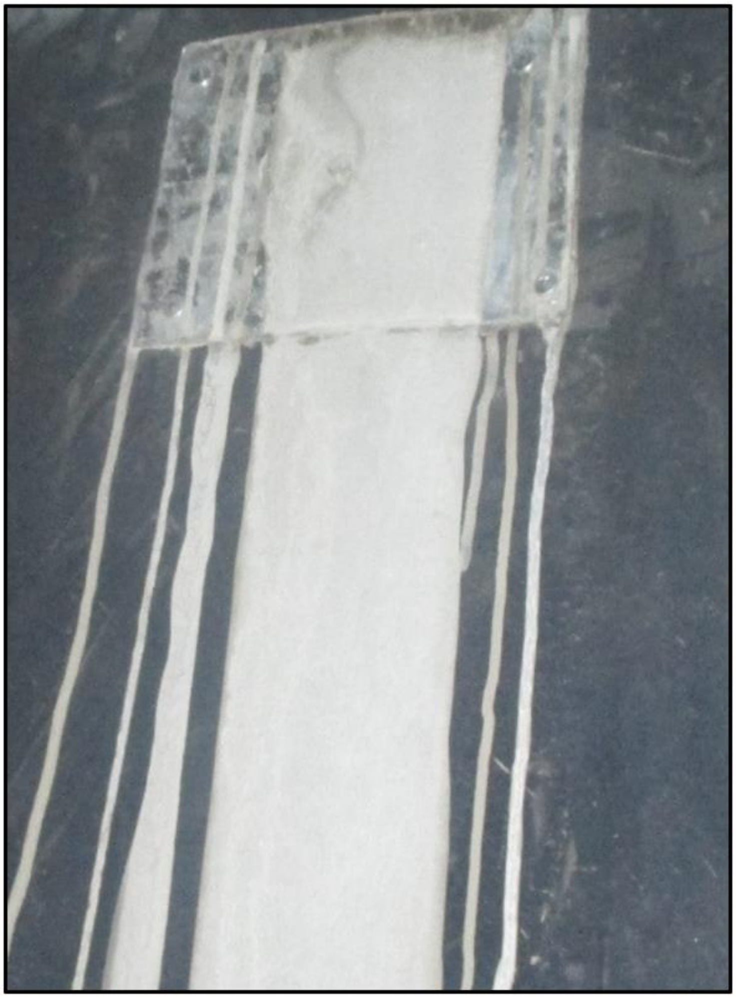

Figure 13.
Cut out pieces

ISSN: 2576-8484
Vol. 9, No. 4: 984-1007, 2025
DOI: 10.55214/25768484.v9i4.6146

Figure 14a.
Placement of GFRP Panels.

3.3. Concrete Reinforcement

Concrete is reinforced by 2 layers of grid consisting of 6 mm GFRP bars at 30 cm spacing [Fig-6,7 & 11]. The first layer is extending only at the area of the king piles while the second is continuous. Both are installed prior to the installation of the composite panels. Steel hooks are attached to the sheet piles using hollow bolts along the application height to enhance bond between the GFRP and the sheet piles.

3.4. Surface Preparation

The entire surface of the sheet piles to get in contact with concrete is grinded to SA 2.

3.5. Geometry and Mechanical Properties of the Composite Panels and Supporting Profiles

3.5.1. Geometry

A_w = 1.53 E-4 m^2/m (cross sectional area of composite per meter width)

W_x = 4.3 E-5 m^3/m (section modulus per meter width)

I_x = 1.17 E-6 m^4/m (moment of inertia around x axis per meter width)

ω_{cp} = 12.5 kg/m^2 (self-weight of composite panel)

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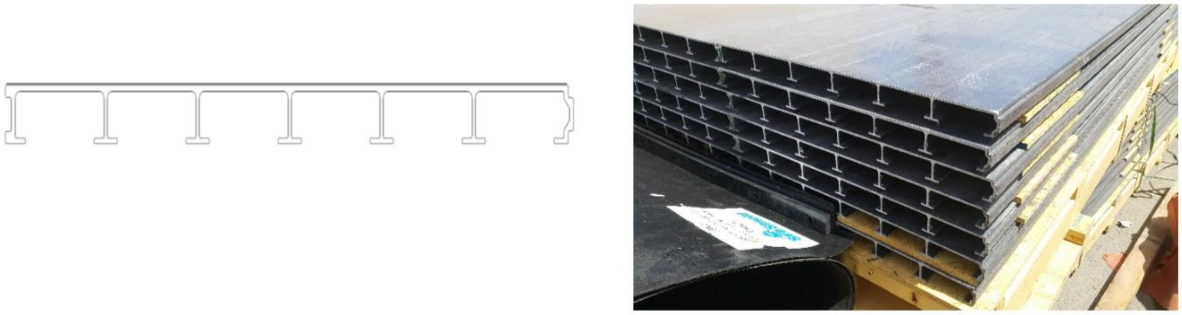


Figure 14b.
GFRP Pultruded panels.

3.5.2. Mechanical Properties

Table 1.
Mechanical properties of the "CPS" panels.

Property	ASTM		
Modulus of Elasticity	D790	20.7	GPa
Maximum Bearing Strength (LW)	D953	206.2	MPa

3.6. Composite Profiles Properties

3.6.1. Geometry

h = 254 mm (height of composite profile)

b = 70 mm (width of composite profile)

t = 12.7 mm (thickness of composite profile)

A_w = 45.0 E-4 m^2 (cross sectional area of composite profile)

W_y = 3.0 E-5 m^3 (section modulus around weak axis)

I_y = 1.59 E-6 m^4/m (moment of inertia around weak axis)

ω_{cb} = 8.84 kg/m (self-weight of composite profile per meter)

Figure 15.
GFRP U shape Beams.

ISSN: 2576-8484
Vol. 9, No. 4: 984-1007, 2025
DOI: 10.55214/25768484.v9i4.6146

3.6.2. Mechanical properties

Table 2.
Mechanical properties of GFRP U channel.

Property	ASTM		
Modulus of Elasticity	D790	19.3	GPa
Maximum Bearing Strength (LW)	D953	227.5	MPa

4. GFRP Pultruded Panels Design

4.1. Durability Design

- The "CPS" is designed to provide enhanced durability to existing sheet piles at aggressive seafront environments. The durability design principle is the introduction of a sustainable passivating layer protecting the steel of the sheet piles. This is formed by a concrete layer that develops a high alkaline environment that passivates the area, stops on-going corrosion and eliminates the risk of future corrosion of the sheet piles.
- In order to sustainably retain the alkalinity of the concrete layer, provision is taken so that carbonation of concrete is prohibited and the ingress of aggressive agents such as chloride ions is prevented. This is achieved by introducing a fiber reinforced polymer (FRP) outer layer that is formed by the composite panels. The panels are designed to be impermeable and at the same time durable both in corrosive and alkaline environment. This is achieved by the use of vinyl-ester resin matrix that results in a water absorption ratio of less than 0.6% per ASTM D570 and exhibits an excellent durability performance in alkaline environments. The FRP panels are also characterized by their excellent durability in corrosive environment. Overall, a sustainable impermeable outer layer is formed that protects the inner concrete layer from being carbonated or impregnated with chlorides.
- Proper detailing is essential for ensuring the long-term performance of the provided system. The concrete layer is reinforced in order to avoid shrinkage and cracking. Reinforcement is provided by a grid of FRP bars made of glass fibers and vinyl-ester resin, designed to resist corrosion and alkaline exposure. Moreover, steel dowels in the form of welded bended bars are used to assure adequate bonding over time between the concrete layer and the sheet piles under all possible in-plane or out-of-plane actions. Full contact is further enhanced by mechanically grinding the sheet piles surface prior to the start of the installation.
- The "CPS" utilizes composite panels that are designed in order to provide monolithic connection with the concrete layer through their fins and thus, the possibility of voids that may cause local crushing under the wave action is eliminated. Both the vertical joints between the panels and their support at the bottom steel angle are sealed by underwater epoxy resin in order to be fully impermeable. Any potential differential movement between the panels that would cause joint opening is prevented by the continuous horizontal FRP channel profiles that link the panels together and simultaneously fix them tightly to the sheet piles.

4.2. Structural Design

- The design is performed for the "CPS" with a height of 4.0 m that is extending from +0.0mCD to the level +4.0mCD. To the safe side, the calculations are valid for lower levels as well. The mid-supports of the composite panels against lateral loading is assured by external composite channel profiles that extend along the length of the sheet pile wall.
- The structural design for every element of the "CPS" is examined below.

4.2.1. Composite Panels Design

- The capacity of the composite panels to support the load of fresh concrete must be verified. For the purposes of this analysis, the uncured concrete is assumed to behave as a Newtonian fluid. The composite panels are simply supported at 4 points along their height by (a) the top and bottom steel angle beams and (b) the 2 linking intermediary composite channel beams. For the analysis of the second concreting phase, the termination level of the concrete of the first phase is considered a fixed support since concrete is cured prior to the initiation of the second phase. The adequacy of the supports in terms of strength and rigidity is verified as well.
- The average thickness of the concrete layer that is supported by the panels is determined by dividing a typical concrete cross sectional area between the panels and the sheet-pile by the equivalent length.

$$t_{average} = \frac{A}{L} = \frac{4016cm^2}{167cm} = 24cm$$

- The horizontal loading ($q_{conc.}$) applied from the uncured concrete to the panels follows a triangular distribution along the height.

$$q_{conc.} = w_{conc.} \cdot D$$

Where,

$w_{conc.}$: the uncured concrete load per square meter of panel

D : the concreting depth

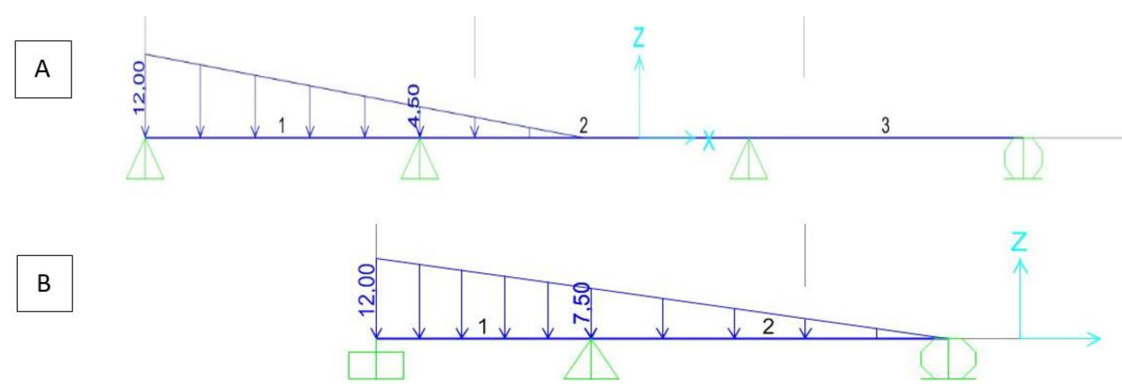
- The uncured concrete load per square meter of panel is defined as:

$$w_{conc.} = 25.0\frac{kN}{m^3} \cdot t_{average} = 6.0\ kN/m^2$$

- The maximum horizontal load per meter width at the base of the panels at each phase (D=2 m) is determined as:

$$q_{conc.\max} = 6.0\ kN/m^2 \cdot 2.0m = 12.0kN/m$$

- The exact load distribution along the height of the panels as well as the resulting moment diagram and the reactions at the supports at both concreting phases per meter width are presented below:



Loading Distribution (kN)

Edelweiss Applied Science and Technology
ISSN: 2576-8484
Vol. 9, No. 4: 984-1007, 2025
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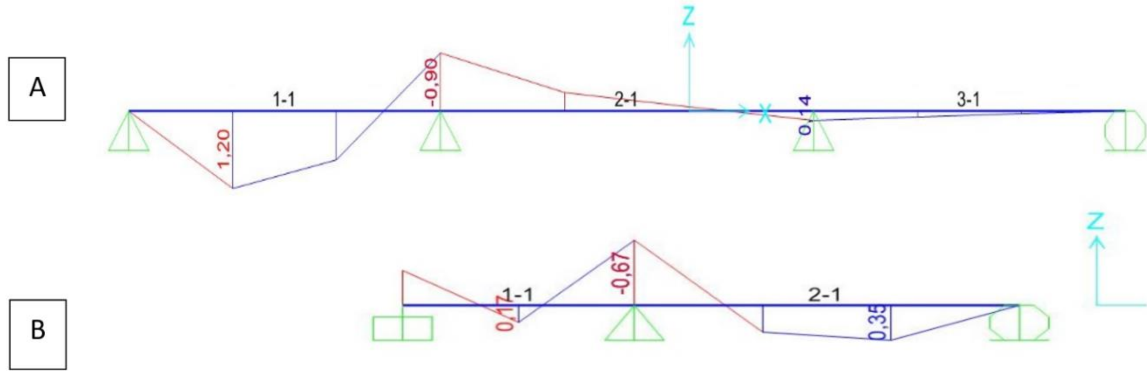
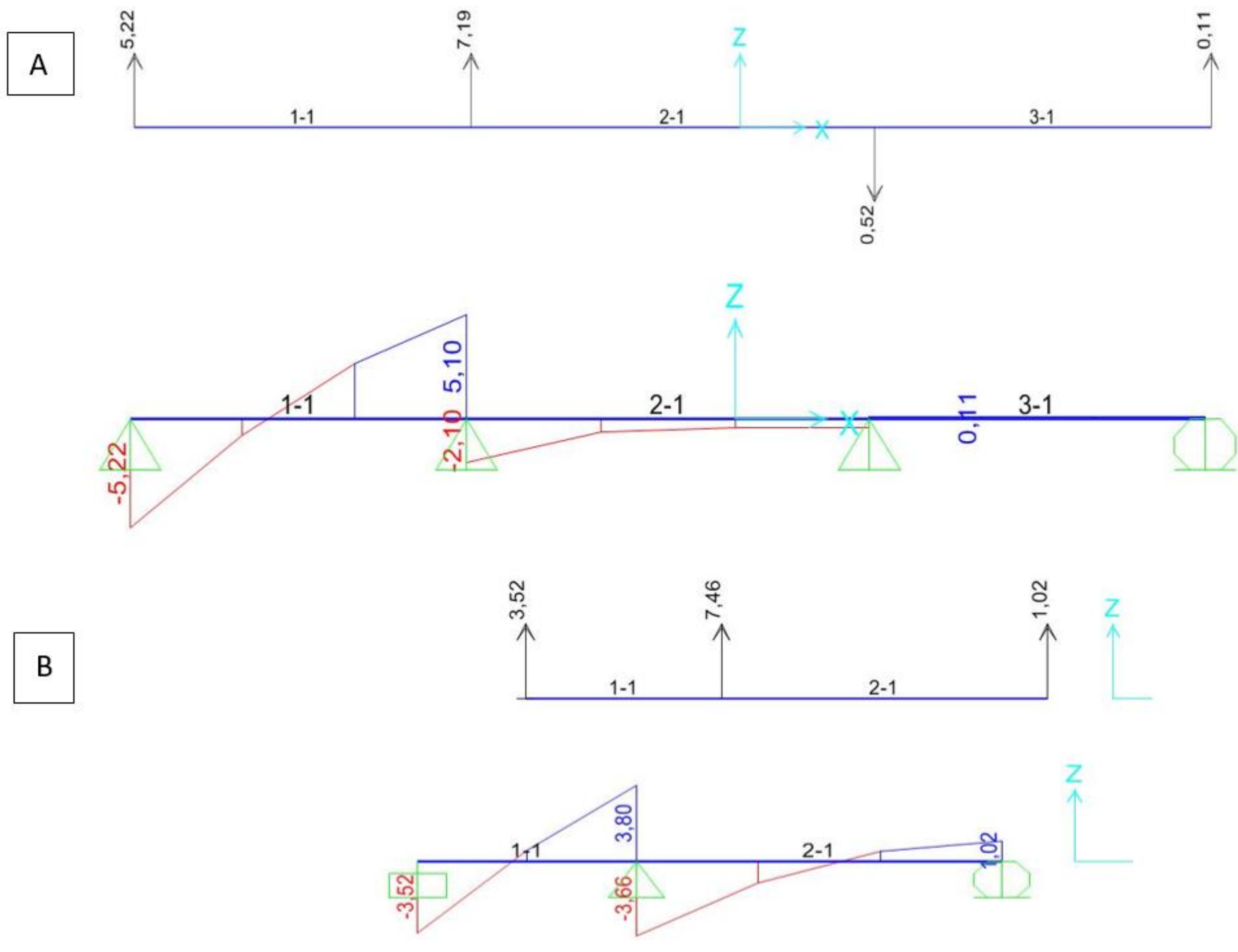


Moment Diagram (kNm)



Reaction and Shear Forces (kN)

Figure 16.
Composite panels design.

Edelweiss Applied Science and Technology
ISSN: 2576-8484
Vol. 9, No. 4: 984-1007, 2025
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- The moment capacity per meter width of the composite panels using a safety factor of 2.5 is defined as:

$$M_R = W_x \cdot \text{Maximum Bearing Strength} \cdot \frac{1}{\gamma} = 4.3E - 5\text{m}^3 \cdot 206.2\text{MPa} \cdot \frac{1}{2.5} = 3.5\text{kNm/m}$$

It is verified that the capacity of the composite panels is adequate to receive the maximum applied moment at the bottom of the panels equal to 1.2kNm/m.

The maximum out-of-plane deflection of the panels occurs during the first concreting phase at the bottom span and is equal to 0.0058 mm, which is acceptable.

4.2.2. Composite Channel Beams Design

- The supporting composite channel beams were verified for their adequacy to withstand the restraining loads defined by the panel analysis.
- Each composite channel section length is equal to 6.7 m, and is connected at 5 points, thus developing 4 spans equal to the distance between the fixations:1.67 m.
- The loading distribution as well as the resulting moment diagram and the reactions at the supports are presented below:

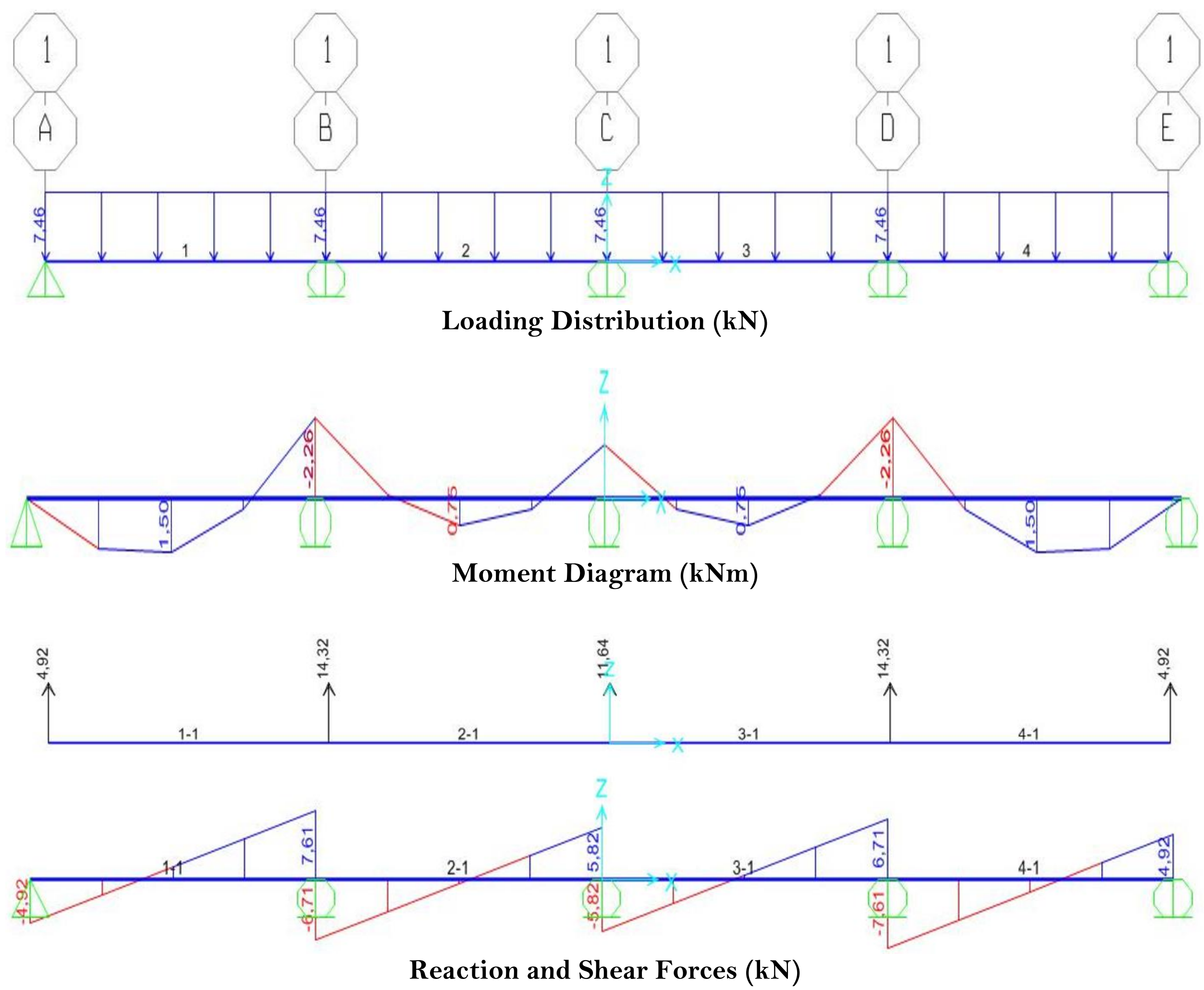

Figure 17.
Composite U channel design.

- The maximum moment capacity of the composite beams using a safety factor of 2.5 is defined as:

$$M_R = W_x \cdot \text{Maximum Bearing Strength} \cdot \frac{1}{\gamma} = 3.0E - 5\text{m}^3 \cdot 227{,}5\text{MPa} \cdot \frac{1}{2.5} = 2.73\text{kMm}$$

It has been verified that the capacity of the composite channel beams is adequate to withstand the maximum applied moment from the panels.

The calculated maximum deflection of the composite beams at the mid-span is 0.011 mm. Therefore, the proposed channel sections are considered rigid enough to support the composite panels.

4.2.3. Bolts Design

- To ensure safety, the bolts used to fix the steel channel columns to the king pile flanges are examined. The bolts must be adequate to withstand the tensile forces from the restraining loads of the supporting beams and the shear forces from part of the self-weight of the 'CPS.

The maximum tensile load requirement for a pair of bolts is determined from the higher intermediary support and is equal to:$F_{tens} = 14.32kN$

The maximum shear force acting on a pair of bolts is determined by the force generated by the self-weight of the 'CPS.' The total self-weight for the corresponding 1.67 m span between the fixations of the 'CPS' is equal to the self-weight of the concrete and is defined as:

$$F_{sw} = w_{conc.} \cdot \text{H} = 6.0\ kN/m^2 \cdot 4\text{m} \cdot 1.67\text{m} = 40\text{kN}$$

Assuming that the top support does not contribute to carrying the self-weight load, each fixation point formed by a pair of bolts is expected to withstand a shear force equal to:

$$F_{shear} = \frac{40kN}{3} = 13.33kN$$

- The ICC approved Hollo-Bolt type LHBM12 is used. This bolt can withstand a tensile load of 20.6 kN and a shear load of 17.3 kN under service and fatigue conditions. This bolt is able to withstand at service and under fatigue action a tensile load equal to 20.6kN and a shear load equal to 17.3kN.
- Two bolts are applied at every fixation point, thus the proposed bolts can resist the required actions with a big margin of safety. Appropriate length type of Hollo-Bolt needs to be selected in order to accommodate the full thickness of the steel channel columns and the king pile flange.

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Vol. 9, No. 4: 984-1007, 2025
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Figure 18.
Hollo Bolts.

5. Conclusion

This paper demonstrates the adequacy of the proposed 'CPS' in terms of its structural capacity and its ability to sustainably protect the existing bulkhead wall of the ATCL Marina in Lebanon against future degradation. The 'CPS' serves as a durable external protective barrier, capable of extending the bulkhead's service life by a minimum of 15 years, assuming no steel section loss occurs due to corrosion from the land side of the bulkhead wall.

Transparency:

The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

Copyright:

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