Ref. Ares(2024)6081460 - 27/08/2024

WHISPER

PV System for Bulk Carrier

Deliverable D2.2 – WP2

This project has received funding from the European Union's Horizon Europe research and innovation program under Grand Agreement Nr. 101096577.

UK Research and Innovation

Lloyd's Register is funded by UK Research and Innovation under project agreement Nr. 10065742.

Deliverable description

REPORT TITLE:	PV SYSTEM FOR BULK CARRIER			DISTRIBUTION: ☐ PUBLIC ☒ SENSITIVE
PROJECT:	WHISPER			
WORK PACKAGE	WP2	DELIVERABLE ID:	D2.2	

APPROVALS AND REVISION HISTORY:					
REV. NO	DATE	AUTHOR	REVIEWED	APPROVED	STATUS
01	2024-20-04	SOL			For internal review
02	2024-08-27	SOL			For publication

ABSTRACT:

Following the design phase described in Deliverable 1.5, various prototypes of the solar panels to be mounted on the cargo ship have been manufactured. Different substrate and different geometry were tested, together with developing (jointly with ANT) the mechanical fixing methods for a reliable installation on the ship deck. A first batch of solar panels was installed on MV Paolo Topic in March 2024, a cargo ship similar to the one where the Whisper demonstrator will be installed in the proceeding of the project. Preliminary data were gathered and after three months of navigation it was possible to study some issues related to the harsh environment and to proceed in improving the solar system and the installation methods to cope with such problems.

© Content from this report may be copied or used if WHISPER is acknowledged as the source of the content.

“Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or The European Climate, Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.”

List of Figures iii
List of Tables iv
List of abbreviation v
1 Introduction 2
2 Prototypes 3
2.1 Solar panels 3
2.2 Fixing 5
2.2.1 Fixing panel to the substrate 5
2.2.2 Fixing the substrate to the deck 6
3 Testing the structure 7
3.1 Remarks concerning the prototype installation 7
3.2 Static and dynamic trials 7
3.2.1 Static test on a streak sample 8
3.2.2 Static test on a sample until material failure 12
3.2.3 Single spot loads on the supporting panel 14
3.2.4 Water load on the supporting panel 16
3.2.5 Wind suction load on the supporting panel 17
3.3 Modal/dynamic trials 18
3.3.1 Results 22
3.4 Conclusions 25
4 Ship installation 27
4.1 Layout 27
4.2 Electric connections 27
4.3 Performance 31
5 Prototype failures inspection 33
6 Improvements 35

List of Figures

Figure 1: Three panels'' solution for the cargo vessel's solar module 3
Figure 2: Solar panels layout 3
Figure 3: Monopolar junction box 4
Figure 4: Modular structure made by panels, substrate, fixing frame 5
Figure 5: Application of solar panels on the substrate 5
Figure 6: Threaded stud 6
Figure 8: Standard configuration for flexural stiffness test method 9
Figure 9:Testing setup for the aluminium core-phenolic fabric pane 9
Figure 10: Testing setup for the aluminium core and skins panel 10
Figure 11: Testing setup for marine plywood panel 10
Figure 12: Bending test on different material specimens 11
Figure 13: Failure point for the aluminium core-phenolic fabric panel 12
Figure 14: Load increment on the aluminium panel 13
Figure 15: Failure test results on material specimen 13
Figure 16: Example of test with concentrated load 15
Figure 17: Spot load on the panel centre 16
Figure 18: Example of water load test 17
Figure 19: Wind suction load test 18
Figure 20: Data acquisition system scheme 20

Figure 21: Accelerometer equipment used for the marine plywood 21
Figure 22: Transducer and accelerometer equipment used fir the aluminium core phenolic infused fabric skins panels 21
Figure 23: Aluminium phenolic panel frequency 0 to 50 Hz range 22
Figure 24: Aluminium phenolic panel frequency 50 to 100 Hz range 23
Figure 25: Aluminium phenolic panel complete frequency range 23
Figure 26: Marine plywood panel frequency range 0 to 50 Hz 24
Figure 27: Marine plywood panel 50-100 Hz range 24
Figure 28: Marine plywood panel frequency range 0 to 50 Hz 25
Figure 29: Panel layout for the cargo ship hatch 27
Figure 30: Electric layout of half hatch 28
Figure 32: Installation of studs 29
Figure 33: Unpacking of solar panels on the ship deck 29
Figure 35: Final installation with all the interconnections covered by protective steel conduits 30
Figure 36: One week of production 31
Figure 38: MC4 connectors' damages 32
Figure 39: Mechanical damages 33
Figure 40: MC4 connector protector 34

List of Tables

Table 1: Single substrate electric characteristics 4
Table 2: Example of test done on plywood panel 14
Table 3: General characteristics review. Green indicates a positive characteristics while red is negative. 26

List of abbreviation

SOL	Solbian
ANT	ANT-Topic
LR	Lloyd's Register
CAN	CANOE
BOM	Bill Of Material
PV	Photovoltaic
MPPT	Maximum Power Point Tracking
WVTR	Water Vapour Transmission Rate
Wp	Watt peak
JB	Junction Boxes
MC4	The state of the art electric connector used in solar installation
MV	Motor Vessel
IHT	Impact Hammer Test
DAQ	Data Acquisition System
FRF	Frequency Response Function

1 Introduction

This document describes the manufacturing and testing of the solar panels and the mechanical fixing methods for the installation of the solar system on bulk carrier cargo ships.

2 Prototypes

In the design phase described in Deliverable 1.5 three proposals about the solar panels layout were discussed, namely a solution with three panels per substrate and a solution with two panels each substrate, where for “substrate” we mean a rigid sheet of material needed for the mechanical fixing of the solar system on the ship deck.

The idea to use a substrate is related to the need of a simple and robust installation, which could not be done by attaching the panels directly to the deck. In fact the simplest solution, with panels attached by adhesive on the deck, was not considered viable due to issue of resistance to waves and strong wind and also because of the choice to have a removable system, for maintenance.

2.1 Solar panels

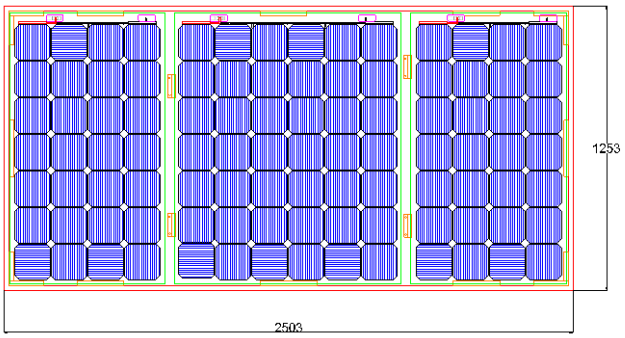


Figure 1: Three panels'' solution for the cargo vessel’s solar module

Even if the three panels solution shown in Figure 1 could look the less optimized for number of panels and electrical connections, at the time of realizing the prototypes, the available polymer rolls width were not enough to go to a two panels solution (max width about 1000 mm instead of the 1200 mm needed). Thus, to avoid delay, we decided to go with such solution, having in mind that change to larger panels would not constitute a fundamental change of the project.

The two types of solar panels needed to complete the configuration on the single substrate are shown in the following picture.

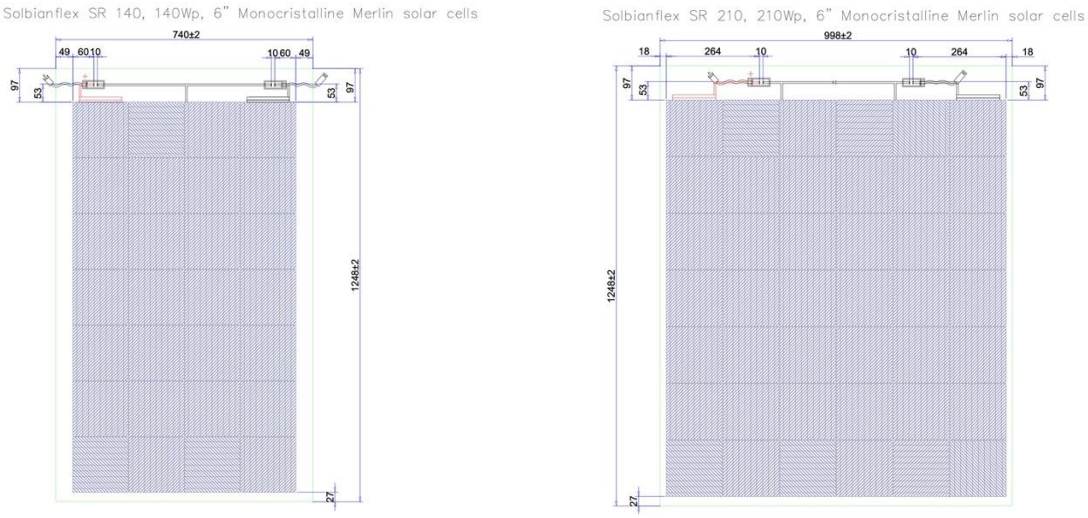


Figure 2: Solar panels layout

The electric data for a full substrate made by two SR140 and one SR210 panels are indicated in Table 1 below.

Table 1: Single substrate electric characteristics

Total number of cells	98 monocrystalline G1 cells
Pmax	492 W
Vmp	51.8 V
Imp	9.5 A
Voc	65.3 V
Isc	9.8 A

The electric connection of the solar panels is done by using single pole Junction Boxes (JB). In such a way, an easy in-line connection is possible, minimizing the complexity. The result is a substrate having the positive on the left and the negative on the right, both leads being close to the upper long side. That will facilitate the electric connection between nearby substrate on the same row.

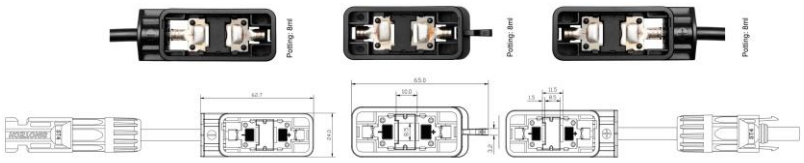


Figure 3: Monopolar junction box

Particular attention was paid to the sealing of the electric leads, envisaging the harsh environment condition related to the presence of salted water and strong wind (creating salted water spray). Each JB is attached on the panel surface by using a special mono-component silicon, suited for photovoltaic applications. A further measure was to seal completely the inside of the JB. In fact, this is a standard measure to reach an IP68 rating of the JB, which means they are water resistant in water to a maximum depth of 1.5 meters for up to 30 minutes, and are protected from dust.
Substrates

Among the available substrate we considered:

1. Fiberglass
2. Polypropylene honeycomb sandwich with epoxy skins
3. Aluminum honeycomb with aluminum or phenolic skins
4. Marine Plywood

Whatever the substrate, the need of fixing it on the deck leads to the design of a metallic frame with also the goal of reinforcing the substrate edges. A view of the substrate + panels + frame system is in the following picture (Figure 4).

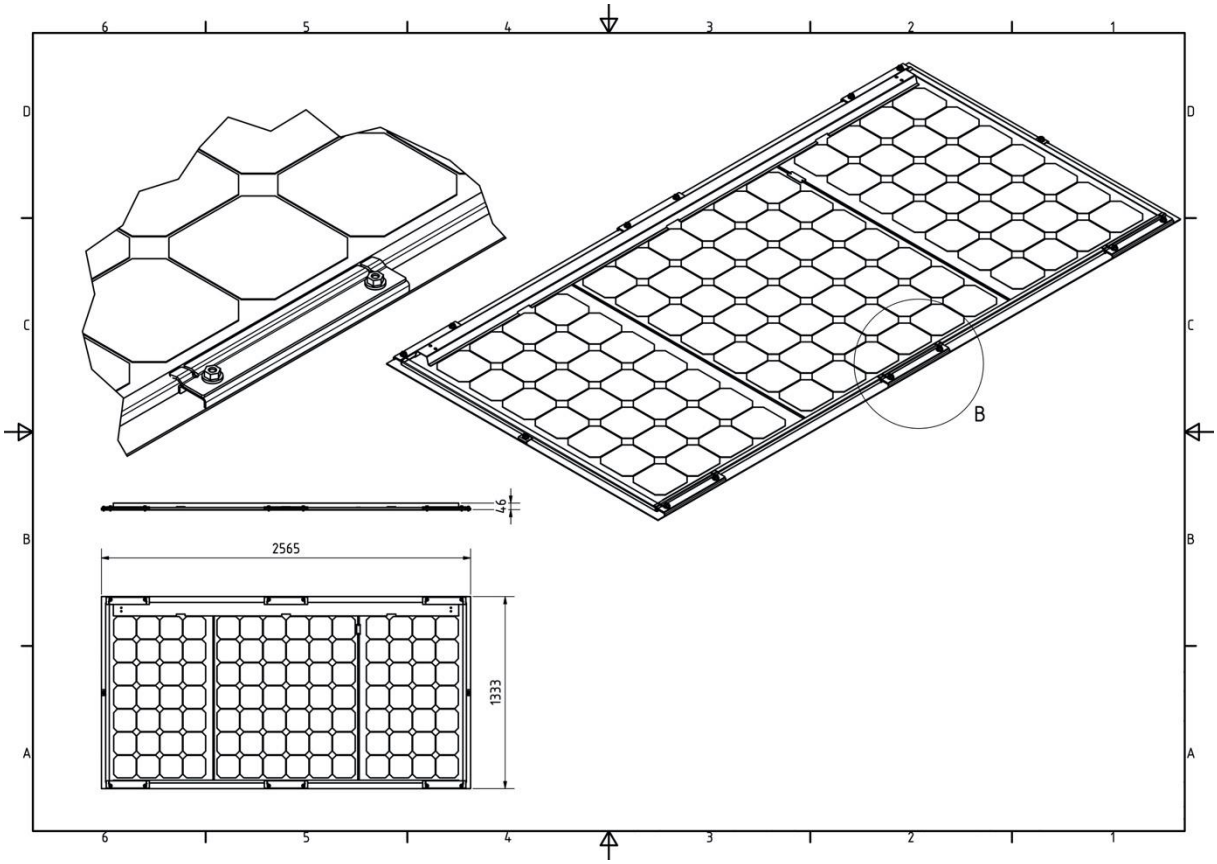


Figure 4: Modular structure made by panels, substrate, fixing frame

2.2 Fixing

The solar panels need to be fixed on the substrate and the substrate will be fixed on the ship deck.

2.2.1 Fixing panel to the substrate

To fix the panels on the substrate we followed various strategies by using both adhesive tape and glues (structural silicon, MS polymers etc.). The easiest and most promising in term of manufacturing and reliability is the solution with full area double side adhesive tape on the back. Figure 5 shows the application of panels on substrate.

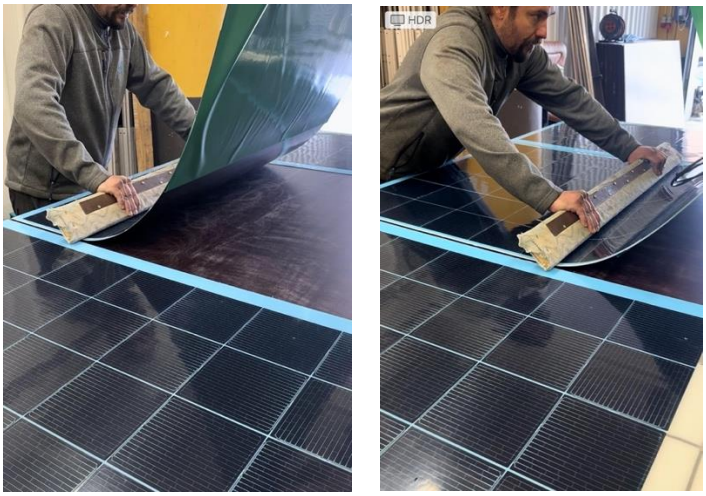


Figure 5: Application of solar panels on the substrate

2.2.2 Fixing the substrate to the deck

Mechanical fixing on the ship deck represents another important aspect of the project. The cargo ships are very heavy vessels. When loaded they are not able to ride the waves and so it is not uncommon that the upper deck is submerged by the water, especially close to the bow of the ship.

A first idea was to weld the steel structure reinforcing the substrate to the deck, but that would have prevented to create a removable solar system, thus other solutions were investigated. The best in term of costs and easiness of application resulted in using threaded studs (Figure 6) that are applied in the deck steel surface with a simple process of drilling and fastening.



Figure 6: Threaded stud

3 Testing the structure

3.1 Remarks concerning the prototype installation

The solar panels system is aimed at being installed on deck of ships that will sail some of the toughest oceans during their voyages; it thus required to be designed to endure aggressive weather loads, both for water on deck and for the wind suction action. Some accidental loads also need consideration, to replicate the damage that can be caused by the cargo hitting the panels during loading and unloading operations. Some targets are also required to comply with existing class regulations for most of the equipment but in some cases, it was necessary to define new ones when assessing characteristics for which the rules have not been written yet.

During the development of the prototyping process there has been a constant contact with Lloyd's Register, That provided input comments of critical importance as well as input for the risk analysis plan. The installation of the PV panel's structure is foreseen as bringing risk to the general safety of the crew on deck. Therefore, it was decided to have critical components comply with the safety regulations concerning bulk carriers.

One of the issues that was addressed is the compliance of the electrical components in marine environment on deck, which could result in incipient fires in case of flaws of the system. In case of a fire, there should be absolute certainty and reliance that the installation of the panels structure do not interfere with the structural integrity of the hatch cover structure because bulk carriers are designed to load all kinds of goods, including dangerous and flammable cargo into the holds.

Another addressed issue was the possibility of a critical failure of the panels in case of strong gusts of wind or heavy waves on deck. The busted parts of the panels frame could become dangerous objects on deck, jeopardizing the safety of the crew.

The tests that have been carried out at the laboratory of the University of Trieste have been carefully chosen in order to strictly relate to the structural requirements that the frame and supporting panel should comply with in order not to break under the loads of wind and water. There are no defined rules for the applications of supporting structure for PV panels on deck yet, therefore, the tests relied on the wind and water loads that can be calculated from LR Regulations for bulk carriers.

Following the basic comments of the register regarding the issues to be addressed during the development of the prototype, the main loads that will affect the frame and structure have been defined. In particular, some key loads to be considered for the structure design have been introduced, such as the Green Sea load, the static load concerning the weight of the panel itself, the dynamic load caused by the accelerations on deck, the wind forces acting on the panel (both the suction force and the wind load in respect to the windage area), and lastly, the allowable stresses that the frame and structure should endure. The loads that have been studied had to be calculated for the specific case considered during the test, therefore the results have been obtained by using Lloyd's Register rules for bulk carriers. Meanwhile, the frame and structure of the prototype must be reliable and strong enough to endure the combined load of all of the above, in order to verify its strength assuming the worst possible working condition.

3.2 Static and dynamic trials

Given the targets that have been set for testing during development and engineering some specific testing procedures have been defined to meet the targets. Intending to assess the flexural and compression resistance of the support panel, it has been decided to carry out some static tests by loading a section of the panel with some static loads and check how much each different panel material is going to deflect under the load pressure. Then, another test concerning the flexibility of the whole panel has been carried out, by fixing the metal structure to the ground and loading it with

weights equal to a standard weight of a person. Further, the deflection of the panel related to the wind suction was measured and assessed. A dynamic test has later been suggested, to better understand which natural frequencies the panels will have, and finally a destructive test was performed to assess the indentation and compression resistance of each panel.

In particular, the following tests have been executed:

1. *Bending test on material samples:*

The test is for assessing the deflection of different materials applying pressure with a span of loads acting on an area as big as the footprint of a standard human. The panel rested on two supports that were spread apart as much as the supports on the widest bay under each solar panel on the supporting structure. The different selection of loads applied define different deflections.

2. *Bending test on the whole panel, human, water and wind load deflection:*

This test was carried out by fixing the metal supporting structure to the ground through the side bracings and by inserting the support panel with the solar panels side facing upwards replicating the installation that will happen onboard. The structure was then loaded with human load and accidental loads from green water condition and checked for breaking, damage and deflection.

3. *Bending test on the whole panel, wind suction:*

The supporting structure was tested by turning the support panel upside down and loading the bottom of the panel which was facing upwards with the wind load defined by the regulations. The structure was then fixed by the sides at a certain height from the ground, leaving space for the whole support panel to bend under the applied load. Such operation represented the effect of the wind suction load when the structure is on the hatch covers.

4. *Dynamic test, modal testing:*

In a similar way as for the bending test for the accidental load of the water, the metal structure is fixed through the side frame supports to the ground, and then hit with a small hammer. The assessment test determines the natural frequencies of the supporting panel, suggesting how it would react to the ship's main vibrations. The natural frequencies that would interfere with the ship's main vibrations could cause stress and critical damage due to fatigue on the weak links of the metal frame, or even damage the electrical equipment linked with the solar panel.

5. *Indentation test:*

The last test performed is a destructive test to assess the panel's resistance to scratching and compression by an accidental load hitting the panel during the loading and unloading operations for the cargo in the holds. The different materials for panels were tested with a round spiked plate that will be loaded with an increasing weight, representing the accidental load that could hit the sides of the hatchcover during the cargo operations. The results assess how much the spiked plate has damaged the support panel, and even if the solar panels on the other side of the support panel have been affected.

3.2.1 Static test on a streak sample

This simple but crucial test has been carried out following the specific standard method tests referenced in the spec sheets of the sandwich panels that have been used during this work.

The aim of the test is to evaluate the core shear strength of the material and to determine the sandwich flexural stiffness. In light of this, the most significant output value of the tests would be the highest applicable load until failure of the material. In case of material failure, the supporting panel could break into smaller pieces and be carried by the wind as a dangerous object for the crew on deck. The safety of the whole structure was the main concern during the prototyping process. The flexural stiffness has been tested using the guidelines to be found in [1] thanks to which the testing procedure and the material specimen dimensions have been defined.

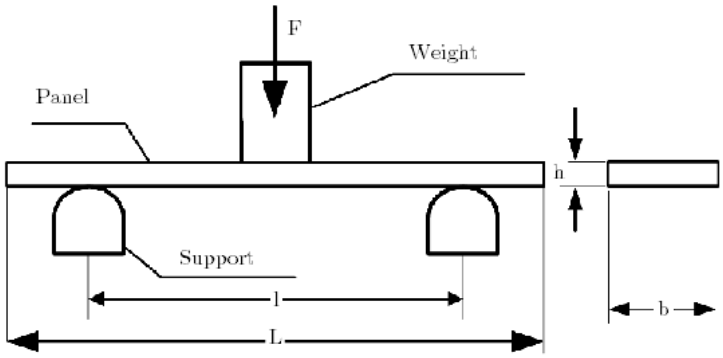


Figure 8: Standard configuration for flexural stiffness test method

The material specimen is requested to be rectangular in cross section, the depth of the specimen shall be equal to the thickness of the sandwich construction, and the width shall be not less than twice the total thickness, not less than three times the dimension of a core cell, nor greater than one half the span length. The specimen length shall be equal to the span length plus 50 mm, or plus one half the sandwich thickness whichever is greater. The span length is identified by the distance between the two contact points on the support side of the specimen, which in this specific case will have a properly defined value. The span length that has been chosen for the material flexural assessment in this work corresponds to the longest span between the supports of the photovoltaic panel structure. The widest span would be equal to the width of the supporting panel onto which the loads will be placed. Having set the span under the specimen material, the remaining geometry particulars have been set following [1]the guidelines provided by the standard method test. The testing configuration for all of the sample streaks of choice is presented in Figure 9, Figure 10 and Figure 11.

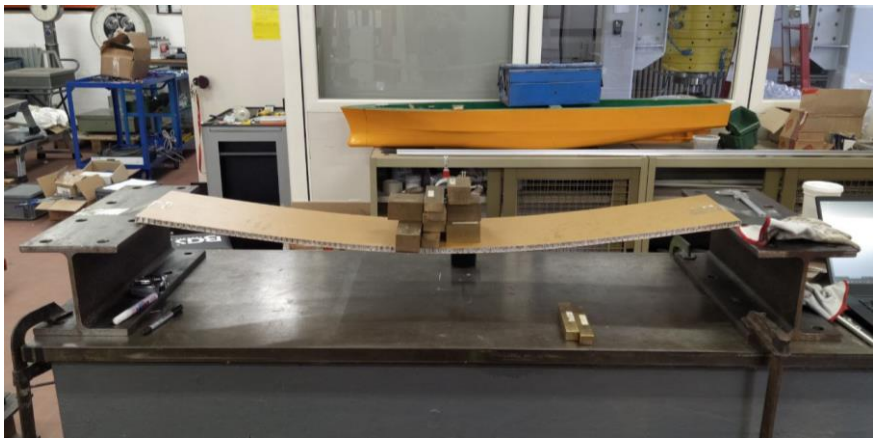


Figure 9:Testing setup for the aluminium core-phenolic fabric pane

1 A. International and files indexed by mero, “Standard Test Method for Flexural Properties of Sandwich Constructions 1,” pp. 1–4.



Figure 10: Testing setup for the aluminium core and skins panel

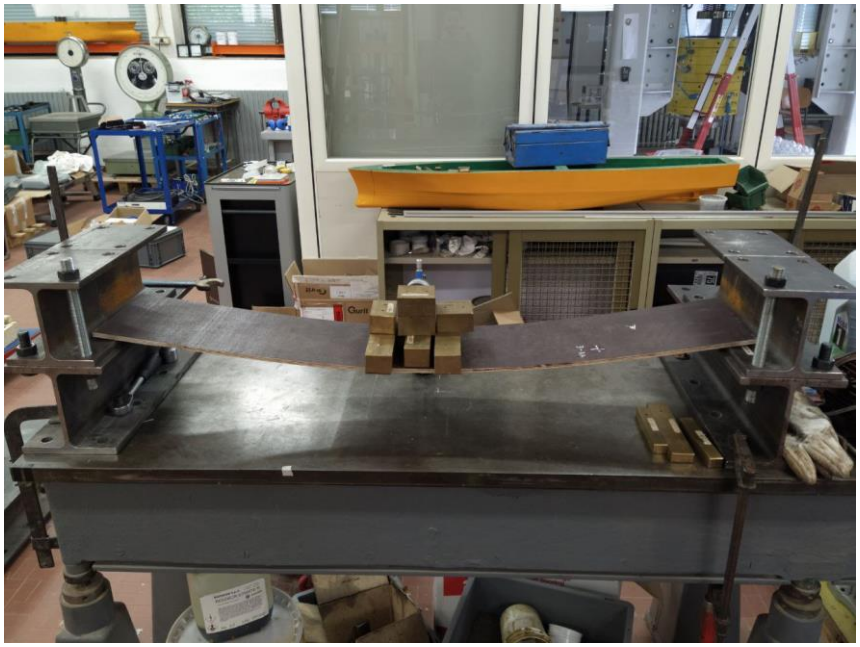


Figure 11: Testing setup for marine plywood panel

During the flexural stiffness assessment, all of the proposed materials for the supporting panel have been tested, however more attention has been given to the two materials which will later result in being more suitable for the final choice, namely the marine plywood and the aluminium core - fibre phenolic resin one. At every iteration of the test on different materials, the specimen has been loaded with pre-measured weights (the loads used have all been weighted and measured with standard equipment beforehand), until the breaking point or weakening point in case of the aluminium. This means that for every weight added, there has been a verification of the actual return to the initial resting position of the specimen. In case of a bend found in the resting position after an added weight, the test has been stopped since the material would have been damaged if more load was applied. For every weight added, the deflection of the streak sample has been registered on the data sheet, together with the total load applied. The deflection of the specimen has been measured using a linear comparator gauge-stand set that has been placed at the middle of the specimen, where the deflection would have had its maximum over the span of the supports. The comparator gauge has been

zeroed using the initial resting position of the streak sample on the supports, and then re-positioned and re-zeroed whenever the deflection of the material would have exceeded the maximum range of the gauge. The maximum deflection of the material streak sample is going to be defined as the sum of the deflections obtained in each iteration of the testing procedure.
The total deflection at each weight added to the total load on the specimen has been registered on the testing data sheet therefore, the results are proposed in graphs showing the deflection trend of each material versus the load applied on the streak sample. References to be found in [2], the Standard Test Method for Flexural Properties of Sandwich Constructions.
The results obtained from this specific test were significant when choosing the final material for the supporting panel, they will provide a clear estimation on the flexibility of the panel material until the breaking point. The prototype that will be installed onboard will be most likely put under constant stress by wind and water thus, the resulting flection of the panel under these frequent loads will be determined by the flexural stiffness of the panel and its failure point.

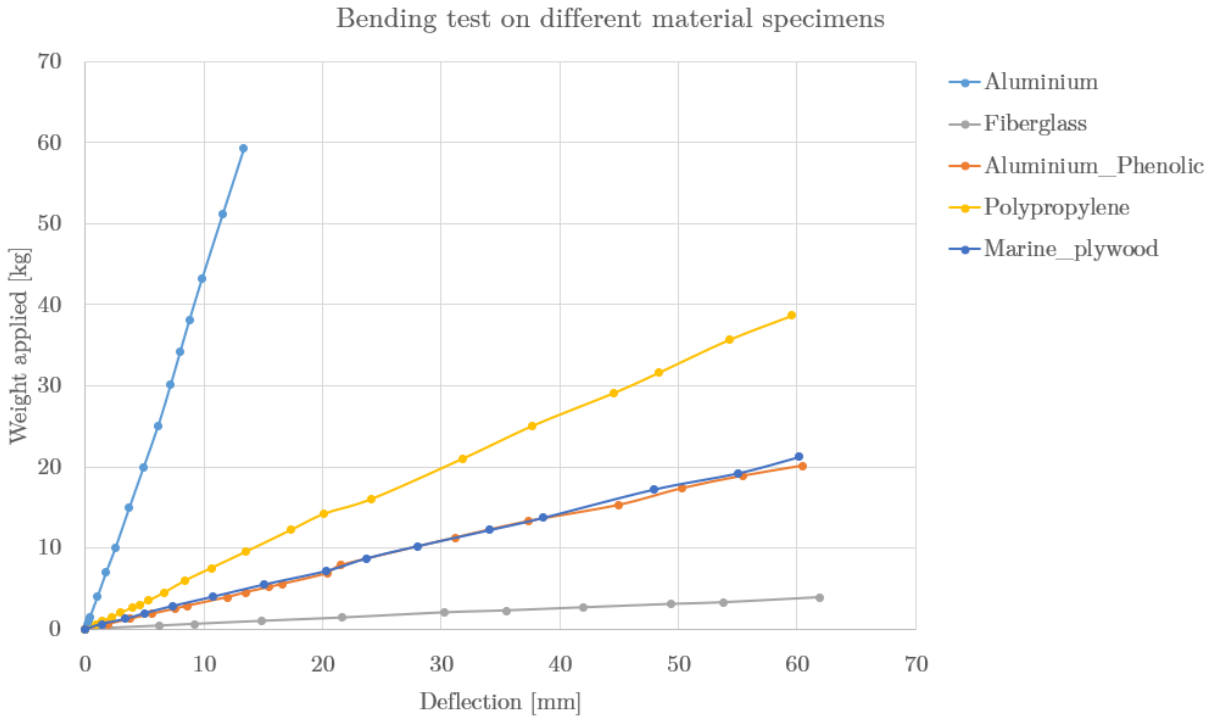


Figure 12: Bending test on different material specimens

The comparison of the different flexural responses of the materials can be seen in the above graph. The elastic deflection of different materials under the load of the weights applied can be clearly visualized. A maximum of 60mm as upper limit for the deflection was chosen in order to safely work in the elastic range of the materials.

The lower the angle of the lines, the higher the flexibility of the material and therefore lower the stiffness of the material. It can be seen that there are some significant differences between the full aluminium sandwich panel and the other materials, where the aluminium has a much higher resistance to bending and it is capable of carrying much higher loads without showing noticeable deflection. On the other hand, the full plastic reinforced with fiberglass panel is the most flexible and elastic one, but it deflects with minimal weight and is therefore not appropriate for use as the “holding” structure for

2 A. International and files indexed by mero, “Standard Test Method for Flexural Properties of Sandwich Constructions 1,” pp. 1–4

the PV panels on board the vessel. On the other hand, polypropylene, marine plywood and aluminium phenolic panels are mostly a compromise between elastic properties and toughness, providing good support for the load and allowing enough flexibility. In conclusion and from the result of this test it was decided that the two materials worth to be further tested on the complete structure with the metal frame mounted on same were marine plywood and aluminium core-phenolic impregnated fabric skins, since they showed very similar flexural behavior, good elastic and flexural properties until 20kg applied.

3.2.2 Static test on a sample until material failure

The different materials have been also tested on the same configuration presented above but with increased load until material failure. The testing procedure has been carried out for every type of panel/material previously presented. The aim of this specific test was to understand at which load the weight applied would exceed the pulling and compression resistance on the specimen surface and on the core of the panel in case of sandwich structure. At every iteration of the test for each material the weight has been constantly increased and carefully added on top of the panel streak. The weights used were previously measured and listed as testing equipment. The load has been increased until structural failure of the specimen, clearly demonstrating how the aluminium panel was by far the most capable of load carrying in terms of flexural and pulling stiffness. The testing process and procedure can be seen through the figures below, showing the failure point of each material under the static load applied.

The comparison between the several sample streaks provides an accurate review on which choice could be the favourite for the on-board installation. The failure point test is of notable importance since the breaking of the supporting panel into smaller pieces on the installation onboard would have the most critical consequence regarding the safety of the crew onboard. If the supporting panel breaks during the voyage, the smaller pieces could be dangerously carried by the wind on deck of the bulk carrier.

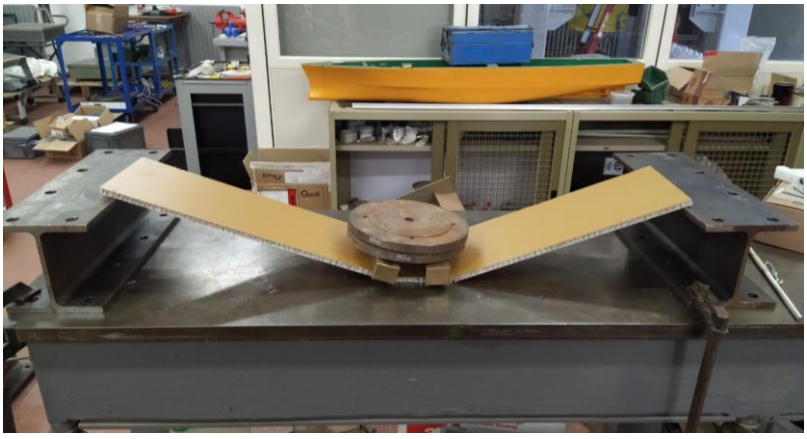


Figure 13: Failure point for the aluminium core-phenolic fabric panel

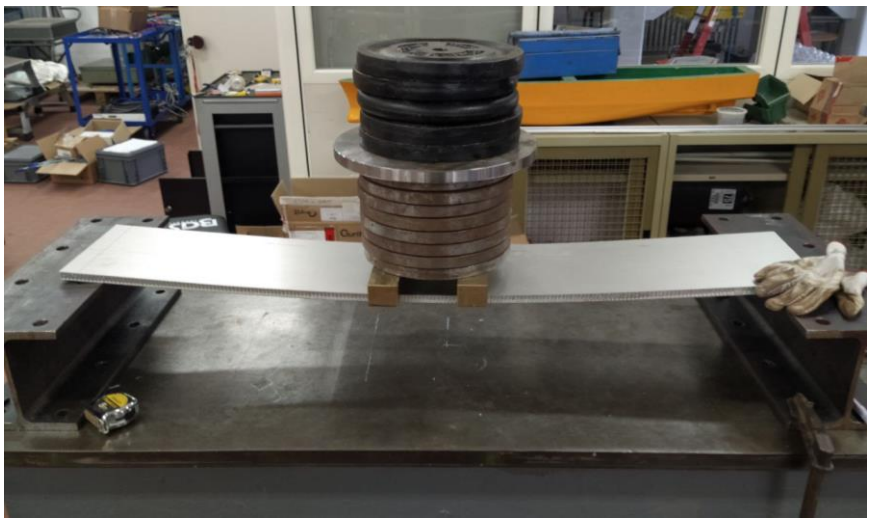


Figure 14: Load increment on the aluminium panel

The comparison for the load to failure test has been proposed in the graph below, the curves show the flexural capabilities of each material until its critical failure point is reached.

The yellow curve represents the behaviour of fiberglass panel that did not reach the critical structural failure, but instead it flexed, almost up to 90 degrees, at which point the test was stopped. On the other hand, the full aluminium sandwich panel demonstrated to be the one with the highest toughness, carrying up a load equal to 210kg before reaching the critical structural failure of the panel. This result is of course remarkable compared to the behaviour of other materials. The other three materials and especially the two chosen for further testing, namely marine plywood (blue curve) and aluminium core-phenolic impregnated fabric skins (orange curve) have similar behaviour but quite different failure points. The marine plywood has better flexural properties, providing higher deflection before critical failure and being capable of carry more weight compared to the aluminium-phenolic panel, which has a more rigid and less tough nature. This panel showed an early breaking point when subject to the test, due to the pulling force failure of the phenolic impregnated fabric skins, which did not provide much support in the flexural resistance.

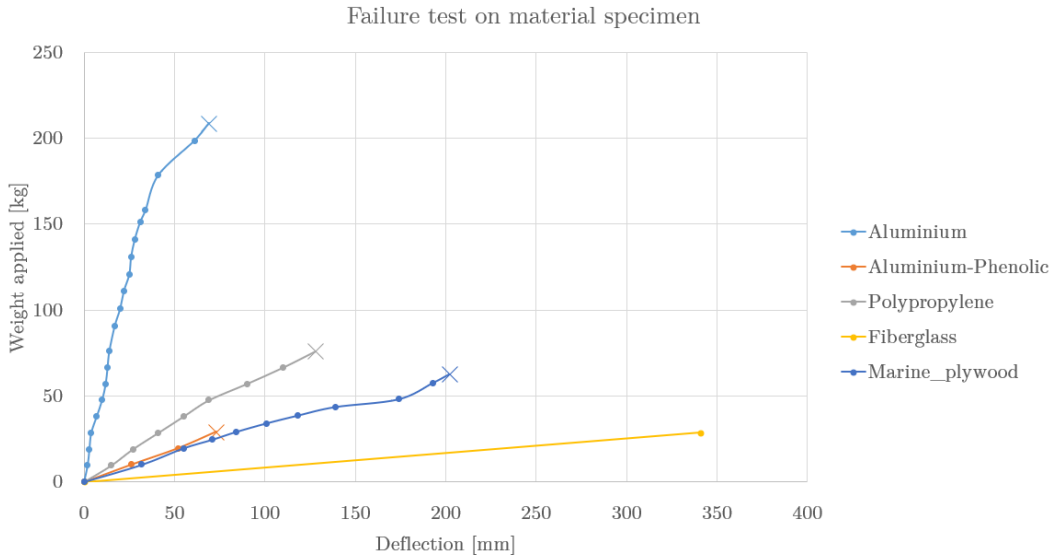


Figure 15: Failure test results on material specimen

Table 2: Example of test done on plywood panel

Iteration n°	Weight [kg]	Deflection [mm]
1	0	0
2	10.033	32
3	19.573	55
4	24.618	71
5	29.083	84
6	34.128	101
7	38.583	118
8	43.628	139
9	48.103	174
10	57.603	193
11	62.643	break

3.2.3 Single spot loads on the supporting panel

Since the panels are installed on the hatch cover of a bulk carrier, there will be the likelihood of occurrence having accidental loads damaging the supporting panels and also the need for the crew, who manages and maintains the photovoltaic panels system, to walk on top or on the sides of the panels without damaging them. Therefore, the supporting panel has been tested with concentrated loads on different parts of the surface of the panel at the configuration in which it will be found during cargo operations (see Figure 16). The weights with which the panels have been tested vary from 0 up to 200kg, representing the presence of some equipment or the weight of at least two people walking on the panel.

The testing procedure has been developed in an iterative manner, increasing the weight applied on the panel and constantly assessing the deflection of the supporting panel under the load. There has also been an assessment of additional accidental damages caused to the metal frame of the system. The testing configuration has contemplated two different positions for the weight to be applied on, the central part of the panel as well as the side part of the panel, which would bring different behavior in the flexural response of the panel. The aim of this specific test was to assess the damage caused by heavy concentrated load on the panel, if any, and possible structural failures of the metal frame.

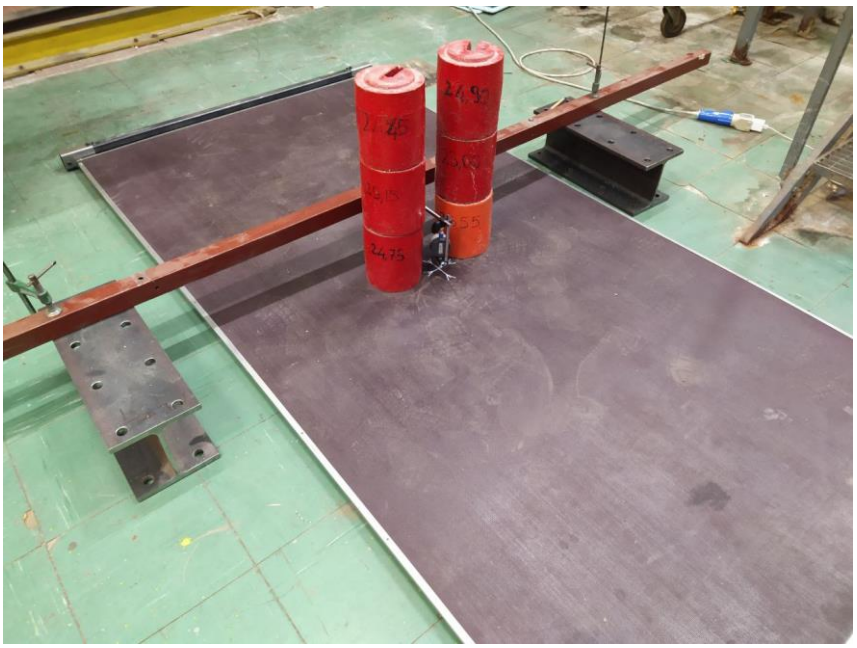


Figure 16: Example of test with concentrated load

For this test, the aluminium-phenolic panel and plywood panel were selected, since they demonstrated the best compromise in performance from the two previous tests. The single spot load test was executed to assess the performance of the two chosen materials for the complete structure test in case of equipment resting on the panel or a person walking on the panel.

The results displayed in the graphs below show the effects of the weight during the weight increase and even during the weight decrease, to test the eventual permanent deformation of the panel. There are prominent differences between the behavior of the two materials and even between the two loading conditions, the side loading point generated a higher deflection compared to the center loading point.

It seems clear from the graphs that there is an overall better flexural response from the marine plywood panel, which in both cases has generated a lower deflection under the loading conditions compared to the aluminium-phenolic panel. In particular, it is notable to point out that on the side load configuration, the aluminium-phenolic panel was resting on the floor during the last two measurements therefore, displaying a vertical line corresponding to the maximum deflection available between the panel and the floor. The metal supports separating the panels from the floors were 26.4mm tall, which is corresponding to the highest deflection at the side of the aluminium-phenolic panel.

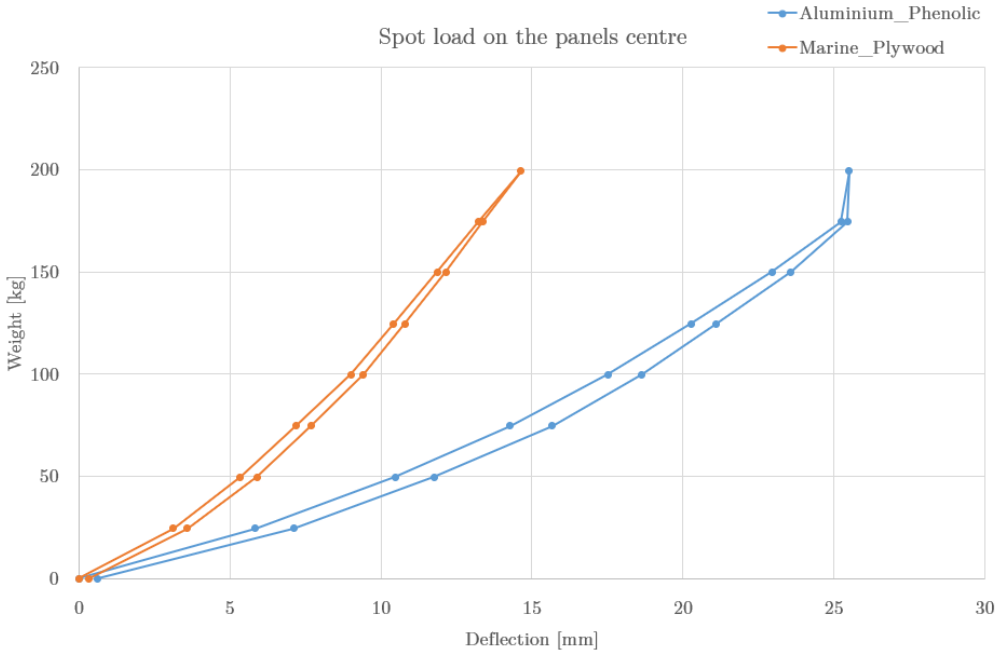


Figure 17: Spot load on the panel centre

3.2.4 Water load on the supporting panel

The photovoltaic panel structure prototype to be installed on deck of the bulk carriers, which are ocean-going vessels, needs to be strong enough to withstand harsh weather and high seas during operation. By far the largest load that can be applied to the supporting panel structure is going to be the sea water surging on deck, the result of the sea waves with considerable significant wave height.

In this test the green water load has been considered, which accounts for a maximum water column on deck, paired to the dynamic motion of the water surging on deck. The load that has been considered is in compliance with the Lloyd's Register regulations [3] & [4] for the green water load for the hatchcover design. The supporting structure of the PV panels being fixed to the surfaces of the hatchcover must withstand equal loads to the hatchcover structure.

The water pressure load to apply is truly consistent therefore, the supporting structure was tested in compliance with the capability of the laboratory infrastructure and equipment. Being the water load applied to the upper side of the panel configuration, meaning the surface of the supporting panel not carrying the photovoltaic panels, the testing configuration reflects the real operational setup for the supporting structure.

During the testing phase, the metal frame and the side metal guides have been fixed to the ground and the supporting panel has been blocked in the resting position inside the metal guides. The testing procedure has been developed by iterations, increasing the weight applied to the panel surface and constantly checking the behavior and signs of damages. Special attention has been also paid to accidental damages that could have been caused to the metal frame.

3 LLoyd's Register, "Rules and Regulations for the Classification of Ships," *Not. No. 9*, no. July, p. 1156, 2020

4 Lloyd's Register CSR, "RULES FOR BUILDING AND CLASSING Common Structural Rules for Bulk Carriers and Oil Tankers," no. July 2012, 2020.

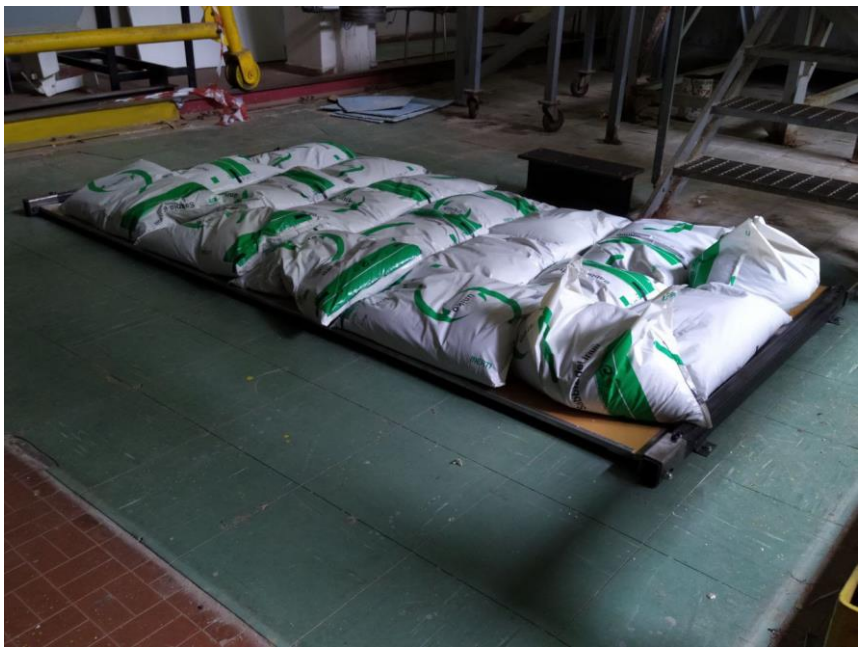


Figure 18: Example of water load test

The testing procedure has been defined in a way to reproduce the most distributed configuration of weights possible, representing the uniform water pressure acting on the structure. The weights used were previously measured therefore the total applied weight could be achieved with a considerable accuracy. The weights used for simulation were made out of sandbags and some other additional weights, which, once applied, have covered the complete surface area of the supporting panel. The total weight applied has been verified in compliance with the Lloyd's Register regulations [5]. The water load test was performed onto the two chosen panels (marine plywood and aluminium core-phenolic impregnated fabric skins). The aim of this specific test was to identify weak points in the supporting structure and to verify if the two proposed supporting structures would fail and/or deform under the load of the water load. The maximum load that has been applied to the prototype structure is 1100 kg of measured weights available at the facility.
In both cases, the effects of the uniform load applied were not in any way permanently damaging for the supporting panel. With the load applied on the upper side of the panels, they both gradually deflected toward the ground lightly resting on it when applying the last 100kg to the weight on top. Thus, the behavior expectations when higher load will be applied could refer to a similar condition, where the two materials would gradually flex towards the ground or towards the hatch cover surface in the application on board the vessel.

3.2.5 Wind suction load on the supporting panel

Another critical test important to assess the durability of the panel onboard under extremely stressing conditions is the flexural stiffness test for the whole structure under the maximum wind suction pressure.

In this specific instance, the panel would be pulled upwards by the lower pressure generated by the wind wiping the surface of the panel, therefore, the panel test has been set to replicate the actual operational conditions onboard. The supporting panel has been suspended only by its side metal guides on stands that have been fixed to the floor and during this testing the supporting panel was

5 Lloyd's Register CSR, "RULES FOR BUILDING AND CLASSING Common Structural Rules for Bulk Carriers and Oil Tankers," no. July 2012, 2020

loaded with some weights to replicate the wind suction load. The stands on which the metal guides were fixed needed to be properly fixed in order to resist to the pulling force during the simulation of wind suction load. During the loading of the structures, at every increase in load there has been a constant inspection of the testing structure and the supporting panel to notice accidental damages or even structure failures before adding some more load. The testing procedure has been defined in a way to reproduce the most distributed configuration of weights possible, representing the uniform wind pressure acting on the structure. The weights used were previously measured, therefore the total applied weight could be achieved with a considerable accuracy. For instance, the first layer of weights used were made out of sand bags which have covered the complete surface area of the supporting panel. The total weight applied has been verified in compliance with the Lloyd's Register regulations. The aim of this specific test was to identify weak points in the supporting structure and to verify if the two proposed supporting structures would fail under the load of the wind suction in case of harsh weather or storms with gusts of wind up to 12 Beaufort. The test was carried out for the two chosen panels (marine plywood and aluminium core-phenolic impregnated fabric skins).



Figure 19: Wind suction load test

The test was successful for both the materials which have endured the load applied and have not been subject to any critical structural failure. There has been however noticed permanent deformation happening in both the panels after the load was lifted, as it is shown in Figure 19. The permanent deformation was much more prominent in the aluminium-phenolic panel compared to the marine plywood one. This is suggesting that the aluminium core of the aluminium-phenolic panels has been suffering from plastic deformation during the test.

It must also be pointed out that the permanent bend on the two panels is strongly related to the permanent plastic deformation of the metal guides of the contour of the panel.

3.3 Modal/dynamic trials

Almost all vibration problems are related to structural weaknesses, associated with resonance behaviour which is natural frequencies being excited by operational forces. It can be shown that

the complete dynamic behaviour of a structure (in a given frequency range) can be viewed as a set of individual modes of vibration, each having a characteristic natural frequency, damping, and mode shape. By applying the modal parameters and performing the modal testing, problems at specific resonances can be examined and subsequently solved. The modal testing consists of an acquisition phase and an analysis phase where the acquisition phase requires an input data obtained through an impact hammer and an output data acquired through accelerometers fixed to the tested structure. The analysis phase will determine the response frequencies of the structure by extrapolating the peaks from the frequency response function graph, narrowing down specific range of frequencies at every analysis iteration.

The classic Impact Hammer Test that has been mostly used in this test can give a solution to find economically, quickly, and accurately, the main dynamical properties governing the behaviour of small and medium structures. It cannot substitute the commercial tools, rigorous but complex and expensive, used to characterize the dynamic properties of structures. The structure tested is the steel frame to which the supporting panel and the PV panels are fixed.

As the Impact Hammer Test (IHT) belongs to methods where the input is measured (here the hammer load), the results representation is mainly done using the transfer function process between the input and output. The output could be measured by accelerometer, velocity, or displacement transducers at the own choice of the test engineer. The classical hammer impact uses the reciprocity of the frequency response function (FRF) to conduct the tests with an important number of outputs, requiring calibration tests for the input load of the hammer. The signal processing is performed step by step in an automatic way. The main criteria to validate the results are the use of the coherence function in a very compact form, which simplify the task without disturbing the signals content. The main assumptions in the chronologic process are:

- The FRF noise level
- The accepted coherence threshold value, it can be changed by the operator.
- Damping and frequency values extracted from the FRFs are interpolated, and magnitude balanced, in the half power band method used for the automatic extraction.

In spite of all above and there might be some limitations other than the structure dimensions and the input energy, such as the accuracy of the transfer function reciprocity property used to capture the measurement process and, on the other hand, the incapacity of the modal extraction procedure, which is based on the peak peaking method, to isolate modes very closed, leading to operational deflection shape instead of pure mode shapes.

The modal testing has been carried out at the University of Trieste using equipment provided by the Ship Noise and Vibrations laboratory.

The main components necessary for the testing procedure are the input components to generate the impulse, the output devices to read the impulse passed through the testing material and the signal analyzer to identify and sort the various signals from the inputs and outputs (see Figure 20). The equipment used for the modal testing is similar to a Data Acquisition System (DAQ) equipment, which is used in every data acquisition test. The modal test performed for this work was a data acquisition test in regard to the response frequencies of the supporting structure for the PV panels. The test determined which ship vibrations would cause a resonant response in the supporting structure, managing the data output from the transducers fixed on the supporting panel.

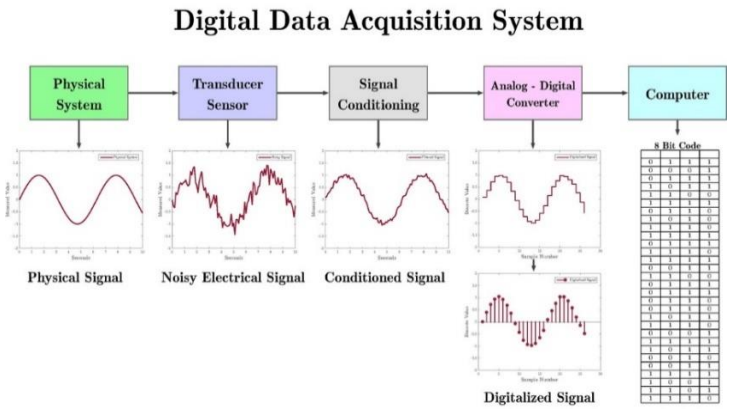


Figure 20: Data acquisition system scheme

As input equipment fixed on the physical system, a calibrated hammer has been used, featuring a transducer behind its contact point and directly connected to the computer via the signal analyzer. The output signal will be provided by some transducers which are carefully fixed on the testing material before-hand, in a way to maximize the field of vibration modes observable thanks to the modal analysis. The accelerometers are made out of a piezoelectric material, which will transform mechanical energy from the panel's vibration into electrical impulses. The electric impulse will then be sent to a signal reader to be processed. The signal analyzer will then read the signal sent by the panel attached transducers, in particular the signal analyzer will also condition the signal input from the transducers and convert it from analogic to digital, to be suitable for the DAQ software.

The results will then be assessed using the frequency response function (FRF) versus frequency graph. The FRF will be independent from the input signal since it has been defined as the output signal of a single accelerometer divided by the input signal of the hammer transducer. If the test has been carried out within the linear range of the material (linear is referring to the structural response of the supporting panel material being tested), then the results shall be comparable with each other, providing final proof of the dynamic behavior of each of the choices also displaying the intensity of the frequency response on each test. In this work the main concern of the test was to provide with the natural frequencies the complete supporting structures for the photovoltaic panels in order to reflect as much as possible to the vibrations present on the ship, which are causing fatigue damage on the installation.

At the beginning of the test, some parameters on the modal testing software have been set, such as trigger, a threshold and other sampling details like the sampling frequency and the sampling range. The details were needed to decrease the statistical human error of the hammer manually used. The hammer is needed to impress a specific impulse on the panel, which will result in vibrations that will be then recognized by the accelerometers.

The testing procedure has requested first to set specific reading points for the accelerometers on the material and then to define the point where the impulse of the hammer could have given the best performance out of the transducer's readings. In order to find the most accurate position on where to hit the panel with the hammer, the software's coherence function has been used. This, provides a clear sight on the similarity of the impulses of the various hammer hits. Moreover, the hammer hit was executed as close as possible to the point where the vibrations would be transmitted in the real application. The positioning of the actual accelerometers has been set to maximize the number of vibration modes registered by same during the hammer's impulse. After various iterations, the best performance configuration has been decided and the panel has been raised from the ground floor and suspended only by the side metal guides. This specific configuration gave the chance to better isolate the natural frequencies over a noisy signal, without changing the actual frequencies (Hz) of the natural frequencies. The hammer strike was more effective if applied directly on the supporting

panel therefore, the strike could be as light as possible, assuring the linear behavior of the panel's material. Every structure has been tested with multiple hammer-accelerometer readings, and the final result was calculated as the mean FRF signal within the signal collection and displayed against the frequencies. The chosen configuration and the testing procedure for the aluminium core- phenolic infused fabric skins and the marine plywood are shown in the figures below (Figure 21, Figure 22) representing the actual testing procedures.

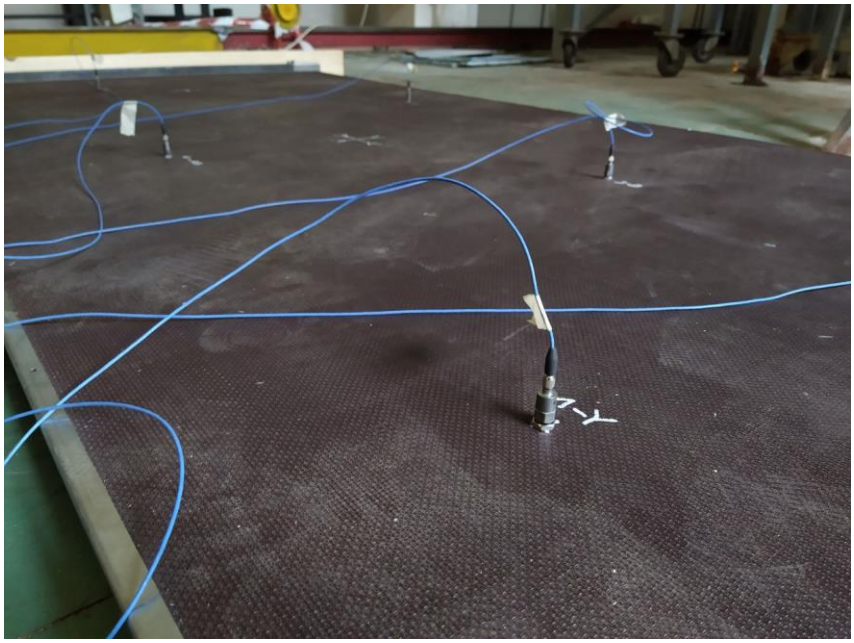


Figure 21: Accelerometer equipment used for the marine plywood

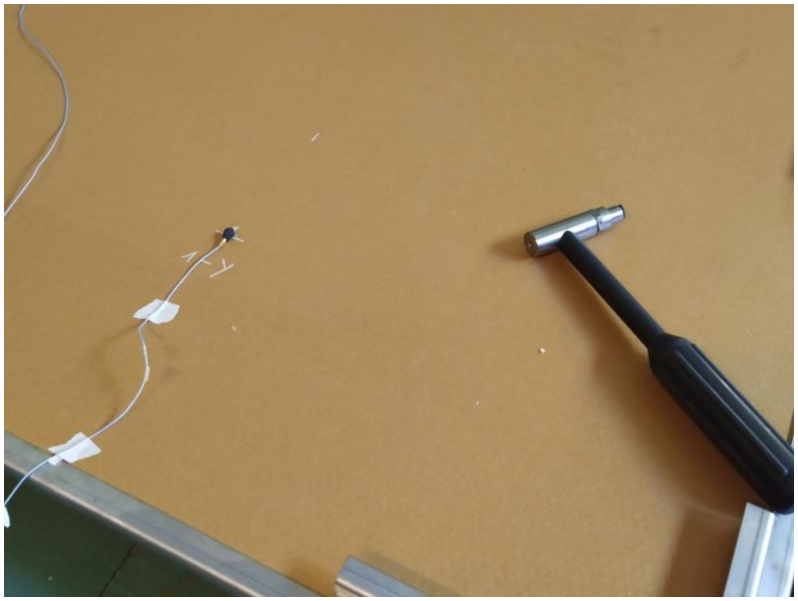


Figure 22: Transducer and accelerometer equipment used fir the aluminium core phenolic infused fabric skins panels

3.3.1 Results

The modal tests carried out in this work provided an early display of the dynamic behavior of the materials tested. The results in the below graphs, show the response frequency functions from which the natural frequencies of each configuration have been extrapolated.

1. Aluminium core – phenolic impregnated fabric skins

Figure 23, Figure 24 and Figure 25 display the dynamic response of the aluminium-phenolic material over a frequency range from 0 to 250 *Hz,* which includes the most common vibrations found onboard from the machinery generated vibrations, to the propeller passing frequencies and in particular the sea waves related frequencies that will be defined up to 5 *Hz*. The tests on the aluminium-phenolic panel are displaying a fair amount of sharp peaks in the 0 to 50 Hz range of the function; this range also contains the corresponding sea waves generated vibrations. It is important to point out that the magnitude of these response is almost 10 dB higher than the one in the same range of the marine plywood panel.

There are some other sharp peaks in the interval within 50 to 100 *Hz* which will be significant in real application due to their relative magnitude. A higher magnitude of the response function will result in a larger resonant vibration of the panel when externally excited.

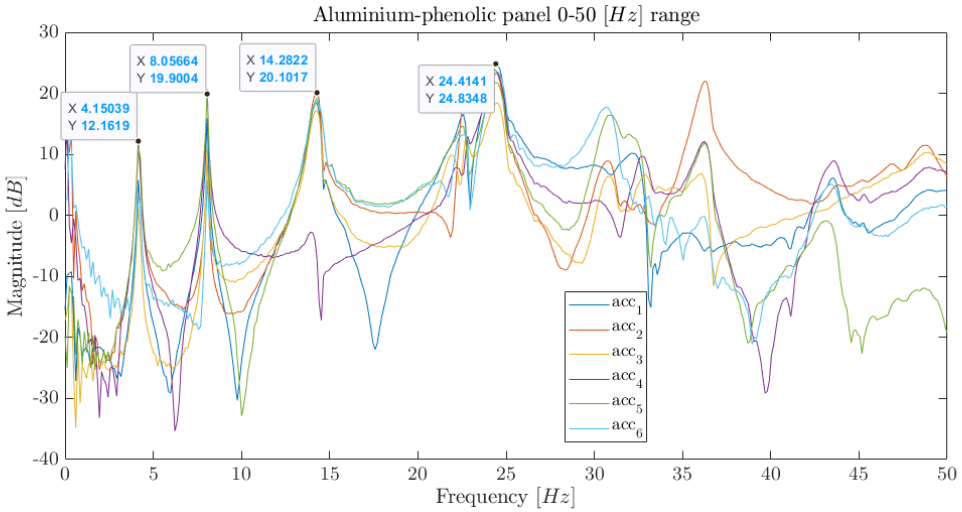


Figure 23: Aluminium phenolic panel frequency 0 to 50 Hz range

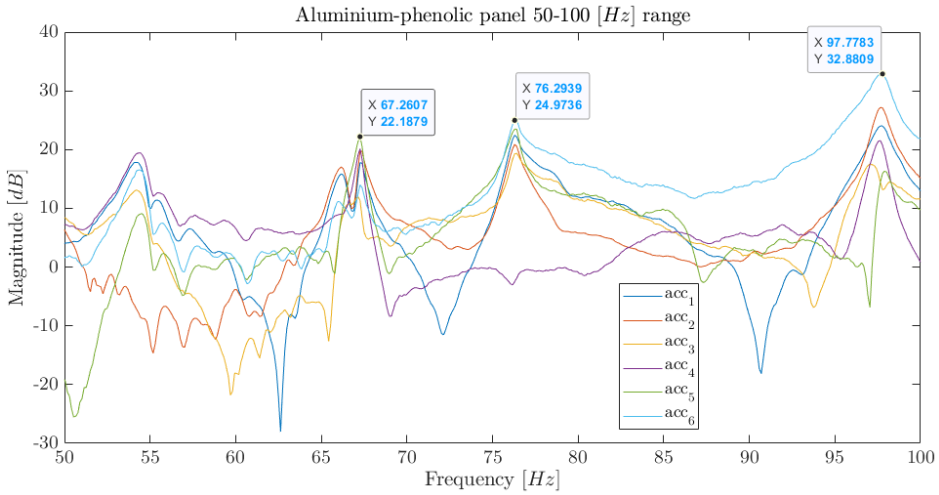


Figure 24: Aluminium phenolic panel frequency 50 to 100 Hz range

In the figure below, which is displaying the whole range of frequencies assessed, the trend of the response functions is demonstrating that the aluminium-panel will have a more rigid nature because of a higher number of natural frequencies compared to the marine plywood. In addition, it will also have lower dampening properties because there are sharp peaks throughout the whole frequency range, and in case dampened they will have less magnitude and will be less visible/noticeable.

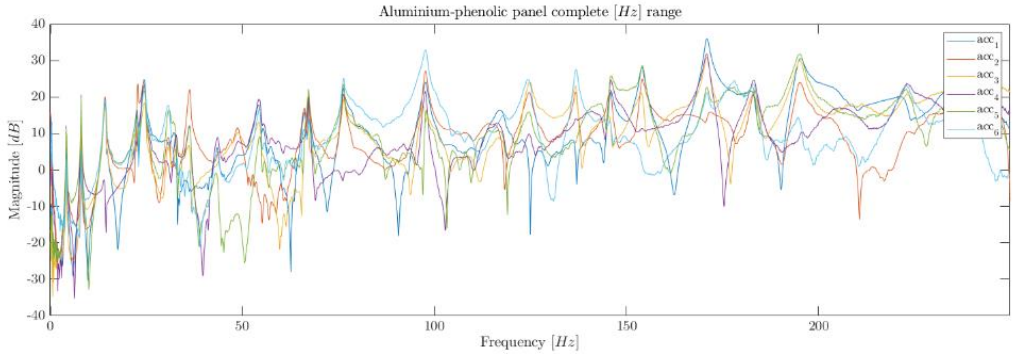


Figure 25: Aluminium phenolic panel complete frequency range

2. Marine plywood panel

The graphs below are displaying the dynamic response of the marine plywood material over a frequency range from 0 to 250 *Hz*.

Compared to the aluminium-phenolic material, the marine plywood panel is displaying less sharp peaks in the 0 to 50 range of the function, which also contains the corresponding sea waves generated vibrations. Notable to point out and as already mentioned before, is the magnitude of these response, that are almost 10 dB lower than the one in the same range of the aluminium-phenolic panel.

There are no other noticeable peaks within the 50 to 100 *Hz* which are surely an advantage when comparing to the performances of other material, in addition to an overall lower magnitude of the function. A lower magnitude of the response function will result in a smaller resonant vibration of the panel when externally excited.

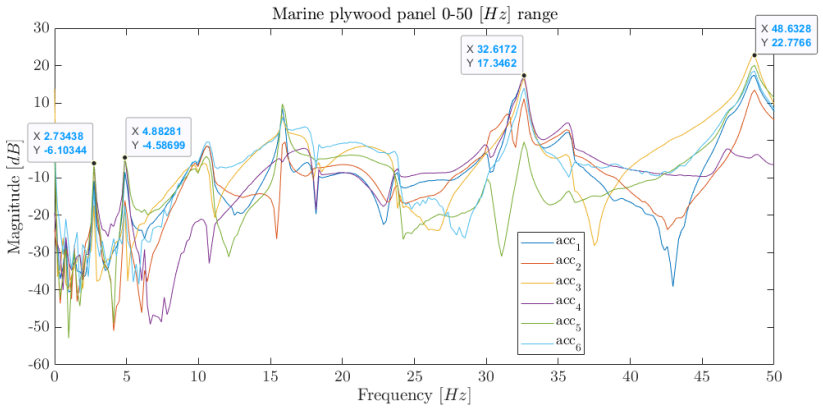


Figure 26: Marine plywood panel frequency range 0 to 50 Hz

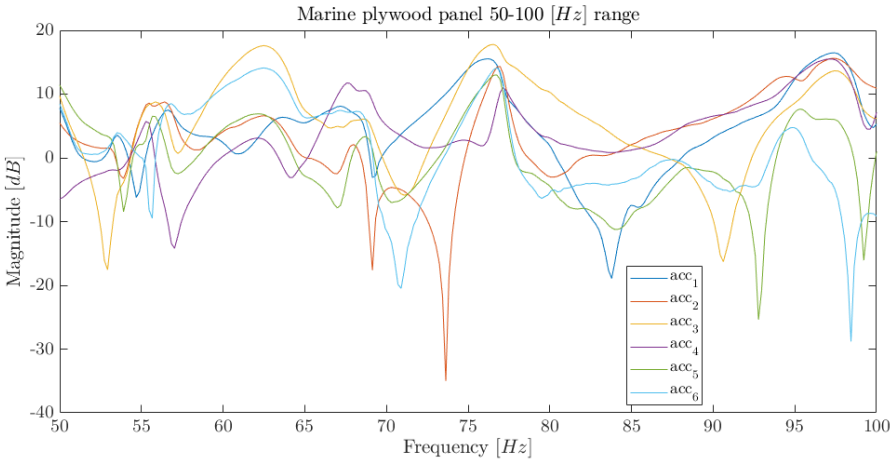


Figure 27: Marine plywood panel 50-100 Hz range

In the figure displaying the whole range of frequencies assessed, the trend of the response functions is demonstrating that the marine plywood material will have a more flexible nature having less natural frequencies compared to the aluminium-phenolic one. Lastly, the marine plywood will also have much more prominent dampening properties as shown in graph for the whole frequency range, since there are no other sharp peaks throughout the whole frequency range. The nature of the marine plywood material has a higher/stronger dampening effect compared to the aluminium core of the other panel, affecting the response functions curves by flattening them and lowering their relative magnitude.

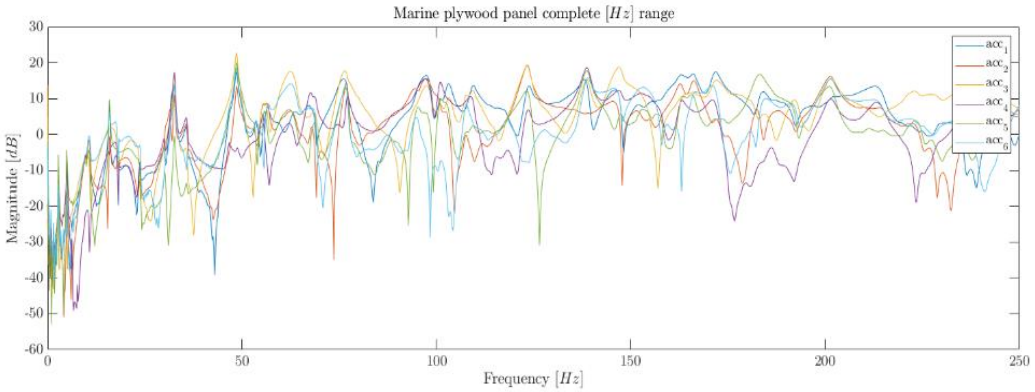


Figure 28: Marine plywood panel frequency range 0 to 50 Hz

3.4 Conclusions

The aim of the work carried out in the laboratory was mainly to assess the structural properties of different materials for the supporting panel of the PV prototype.

The tests have been performed with the aim of understanding the different properties and behaviors of the materials as potential choice for the supporting panels of PV system.

Five panels from different materials have been considered:

1. **Fiberglass panel;**
2. **Polypropylene honeycomb sandwich with epoxy skins;**
3. **Aluminium honeycomb with aluminium skins;**
4. **Aluminium honeycomb with phenolic skins; and**
5. **Marine plywood panel.**

Some of the above listed materials, namely the first three, were excluded from further testing because of poor results from the first tests, namely bending test on the material's specimen, or even because of their poor fire retardant/resistant properties. Being the bulk carriers ships, built and certified to carry dangerous goods cargoes, fire retardant properties of the materials are very important. Therefore, only two of these materials have been selected for further tests with and without the supporting metal structure, namely the aluminium honeycomb core-phenolic resin impregnated skins and the marine plywood one. In the further testing these two type of panels were expected to endure water and wind uniform loads and to be subject to a modal testing procedure which would assess the dynamic response of the two different materials. As it emerges from the results the flexural properties of the panels when installed in the supporting metal frame configuration would see better behavior for the marine plywood panel compared to the aluminium-phenolic one. During the water load test the marine plywood performed better because of less deflection generated under the same load applied, where in the wind suction loading test the results were comparable, with both the panels enduring the weight applied without showing critical failures. The noticeable difference was in the permanent deformation on the aluminium-phenolic one, which was much more pronounced compared to the marine plywood. This last material demonstrated to be more flexible. The two panels were at last tested with modal testing equipment to determine the dynamic response of each material. The results show the increased flexibility of the marine plywood panel and its higher dampening properties when assessing the response frequencies. On the other hand, the aluminium-phenolic one manifested a more rigid nature, having more natural frequencies which could ultimately excite it and in addition to that resulted in having less dampening capabilities, therefore permitting higher vibrations when being externally excited.

Considering all the above and the results from the tests, the best performing material showed to be marine plywood. In addition to that, if we consider also the availability of the material and the cost of the supporting panel, then the marine plywood is definitely the best choice. The only negative aspect that the use of marine plywood as supporting panel for PV panels brings with is the increased weight compared to the aluminium phenolic panel, since it is 3 to 4 times heavier and therefore it is quite in important impact. Nevertheless, when considering all pros and cons, the marine plywood is still resulting in being the best choice.

The criteria for the choice of the marine plywood can be resumed in the following table, where the main characteristics of the substrate are reviewed. It is clear that some of them are more important than others. For example, while weight is important but an heavier solution can be accepted, if in the range of manual handling capability, a too high price would prevent the system to be economically viable

Table 3: General characteristics review. Green indicates a positive characteristics while red is negative.

	Cost	Mechanical resistance	Fire resistance	Deformation recovery	Resistance to corrosion	Weight
Fiberglass	high	high	medium	high	high	medium
PP honeycomb	medium	medium	low	medium	high	low
AL honeycomb	high	medium	high	low	low	low
Plywood	**low**	**high**	**medium**	**high**	**high**	**high**

4 Ship installation

For the validation of the prototypes we chose to do a partial installation on the bow hatch of the MV Paolo Topic, a sister vessel of the one which will host the full scale installation as referred in Task 4.2. The installation was done in two phases, constrained by the ship availability, in the first quarter of 2024. In the first phase the ship crew prepared the hatch with the HILTI studs for the mechanical fixing and the prototypes were sent on the ship. Later, on March 2024, at Huston, the installation was completed together with the electric system and became fully functional.

4.1 Layout

The general layout of a solar system covering a full hatch was already discussed in Deliverable 2.2, where geometric and electric considerations lead to the following configuration for the hatch:

.

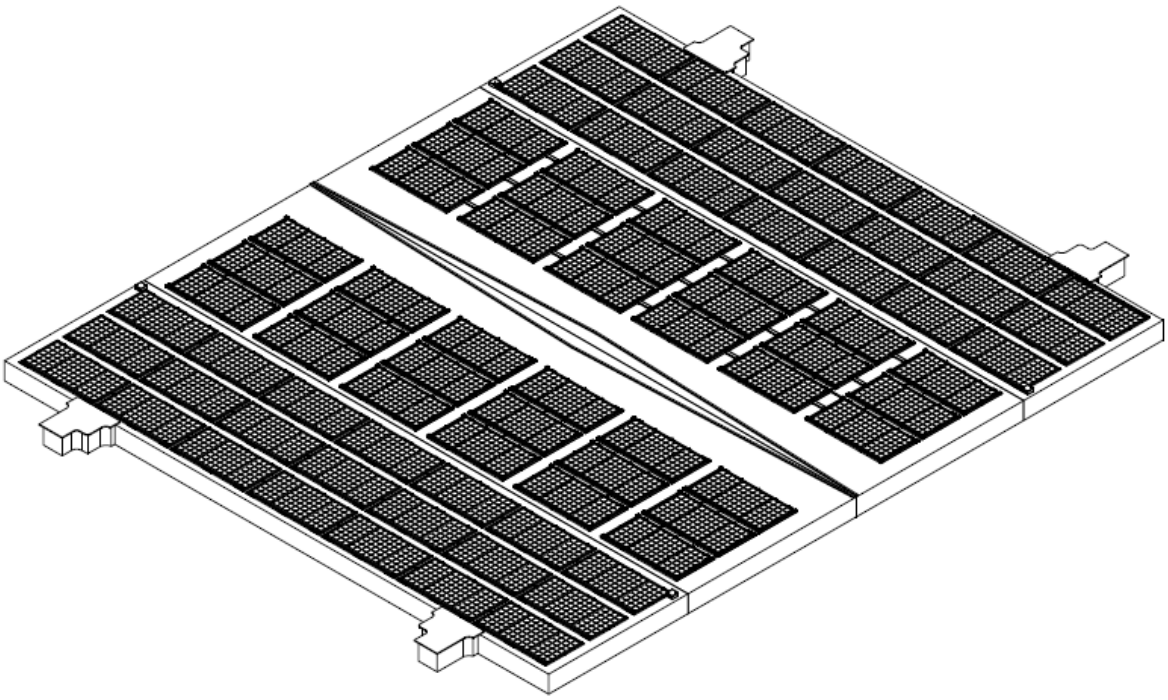


Figure 29: Panel layout for the cargo ship hatch

The goal of the prototype was to install the twenty-one panels, which correspond to the first three rows starting from the edge.

4.2 Electric connections

A general scheme for the electric connection is shown in the following figure. The idea is to create strings of panels connected in series from one side to the hatch to the other side. In such a way all the positive cables will run on one side and the same for the negative on the other side. The picture shows half of the bow first hatch cover. The red lines indicate the series connection of the panels. The blue lines show 3-wires conduit and the green indicates conduits where 6 wires are running.

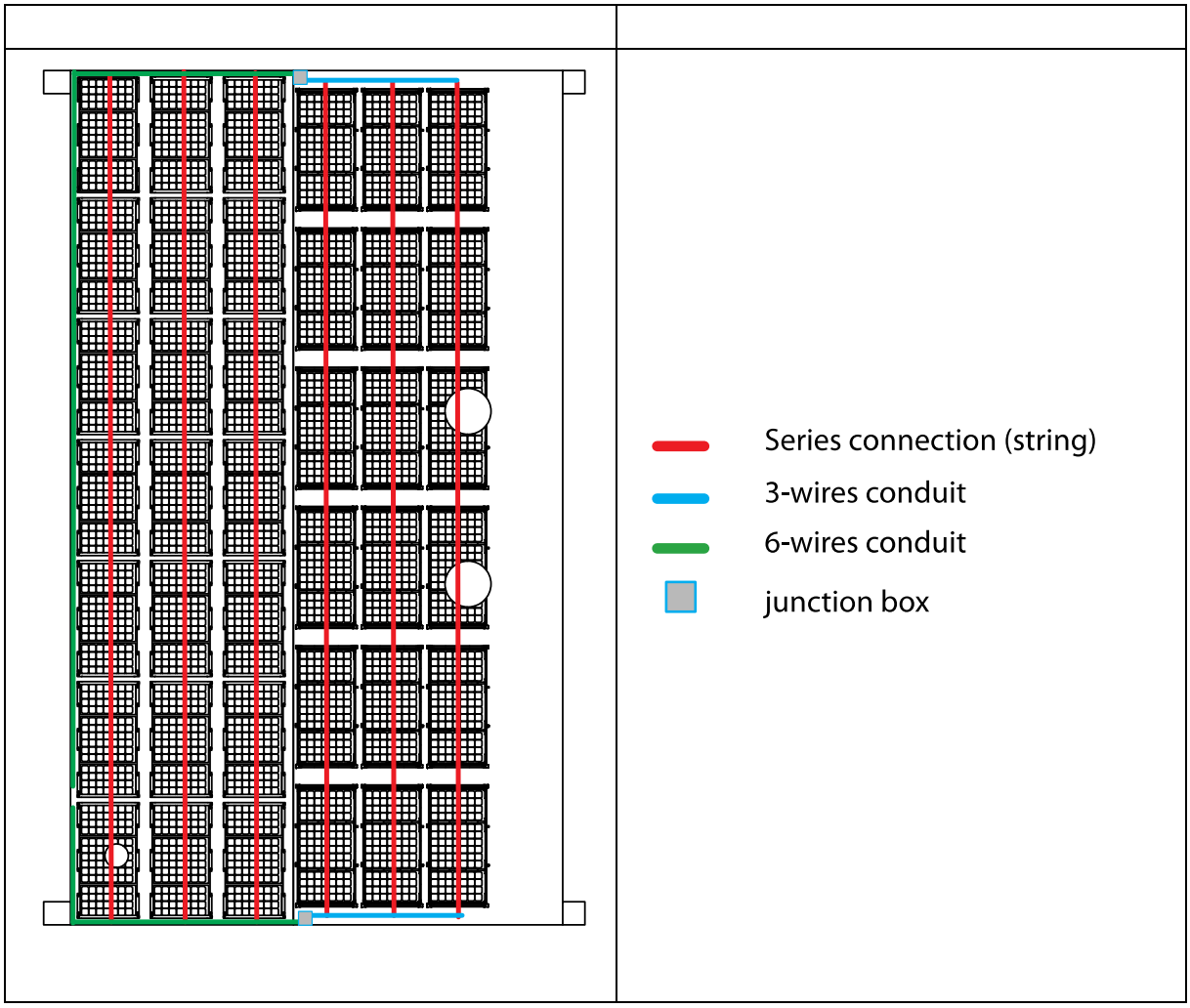


Figure 30: Electric layout of half hatch

The idea is to use a distributed MPPT (Maximum Power Point Tracking) strategy, namely by using strings MPPT optimizers. In such a way, we obtain higher efficiency and failure resilience because the individual strings (made by connecting in series seven plywood tray in the prototype) can work independently. The electric characteristics of the prototype strings are:

Tabella 1: Electric characteristics of a seven plywood substrates string

Pmax	3430	W
Vmp	361	V
Imp	9.5	A
Voc	457	V
Isc	9.8	A

The output of the string optimizer is a DC power that can drive directly a solar inverter, where the MPPT input stage can be disabled due to the previous optimization of the strings. In the prototype, we used a Huawei SUN2000 40KTL inverter properly suited for the three phase ship 440 Volt/60 Hz grid (such inverter is capable of handling the power of a full hatch installation, being its nominal power 40 kW) and a Meteocontrol WEB'log device for the connection to the cloud and the remote monitoring.



In the following, we show pictures of the prototype installation.



Figure 32: Installation of studs

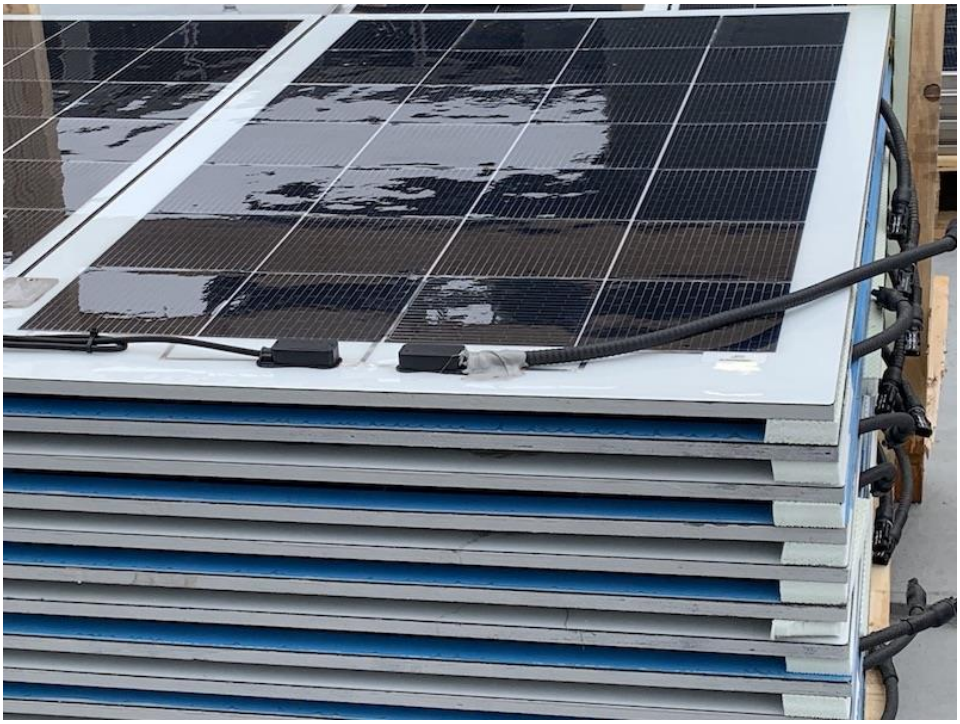


Figure 33: Unpacking of solar panels on the ship deck



Figure 35: Final installation with all the interconnections covered by protective steel conduits

4.3 Performance



Figure 36: One week of production

Figure 35 shows one week of production for the prototype during the month of March 2024. The peak power is consistent with the period of the year and the ship position. The goal of testing the system functionality is achieved.

5 Prototype failures inspection

During the trial period, the ship travelled for most of the time, also encountering quite harsh sea conditions, with even a force 10 storm. The result was a severe damaging of the installation but that served undoubtedly as a quite realistic testing. Before the damages due to the storm, other issues emerged, especially related to the stresses on the electric connections. Some panels suffered of electric arc on the junction boxes and the MC4 standard solar connectors suffered burnings too, due to the joint effect of salted way (especially salted spray) and mechanical stress due to wind and waves.

Here is a list of the major faults registered.

a) Electric arc between junction boxes (JB) and the metallic environment; water infiltrations.
b) MC4 connectors melting due to electric arc

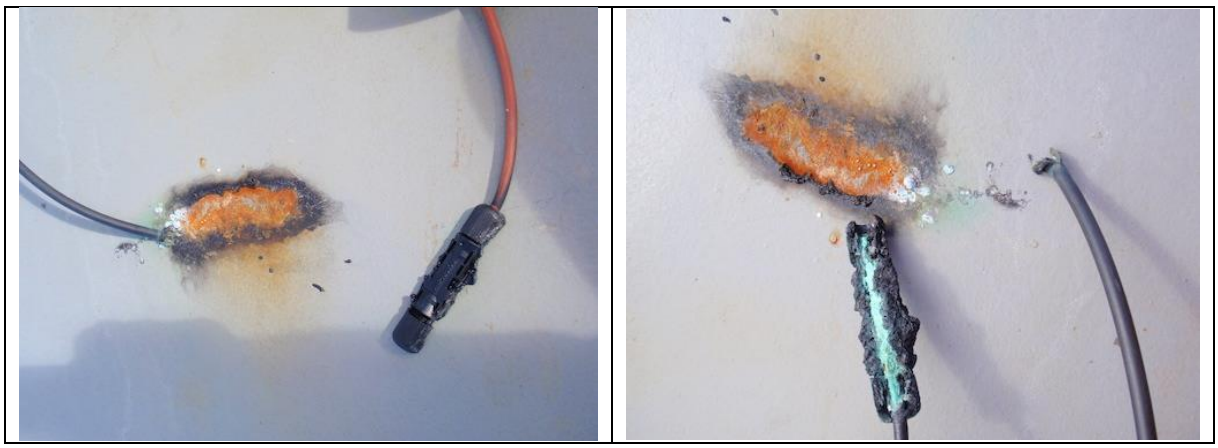


Figure 38: MC4 connectors' damages

c) Failure of the mechanical fixing



Figure 39: Mechanical damages

The failures involve both the mechanical fixing of the panel to the substrate and the fixing of the substrate to the ship.

6 Improvements

By examining the pictures of the failures and the samples of junction boxes and connectors, a preliminary analysis can be summarized as follows.

The electric failure of the junction boxes (JBs) is due to the creation of conductive paths between panel electric leads and the external ground (the ship). The JBs are attached to the solar panel surface by using proper silicon (mono component). The goal being forming a strong adhesion and a perfect sealing. Inside of the JB we have the electric leads and other electric component as the bypass diodes which are needed to manage partial shadings and prevent hot-spots in the panels. Both leads and diodes must be protected from moisture and this is realized by potting the interior of the JBs with a proper resin as described in Cap. 2.1. By examining the damaged JBs, we realized that the matching between the polyurethane potting and the sealing silicon was not perfect, leaving room to the creation of the conductive path under the force of the salted water spray. A solution working in most of the standard installation case had to be revisited for the harsh marine environment of a bulk carrier. New materials for sealing and potting have been searched and they are currently under testing.

The electric failure of the MC4 connector was actually unexpected, being such connectors the state of the art in the solar filed, used in billions of pieces all over the world. Once more the installation on a bulk carrier showed exceptionally difficult as for the electric insulation is concerned. A broad research on the market for better connectors, better suited to the marine environment, did not resulted in good solutions. We found only oversized and definitely too expensive connectors suited for much larger currents. We thus decided to proceed along two different lines, one being quite ambitious, which is the study and the realization of a new connector with a stronger marine grade, the other to use special protectors studied for sealing two MC4 mated connectors, shown in the following picture.



Figure 40: MC4 connector protector

WHISPER