applied sciences

MDPI

Article

FPSO Hull Structures with Sandwich Plate System in Cargo Tanks

João Pedro Silva [1], Bai-Qiao Chen [2,*] and Paulo Mauricio Videiro [3]

1 Companhia Siderúrgica Nacional (CSN), São Paulo 04538-132, Brazil
2 Centre for Marine Technology and Ocean Engineering (CENTEC), Instituto Superior Técnico, Universidade de Lisboa, 1049-001 Lisbon, Portugal
3 Laboratory for Reliability Analysis of Offshore Structures (LACEO), Universidade Federal do Rio de Janeiro, Rio de Janeiro 21941-596, Brazil
* Correspondence: baiqiao.chen@centec.tecnico.ulisboa.pt

Abstract: Nowadays, the floating production storage and offload system (FPSO) is one of the most common platform types for offshore oil production. The traditional arrangement of the stiffened panels creates obstacles for automated cleaning and inspections by remote devices. This paper summarizes the results of an initial study for the design and construction of FPSO hulls with SPS in order to overcome this problem. The main goal is to have the walls and bottom of the cargo tanks free of stiffeners. This research is conducted by first designing the hull with a conventional structural arrangement using steel according to the ABS rules as a benchmark. Following that, the equivalent hull structure with sandwich plates is designed in accordance with the guidelines for SPS construction from DNV rules. Finally, this paper provides the results of a finite element analysis to compare the stresses and ultimate strengths of both types of structures. Briefly, the main results are that the SPS design provides a reduction of 2.8% of the total weight and a better overall structural performance by an increase of 26% for the ultimate strength of the hull.

Keywords: FPSO; offshore structures; SPS; finite element analysis; ultimate strength

check for updates

Citation: Silva, J.P.; Chen, B.-Q.; Videiro, P.M. FPSO Hull Structures with Sandwich Plate System in Cargo Tanks. *Appl. Sci.* **2022**, *12*, 9628. https://doi.org/10.3390/app12199628

Academic Editor: José A. Orosa

Received: 30 August 2022
Accepted: 22 September 2022
Published: 25 September 2022

1. Introduction

The FPSO structure is based on stiffened panels and the classification societies demand three kinds of inspections for safety reasons: annually, every 2.5 years (intermediate) and every 5 years (Special Periodical Survey). However, these surveys are a time-consuming and risky activity, requiring, for instance, the entrance of people inside the tanks for cleaning and thickness gauging. This activity can be dangerous and time-consuming because it involves confined and high places. Another reason is that this survey is conducted while the FPSO is at sea in full operation. It may take 1 to 1.5 years just to install the risers on the vessel. In other words, there is no possibility to move it to a dry dock and perform the inspection there, as it would turn financially unattractive. Thus, the FPSO crew needs to first reallocate the liquids from the tank, which will be inspected, to the others from the vessel without jeopardizing the oil and gas production. The oil tank to be inspected may be out of operation for up to 10 or 15 days. The storage of the produced oil in this period shall be rearranged in the remaining tanks. This rearrangement can be quite tricky in the earlier years after the beginning of the operation because it is when the production reaches its peak. Therefore, the faster the crew can clean it and inspect it, the less time the production capacity will be reduced and, therefore, the more revenue the FPSO will generate.

In this context, new technologies are arising to try to overcome or minimize this problem. One of them is the use of sandwich plates in offshore structures. A sandwich structure is a fabricated material that consists of two steel plates joined to either side of a low-density core material or structure [1,2]. For example, the sandwich plate system (SPS) was shown in [3]. The last type of panel is made of two steel plates bonded to a compact polyurethane elastomer core. These sandwich panels are mainly used as a side shell protection against collision from tugs or supply vessels that approach the FPSO during its operation.

This study focuses on the research for the design and construction of hulls of FPSOs with sandwich plates without stiffeners in the bottom plate and longitudinal bulkheads of cargo tanks. The main goal is to have the plates of the longitudinal bulkhead and bottom of the cargo tanks free of stiffeners to allow remote cleaning and thickness inspection of bottom and bulkhead plates using autonomous equipment. Therefore, these structures will be replaced by sandwich panel systems (SPS). The steel scantling design to be used is shown in Figure 1, and the thickness of the panels will be determined later.

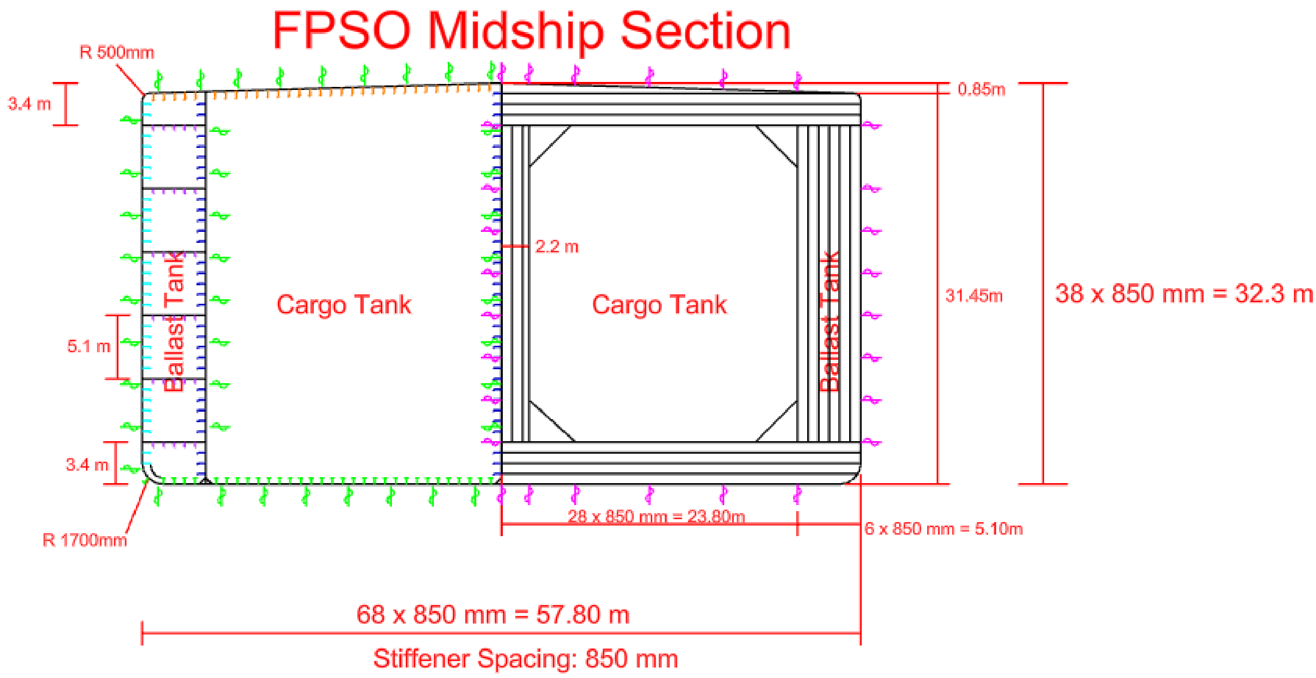

Figure 1. FPSO midship section.

2. Literature Review

2.1. Fundamentals of Ultimate Strength

A good practice in any design for ships and offshore structures is to use one or more limit states as criteria in addition to the yield stress during the total strength assessment. Ultimate strength is critical in the strength assessment of a ship or offshore structure, and it is defined as a point beyond which the loading exceeds structural capacity and the structure collapses [4–8]. They can vary from more simplified to more sophisticated. However, determining this property is a challenging task because it depends on three types of uncertainties: geometry, material and numerical.

Nowadays, there are three ways to evaluate the ultimate strength of ships and marine structures: experiments, numerical simulations and analytical modeling. Due to the size of ships and the lack of standardization of ship types, it is difficult to frequently perform experimental tests. Therefore, the development of numerical and analytical approaches is a satisfactory solution to this problem [9]. Although numerical simulations can provide good predictions without the need to build/evaluate a structure, the complexity of the problem can increase drastically when considering different kinds of uncertainties. This can be quite time-consuming and expensive because it requires good computers. Thus, analytical methods also have their use once they provide simplified and quicker checks. In this light, the main responsibilities of the classification societies are to provide both analytical and numerical approaches, based on the literature and studies, with the recommended safety factors in order to achieve a safe design of structures. Each classification society, such as ABS, BV, DNV, LR and more, has developed guidelines for both approaches for the corresponding limit state based on either the working stress design (WSD) method or the load resistance factor design (LRFD) method.

2.2. Sandwich Plate System (SPS)

The studied FPSO uses a sandwich plate developed by Intelligent Engineering Limited (IE), considering a composite laminate with two metal layers and an elastomer core instead of conventional steel structures of stiffened plates. It was reported to have an enhanced capability in terms of impact absorption in the structure with this sandwich plate system (SPS) when compared to the conventional structures made of steel [2,3]. This is due to the so-called "sandwich effect", when the second moment of area and bending stiffness are significantly increased in the cross-section of the structure [1].

Regarding the marine and offshore structure environment, the SPS panels are used in several designs as an alternative to the traditional steel structure [10]. For example, an engineering study [11] confirmed the impact resistance of the SPS overlay in an impact scenario between an FPSO and a supply vessel. It was studied as a form to offer equivalent protection to an FPSO monohull as a double hull. The main results showed that the SPS attached to the side plates was able to provide increased local impact resistance, reduced critical fatigue stresses, reduced risks and costs during fabrication and inspections and less maintenance.

Furthermore, Bond et.al [3] studied an innovative method for the repair of in-service FPSOs using the SPS overlay as a way to reinstate the strength and corrosion allowance. In the SPS plate, the existing stiffened plating was considered one of the plates, with a second plate attached to it with an elastomer core. The study carried out several structural evaluations comparing both arrangements (AH/DH32 steel and SPS overlay) for the bottom structure of the FPSO using the finite element method (FEM). The main results showed that the sandwich plate configuration had a better performance, reducing the stresses at the static load case and also increasing the ultimate strength of the structure.

The Transport Industries Under European Commission in 2013 [1], with the help of several classification societies and universities, proposed a coordination action on advanced sandwich structures in the transportation industry. The result was a guide for best practices for sandwich structures, including the SPS, in marine applications with the main objective to provide knowledge of diverse types of sandwich plates in order to help their integration in ship design and fabrication. It was focused mainly on the design of plates with the analytical/numerical/ experimental analysis of several limit states, such as ultimate strength, buckling and fatigue, and other types such as vibration and crash response.

3. Global Load Estimation

3.1. FPSO for Case Studies

The main dimensions of the FPSO are a length overall (LOA) of 323 m, a breadth (B) of 57.8 m and a depth (D) of 32.3 m with a block coefficient (Cb) of 0.92. The design draught is 26.8 m. The load case can be further discussed, but it is obtained by filling the maximum amount of cargo tanks (10 of 12) and complying with the equilibrium conditions imposed. Moreover, the midship section used is presented in Figure 1, and a lines plan is presented in Figure 2.

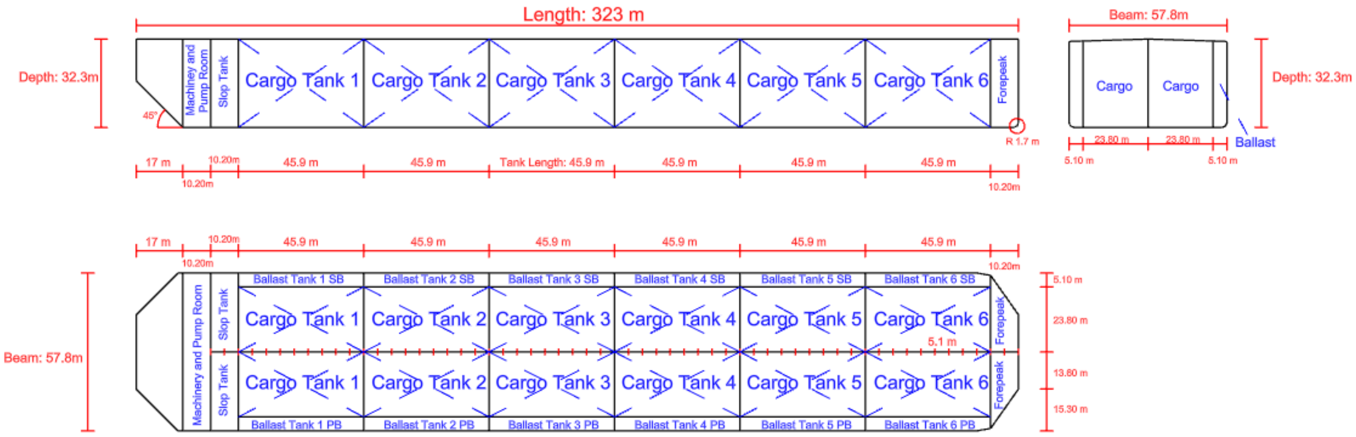

Figure 2. Lines plan of the hull.

3.2. SESAM Modelling

SESAM software developed by DNV is a collection of applications and services for design and strength assessment of offshore wind, oil and gas and maritime structures. Two modules of SESAM were used in this research: HydroD and GeniE. The sequence to solve the hydrostatic problem of the FPSO is described in several tutorials provided by the user manuals for GeniE, HydroD and Wadam [12,13]. The hydrodynamic can be a panel, Morison, dual or composite model, and the adequate choice depends on the type of the problem.

The mass model covers the creation of the structure of the FPSO, the boundary conditions and the loads imposed. It is used both in the hydrostatic calculations to report imbalances between weight and buoyancy of the structure and in the hydrodynamic motion analyses. The first part of the mass model is the permanent loads. They are related to the structure, and equipment for the oil and gas extraction are displayed in Table 1. The variable loads are those related to the percentage of liquid in the cargo and ballast tanks. These must be added to the permanent ones to find the final load applied to each span of the FPSO.

Table 1. Permanent loads to be considered in the mass model.

Item	Weight [ton]	VGC [m]	VGC Reference	Description
Process Plant	30,000	15.0	Main Deck	Structure and Equipment
Hull Items	7200	26.0	Base Line	Equipment, Machinery, Pipes, Painting, Mooring System
Hull Stern	4500	9.0	Main Deck	Accommodation, Helideck, Fire Fight, Offloading System
Hull Bow	600	20.0	Main Deck	Flare Tower, Hull Equipment, Offloading System
Lower Riser Balcony	600	4.0	Base Deck	Structure and Equipment
Upper Riser Balcony	1500	5.0	Main Deck	Structure and Equipment
Riser Loads	10,000	4.0	Base Line (Stability)	Structure and Equipment
		−1.0	Main Deck (Structure)	
Mooring Loads	5000	15.0	Base Line (Stability)	Structure and Equipment
		0.0	Main Deck (Structure)	

In addition to the models, the environmental data and loading conditions must be applied, and then, a hydrostatic analysis is performed. The module returns as output different parameters such as the distribution of contents (oil and ballast) in the tanks for a static equilibrium condition, the GZ curve, still water sectional loads (shear force and bending moments) and stability checks against international codes.

Summarizing the permanent loads with several tanks filling and distribution, five load cases were simulated to observe the structural behavior for different cargo capacities. These conditions are: the minimum draught (all 12 cargo tanks empty), the maximum (10 of 12 cargo tanks filled) and three intermediate values. Figures 3 and 4 show the distribution of the bending moment as well as the shear force for each draught, respectively.

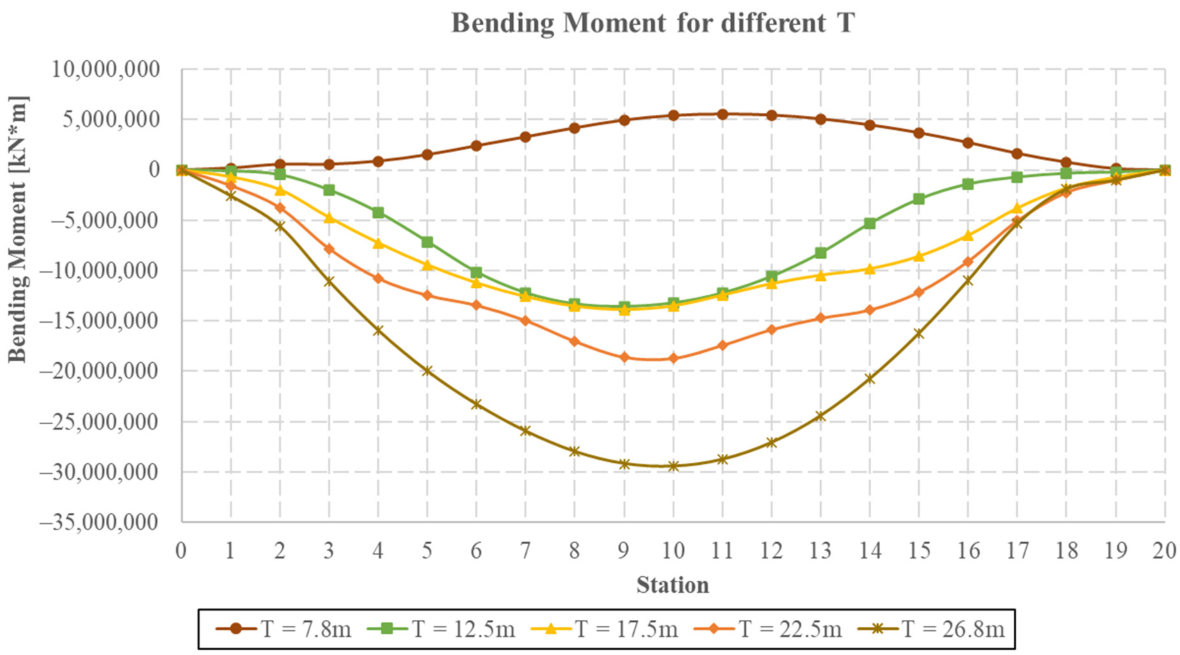

Figure 3. Bending moment distribution for different draughts.

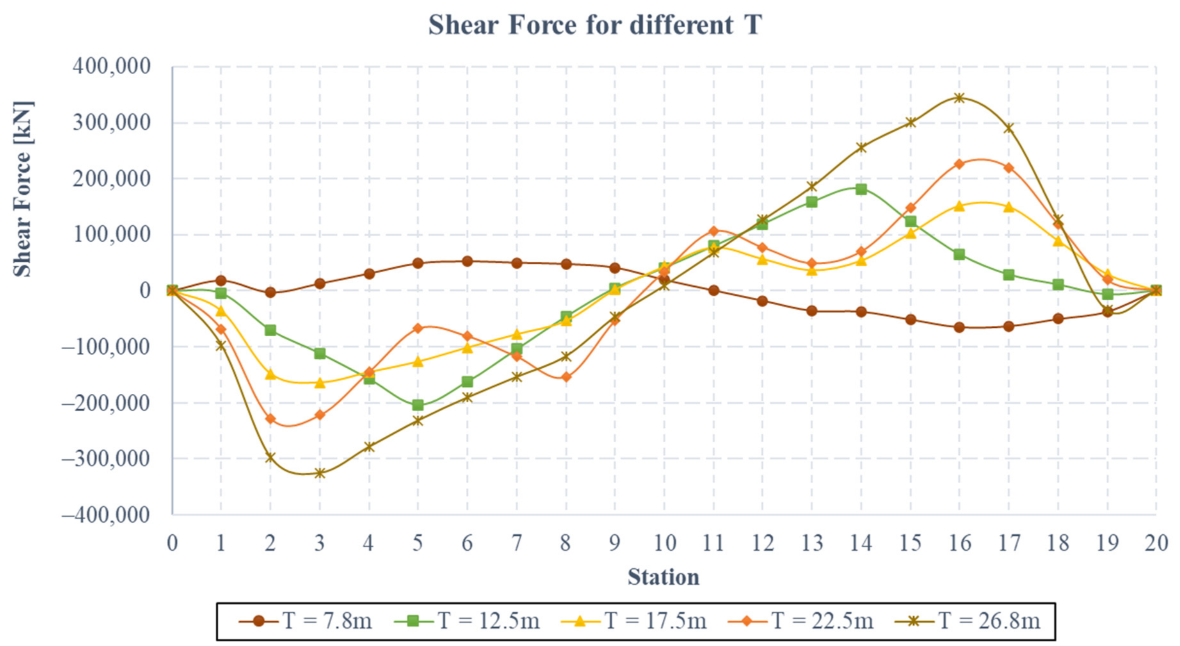

Figure 4. Shear force distribution for several draughts.

4. Traditional Steel Structure Scantling

4.1. Design According to the FPI and DNV Rules

As stated in [14], the design criteria are applied in two phases. The first one provides the basic hull design. In another word, it consists of the initial requirements for plating, the section modulus of longitudinal or stiffeners, and the scantlings of main supporting structures. The second phase is the total strength assessment (TSA), with several strength criteria such as buckling, yielding and ultimate strength.

Therefore, a methodology must be followed in order to estimate the dimensions for each element of the midship section. The first one is to check the material properties and their units that are required in the given formulas of the rules. Following that, the global loads of the hull and the local loads for its structure are estimated. In the first phase, the nominal, maximum expected loadings of a component for ocean service as stated by classification society rules are considered. This includes loads/accelerations from pitch, roll and yaw and the various kinds of pressure existing in the ship such as external, internal, sloshing, etc. Moreover, to adjust the loadings and load effects of the site-specific long-term environment, several environmental severity factors (ESFs) are considered at the installation site. The third step is to estimate the hull girder strength design parameters such as the minimum section modulus and the inertia of the section. With all information in mind, the last step is to use all of them as input in different formulas to estimate the thickness (net and gross) and take the bigger one and round it up so it can have a practical thickness to be built. For example, a thickness of 12.4 mm is rounded up to 13 mm.

This design will include the dimensioning of:

- Bottom plates and longitudinal stiffeners
- Side plates and longitudinal stiffeners
- Deck plates and longitudinal stiffeners
- Longitudinal bulkhead (center and side) plates and longitudinal stiffeners
- Transverse bulkhead plates, vertical and horizontal stiffeners
- Web frame structure: plates, stiffeners and brackets

The main characteristics of the steel used for the dimensioning are:

- The minimum specified yield point, taken as 355 MPa for Grade H36 Steel [14]
- The Young's modulus of the material, taken as 2.06×10^{11} MPa for steel [14]

Following the guidelines presented in [14], the traditional midship section arrangement could be designed (plates and stiffeners), and Table 2 shows the gross thickness of the panels designed for each region.

4.2. Strength Criteria

In any project, one of the crucial objectives is to design a product with the lowest cost as possible in order to make a profit. In the shipbuilding industry, this can be achieved by building a ship or a platform without over-dimensioning the whole structure. In this study, the optimal design is the one with the lightest structure that satisfies all the strength criteria (buckling, yield and ultimate strength [14]) imposed for both load conditions (static and dynamic) simultaneously. However, this is not a simple task. For example, in this primary section, there are 37 plates whose thickness can vary between the minimum value imposed by the rule and a maximum value, which is considered 32 mm. In this aspect alone, finding an optimal solution is complicated. In addition, each individual plate interferes directly with the strength criteria from the other plates, because they can modify the neutral axis height and the moment of inertia and, therefore, the normal and shear stress in the structure.

Table 2. Gross thickness obtained after the design based on the FPI guidelines [14].

Structure	Plate Number	Gross Thickness [mm]	Structure	Plate Number	Gross Thickness [mm]
Bottom	Keel	24	Side Longitudinal Bulkhead	22 S	16
	Cargo Area	23		23 S	16
	Ballast Tank	22		24 S	16
Side	5	19		25 S	16
	6	18	Horizontal Plate	5 H	18
	7	18		6 H	18
	8	18		7 H	18
	9	18		8 H	18
	10	18		9 H	18
	11	18		10 H	18
	12	18	Transversal Bulkhead	17 T	20
	13	19		18 T	19
Deck	15	22		19 T	19
	16	23		20 T	18
Longitudinal Bulkhead	17	20		21 T	17
	18	18		22 T	17
	19	17		23 T	17
	20	17		24 T	17
	21	17		25 T	17
	22	17	Web Frame Bottom	1	23
	23	17	Web Frame Side	2	20
	24	17		3	18
	25	16		4	17
Side Longitudinal Bulkhead	17 S	22		5	16
	18 S	19		6	16
	19 S	17		7	16
	20 S	16		8	16
	21 S	16	Web Frame Deck	9	17

Thus, the optimization problem used to obtain a feasible solution is described below.

- Objective Function
    - Minimize (total weight)
- Variables
    - Thickness from longitudinal plates
- Constraints
    - Strength criteria
    - Maximum thickness of 32 mm
    - Minimum moment of inertia and section modulus
- Load Cases
    - Static: still water condition
    - Dynamic: still water + wave load conditions

The results from the solver can be seen in Figure 5. The solution found complies with most of the strength criteria. The exception is the deck plates for the static load case, which are 3–5% higher than the allowed value (the maximum allowed is 355 × 0.6 = 213 MPa). Despite this, the solution is feasible for two reasons. First, the condition in which this exceedance of the onboard safety factor takes place is not the worst of all. This helps as a reference for dimensioning, but the important thing is that the plates are able to withstand loads of the worst condition without exceeding the yield stress, which in fact happens. The second reason is that the vast majority of plates meet the buckling and yield requirements for the calm water condition and all of them are within the stipulated limits for the buckling, yield and ultimate strength criteria for the worst condition in which a large amount of calm waters plus waves exist.

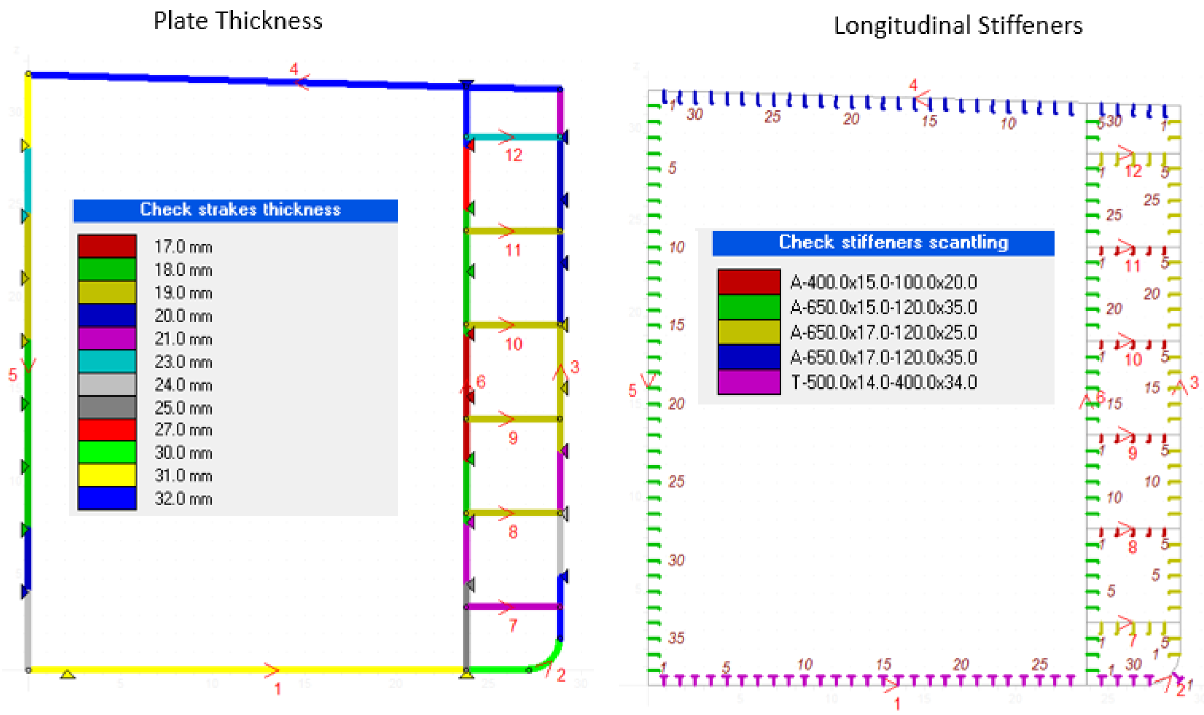

Figure 5. Final distribution of plate thickness and the longitudinal stiffeners.

Moreover, most the of values range from 0.4 to 0.5 and 0.75 to 0.85 of the yield stress for the static and dynamic load cases, respectively. This indicates that the achieved solution is good because the structure is not over-dimensioned.

5. SPS Plate Scantling

This section has the purpose of detailing the dimensioning of the SPS plates according to DNVGL-CG-0154 and Lloyd's guidelines rules [15,16]. The basis of the SPS design principles is that SPS structures should have strength at least equivalent to that of a conventional steel structure that performs the same function. Therefore, the approach, in this case, is to take the minimum conventional steel scantlings for structural items, calculated from the class rules, and then calculate the "equivalent" SPS scantlings.

The SPS plate is a structural composite material composed of steel and a polyurethane elastomer. Thus, it is essential to define the mechanical properties of each material for the panel design. According to the DNVGL-CG-0154 [16], the mechanical properties of the steel are high steel grade 36 [14] and it is considered the same grade of steel, Grade H36. The core characteristics were obtained through the DNV rule [16] and Lloyd's Guidelines [15]. The material properties of steel H36 and the core are shown in Table 3.

Table 3. Material properties of steel H36 and the core.

Material Properties	Steel H36	Core Material
E [GPa]	206	748
G [GPa]	79.3	297
ν [-]	0.3	0.26
Yield Stress [MPa]	355	21
Density [ton/m^3]	7.85	1.05

Moreover, the considered bending moments (BM) and shear forces (SF) are the ones presented in Table 4. They are the sum of a static load from a draught of 26.8 m from Figure 3 and the dynamic load obtained from FPI Rules [14]. The final plate should withstand both cases. Furthermore, the plate dimensions are similar to the ones from the conventional steel structure. It is a square plate with a length of 3.4 m.

Table 4. Loads condition to be considered.

Load	Conditions	Value	Unit
VBM	Still Water Wave Load	−29,453,568 −11,873,315	kNm kNm
VSF	Still Water Wave Load	344,989 97,328	kN kN
HBM	Wave Load	5,976,145	kNm

As stated in [16], there is a range of thickness in which the steel plates and core elastomer are submitted. Typically, it is from 3 to 30 mm for the first element and from 15 to 100 mm for the second. In addition to this constraint, there are also a minimum net and gross thickness for the steel plates of the composite panel. They are dependent on the region of application (i.e., bottom structure, side, deck and so on) and the corrosion addition.

5.1. Design Process

Scantlings of a hull structure with sandwich panels shall satisfy buckling, stress and deflection criteria from relevant responses [16]. In addition to this, the sandwich panels shall also be designed to avoid the major plastic yielding of the steel face plating and the core material, to avoid the failure of the bond and to be lighter than the traditional steel configuration.

The Lloyd's Register guidelines [15] propose a flowchart as a methodology that is used to design SPS plates (see Figure 6). Moreover, in Appendix B of [16], there is a support Excel tool developed by DNV for calculating all these strength criteria properties and comparing them with the rule's requirements. This tool was used in this study to make sure the classification society method was followed properly.

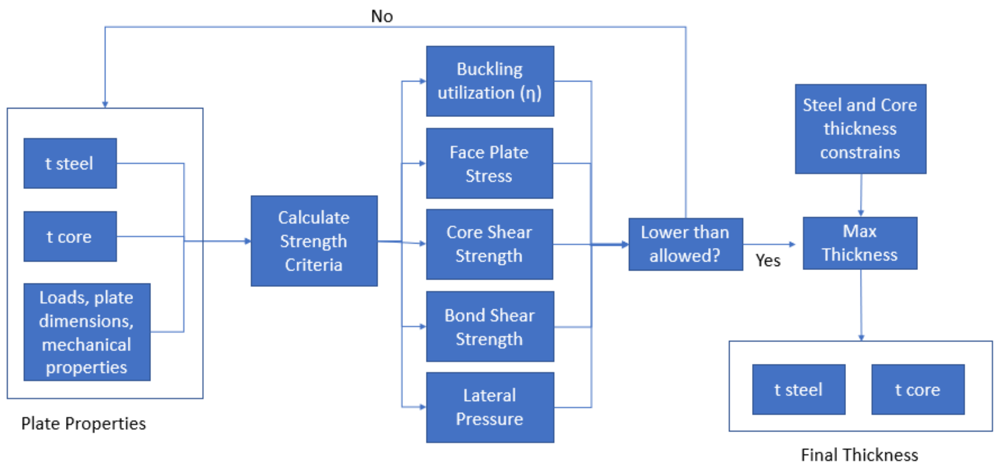

Figure 6. Flowchart to design the SPS panel.

Also, in summation of the basic principles, it is interesting to keep the thickness of the core as low as possible in order to make the panel cost-effective. The DNVGL-CG-0154 [16] suggest a minimum and a maximum of 15 and 100 mm for the core, respectively.

5.2. Results

Therefore, by combining information from the previous section, such as the hypothesis adopted, the goals established, the methodology to follow and the strength criteria to judge, the results to obtain the thickness for the steel and core of the composite plate could be achieved. Notice that for the same load, different combinations of thickness pass the several criteria imposed. Thus, the panel selected was the one that had the best combination of the least core material used, a lighter structure and the structure as a whole complies with the buckling, yielding and ultimate criteria for both load cases. Thus, the thicknesses from Table 5 were selected as the final ones.

Table 5. Final distribution of the thickness for the SPS panels.

Structure	Plate Number	St. Net Thickness [mm]	St. Gross Thickness [mm]	Core Thickness [mm]	Weight SPS [ton]	Weight Steel [ton]	Difference
Bottom	Keel	15	18	55	0.73	0.85	−13.6%
	Cargo	15	18	55	8.23	10.46	−21.3%
	Ballast	15	18	55	1.76	2.3	−19.9%
Center Longitudinal Bulkhead	17	12.5	16	50	1.25	1.29	−2.9%
	18	12.5	16	50	1.05	0.96	9.9%
	19	12	15	45	0.98	0.9	8.3%
	20	10.5	14	45	0.92	0.9	2.4%
	21	10	13	45	0.87	0.9	−3.6%
	22	10	13	45	0.87	0.93	−6.3%
	23	10	13	45	0.87	0.93	−6.3%
	24	11	14	45	0.92	1.04	−10.8%
	25	14	17	55	1.12	1.25	−10.1%

5.3. Hull Weight Estimation

This section aims to estimate the hull's weight for both steel and SPS arrangements based on the thickness and dimensions of the structural elements obtained. The structural elements are not designed for the aft part where the machines and pump would be located. Generally, this part corresponds to between 5–15% of the cargo tanks' weight (longitudinal and transversal), and for this study, it is considered 10%.

The methodology to calculate each part of the structure is presented below. As can be seen in Table 6, the final hull with the SPS panels is 2.8% lighter than the traditional steel hull with the bottom structure being the main responsible for reducing the total weight. A reduction of, approximately, 1250 tons. This is due to the fact that it is the area with one of the highest thicknesses for the steel panels and the stiffeners with the highest weights.

- Longitudinal Weight
  - $W_{total,\ long} = (45.9 * 6 + 10.2) * \sum \rho_i A_i$
  - Where ρ is the material density, and A is the transversal area of the element i
- Transversal Weight
  - $W_{total,trans} = 6 * W_{bulkhead} + 54 * W_{web\ frame}$
- Aft Weight
  - $W_{aft} = \left(W_{total,\ long} + W_{total,\ trans}\right) * 0.1$
- Total Hull Weight
  - $W_{total} = W_{aft} + W_{total,\ long} + W_{total,\ trans}$

Table 6. Calculations of the weight for each part of the structure for both arrangements.

Structure	Steel Arrangement [ton]	SPS Arrangement [ton]	Difference
Bottom	6950	5709	−18%
Side	8920	8920	-
Deck	6251	6251	-
Long BKD	2541	2530	−0.4%
Side BKD	4748	4748	-
Trans BKD	3062	3062	-
Web Frame	8487	8487	-
Aft	4096	4096	-
Total Hull	45,055	43,804	−2.8%

6. Ultimate Strength Analysis

Many classification societies require the performance of an FEA of ship structures for the total strength assessment (TSA) because it has several advantages [17]. One of them is the adaptability and accuracy of the technique once the FEM can model complex shapes with several loading and boundary conditions and provide an accurate solution, which would be impractical to be performed by hand. Consequently, the engineers can easily simulate several conditions without building real-life models and spot vulnerabilities in the design before constructing the definitive project.

6.1. Finite Element Model

The FPI rules [18] have some requirements for the finite element model that must be followed. First, the strength analysis follows a "net" ship approach. Therefore, the nominal design corrosion margin must be deducted from the scantling for the FEA. Second, the analysis must be a three-dimensional global model of three cargo tanks located at amidships with two frames of the end bulkheads (see Figure 7). Thus, the primary load-carrying members will be modeled as shown in Figure 7, which includes: transverse web frames, longitudinal and horizontal girders, centerline ring frames, side stringers, etc. This is due to the fact that the 3D finite element analysis (FEA) is used to determine the primary and secondary bending of the hull girder, as well as appropriate boundary conditions for the use in the fine-mesh FEA of local structures.

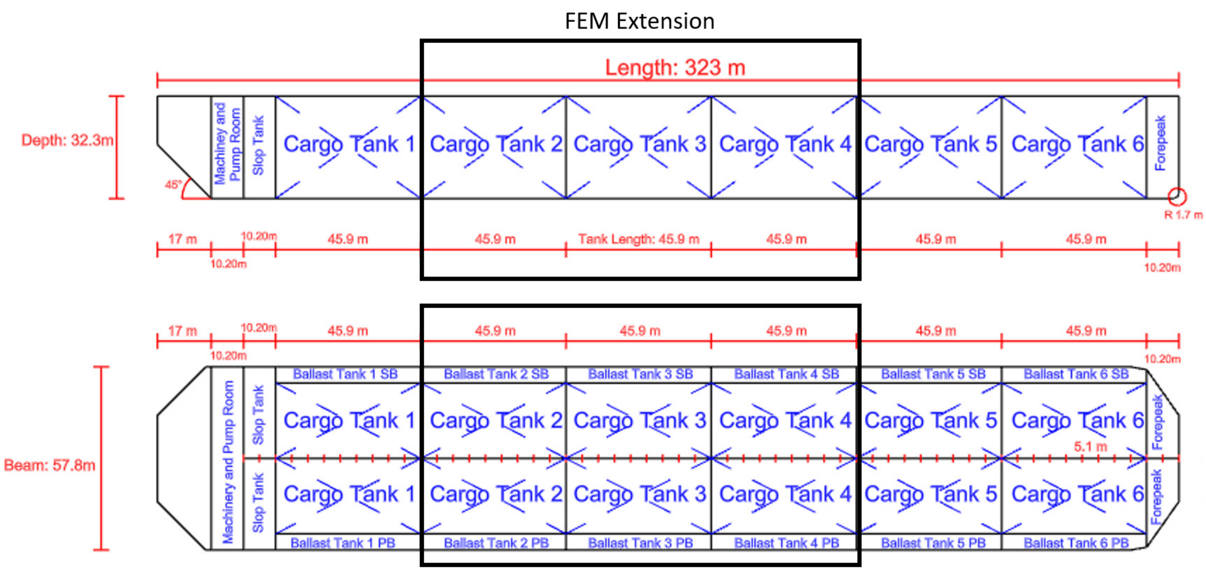

Figure 7. FEM extension considered in the study.

Moreover, the consistent modeling throughout the three cargo tanks is preferred. The desired mesh is considered in the middle tank, aiming at more accurate results in the strength assessment.

According to [18,19], the equivalent thickness model is an accurate model for the assessment of the ultimate strength and the distribution of the stresses. This model consists of using thicker plates that have inertia equal to a plate with longitudinal stiffeners. There are two benefits to it. The first one is the simplification of complex geometry. The second is that with fewer nodes and elements, less computational power is needed, and it is easier to achieve a converged solution. Therefore, the steel plates used both in the traditional and with the SPS plates structures are shown in Table 7.

Table 7. Equivalent thickness for the steel plates.

Structure	Plate Number	Equivalent Thickness [mm]	Structure	Plate Number	Equivalent Thickness [mm]
Bottom	Keel	47	Side Longitudinal Bulkhead	22 S	33
	Cargo Area	52		23 S	33
	Ballast Tank	44		24 S	42
Side	5	46		25 S	47
	6	38	Horizontal Plate	5 H	33
	7	35		6 H	25
	8	33		7 H	25
	9	33		8 H	26
	10	34		9 H	26
	11	34		10 H	26
	12	34	Transversal Bulkhead	17 T	31
	13	34		18 T	30
Deck	15	44		19 T	30
	16	46		20 T	28
Longitudinal Bulkhead	17	36		21 T	28
	18	34		22 T	28
	19	32		23 T	28
	20	32		24 T	28
	21	32		25 T	28
	22	33	Web Frame Bottom	1	29
	23	33	Web Frame Side	2	27
	24	37		3	25
	25	46		4	24
Side Longitudinal Bulkhead	17 S	40		5	23
	18 S	36		6	23
	19 S	33		7	23
	20 S	32		8	23
	21 S	32	Web Frame Deck	9	23

In the context of FEA of steel sandwich plates, there are several references on how to model it, such as [16]. Generally, one of the combinations below is required:

- A single layer of layered shell elements, to be used through the thickness of the entire sandwich plates.
- Shell elements for the faces, solid elements for the core, with the isotropic material properties for both.
- Solid elements for both the face and the core with isotropic properties.

The difference between them is related to the size of the model applied. According to the experience of SPS Technology and the DNV-CG-0154 [16], for more complex models, an accurate solution can be obtained by using the single layer of shell elements for the same reasons as the equivalent thickness model described above.

Although the use of solid elements can model the geometry to the degree of detail wanted, this implies a large number of nodes and elements, meaning large computational efforts.

Therefore, the equivalent steel plate would have equal inertia to the plates obtained in Figure 5. Since the geometry should be the same, only the thickness was varied to obtain the equivalent plate. The new plates are shown in Table 8.

Table 8. Equivalent thickness for the SPS panels.

Structure	Plate	Thickness [mm]
Bottom	Keel	72
	Cargo	72
	Ballast	72
Longitudinal Bulkhead	17	33
	18	33
	19	31
	20	29
	21	27
	22	27
	23	27
	24	29
	25	35

For each type of element, there are several options to choose and the appropriate one depends on the type of the analysis pursuit. For the steel plates, the best type of element is the shell one. Furthermore, the most suitable for the scope of this study is SHELL181.

In addition, a sensitivity analysis was performed in order to check how the results vary with the mesh size (Table 9). It compared the FPI with a refined one that has all elements with a size of 0.85 m. There were five main variables studied: neutral axis height from the baseline, the normal stress from the bottom and deck plates, the spring reaction at the ends and the time required to run the simulation for the static and ultimate load case.

Table 9. Sensibility analysis for different mesh sizes.

Parameter	FPI Mesh	Refined Mesh	Reference	Difference FPI Mesh	Difference Refined Mesh
Neutral Axis [m]	15.64	15.58	15.47	1.1%	0.7%
σ bottom [MPa]	210	209	208	1.0%	0.5%
σ deck [MPa]	−220	−230	−226	−2.8%	1.7%
Spring Reaction	0.2%	0.1%	0.3%	OK	OK
Time Static	00:20:30	00:35:20	00:20:30	0%	72%
Time Ultimate	00:45:00	01:37:00	00:45:00	0%	116%

The first three parameters of the reference column were obtained through the beam theory using the geometric properties and loads, the spring reference is detailed, and the time static/ultimate was considered as a reference to the mesh proposed by the FPI rules. As it is expected, the refined mesh provided more accurate results compared to the FPI mesh. However, the computational time required to perform it was 72% and 116% more for the static and ultimate load cases, respectively. Moreover, the results obtained are similar to the reference ones. Thus, the best trade-off between the accuracy of results and computational time required is the one from the FPI rules, and this is the one used for all models.

Uniaxial springs are used at the ends of the model as the boundary condition. According to the ANSYS Manual [20], one suitable element is the COMBIN14, which is a uniaxial spring-damper. Since it becomes a spring only, the user must input zero as the damping coefficient.

The material used here is the same as the one in the design process, which is high strength steel with a yield stress of 355 MPa. As seen in ABS material properties [14], the ultimate strength of this steel depends on its grade (AH, DH, EH or FH), which is between 490 to 620 MPa. However, the ANSYS requires the values from the true curve of stress-strain to calculate the stress/displacement of the plates above the yield stress. According to [21], grades AH and DH have the highest and lowest ultimate strength, respectively. Therefore, it was assumed that the structure would be constructed with DH steel, and one suitable way to model this steel is the multilinear isotropic hardening (MISO) model, which uses the von Mises yield criterion and isotropic work hardening.

According to the FPI guidelines [14], the boundary conditions at the ends of the cargo tank are ground spring elements with one end constrained in all six DOFs. The stiffness of one vertical spring can be calculated from the buoyancy equation divided by the total number of vertical springs, once this can be considered as a parallel spring association. The transverse and axial stiffness were considered 10% of the water plane stiffness coefficient divided by the number of the respective type of spring. This value was taken to reduce stress concentration from the spring in the plates at the ends of the model.

The objective of the application of the loads is to replicate as fairly as possible the vertical shear force (VSF) and vertical bending moment (VBM) distributions on the three cargo tanks in the FE models. Therefore, it is applied at the end of the model the BM and vertical force corresponding to that location as shown in Figure 8.

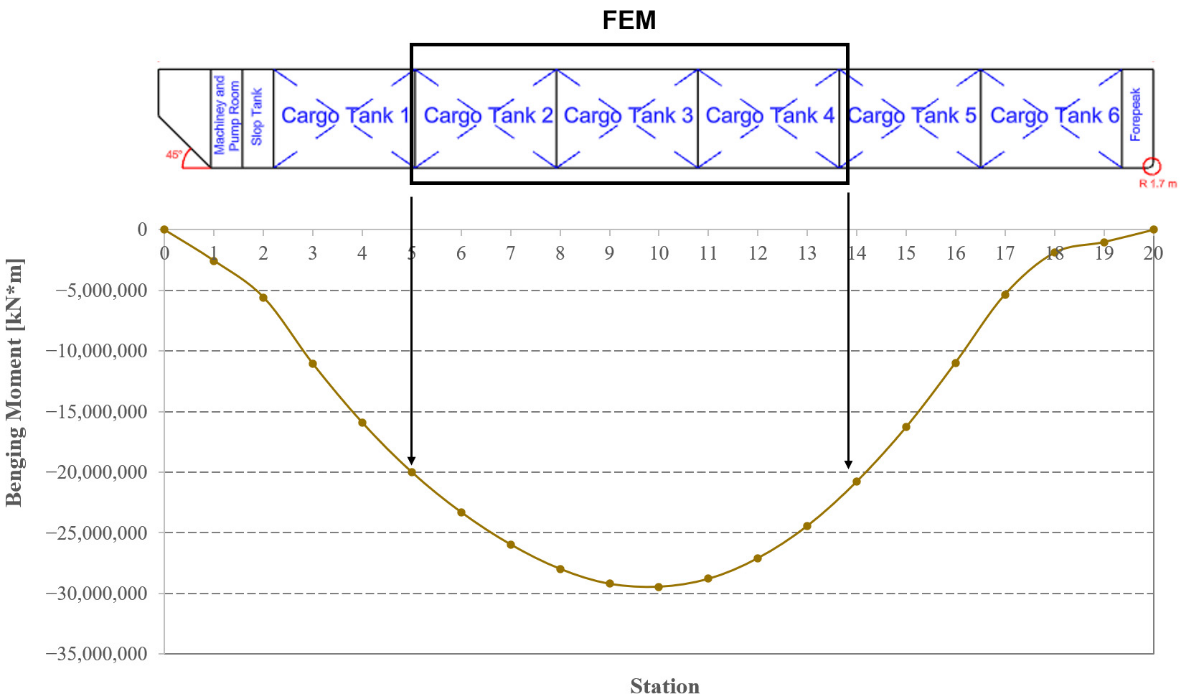

Figure 8. Boundary loads to be applied.

6.2. Static Loads

Before the calculation of the ultimate strength, the static load from one load condition was applied (draught equal to 26.8 m) for each structure. There are two objectives for this step. The first one is to check if the model is well-calibrated. This is done by comparing the results with the ones expected by the Euler–Bernoulli beam theory and by analyzing how much the reaction force at the spring is related to the resultant forces applied. If the model is well-calibrated, the stress at the structures should be similar to the beam theory, and the reaction forces at the springs should be lower than 0.3%. The other reason for applying the static load first is because the ultimate strength loads are obtained using the static load as a reference. For example, the input for the ultimate strength analyses can be two times the load applied at the static load case.

The first result to compare between structures is the vertical displacement in Table 10. As can be seen, the steel structure has a bigger deflection than the SPS structure, approximately, 19% bigger. This can be explained because the SPS structure has a higher moment of inertia (2391 m^4) rather than the steel structure midship section (2191 m^4), indicating a greater force required.

Table 10. Static displacement.

Structure	Condition: Sagging
Steel	154
Composite	130

The second result is a comparison between the FEM and beam theory presented in Table 11. The points taken to be analyzed are at the midship section of tank 2, where the shear stress is zero according to the shear force distribution from HydroD, to minimize the boundary effects on the forces by the extremities. At first, it can be seen that the model's loads are calibrated because the spring reaction is lower than the reference. Furthermore, the normal stress and neutral axis are similar to the ones expected by the beam theory for both models. The difference between them can be explained by the slight change of the neutral axis, and the beam theory does not consider the plate's thickness, which can change the stresses.

Table 11. Comparison of the static load case for both arrangements.

Comparison	Steel			SPS		
Parameter	FEM	Reference	Parameter	FEM	Reference	Parameter
Neutral Axis [m]	15.64	15.47	Neutral Axis [m]	15.64	15.47	Neutral Axis [m]
σ bottom [MPa]	210	208	σ bottom [MPa]	210	208	σ bottom [MPa]
σ deck [MPa]	−220	−226	σ deck [MPa]	−220	−226	σ deck [MPa]
Spring Reaction	0.2%	0.3%	Spring Reaction	0.2%	0.3%	Spring Reaction

As can be noticed in Figure 9, there are some differences in the normal stress between parts of the structure for the same height (side, side longitudinal bulkhead and central longitudinal bulkhead). This happens because of two reasons. The first one is the difference in thickness between plates and joints of structure (for example the side and bottom) that can distribute the stresses. The second reason can be explained by a phenomenon called warping [22], and it is related to the distortion of the longitudinal stresses in the cross-section due to the transverse shear or torsion.

6.3. Ultimate Loads

A ship's hull in intact condition sustains the applied loads smaller than the design values. In normal seagoing and cargo loading conditions, it will not suffer any structural damages (e.g., buckling and collapse). However, the loads are uncertain due to the nature of rough seas, as well as human errors leading to unusual loading/unloading of cargo [23]. Therefore, the ultimate hull girder strength needs to be accurately evaluated when taking into consideration the structural safety of the hull. However, closed-form methods, especially from classification societies, tend to underestimate the real ultimate bending capacity of structures in order to achieve a safety design [22]. Thus, the FEA is a powerful tool to estimate the ultimate BM of the hull.

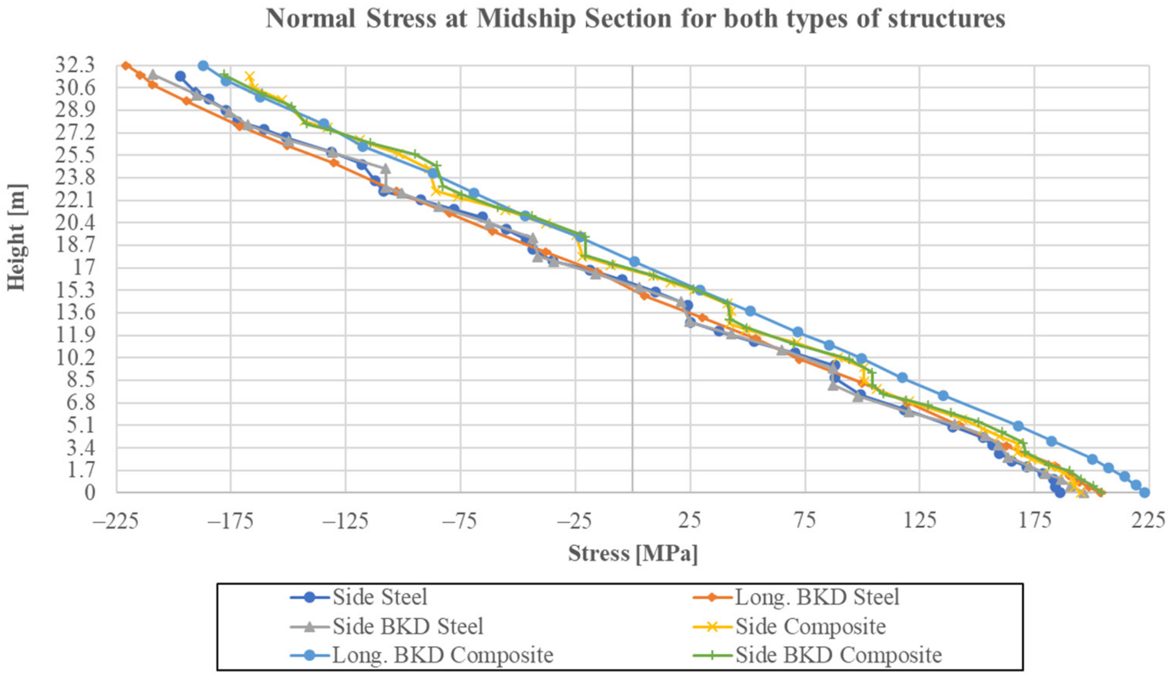

Figure 9. Normal stress distribution for the side, center and side longitudinal bulkhead.

Moreover, the ultimate strength load is obtained by increasing the load from the static load gradually until the structure reaches either a stress value near 665 MPa, which is the maximum stress from the true stress—true strain curve of DH36 steel—or there is a collapse due to classical plate buckling. This is because the applied loads are beyond their design values, structural members buckle in compression and yield in tension. The hull girder can normally carry further loading beyond the onset of limited buckling / yielding, but the structural effectiveness clearly decreases, and the individual stiffness can even become "negative" [23]. It is important to notice that this is a simplistic simulation once it used the model of the equivalent plate and not the stiffened panels. This could change the buckling behavior of the plates.

The FEA showed that the steel structure and the structure with SPS could withstand 1.94 and 2.45 times the static load, which is a 26% increase. This can be explained by the moment of inertia, which is inversely proportional to the normal stress. Therefore, the bigger the inertia, the bigger the bending moment required to reach a specific value. Furthermore, since the SPS structure has a bigger one than the steel structure (almost 10% bigger), this structure can reach higher values of bending moments. Table 12 summarizes this information.

Table 12. Ultimate strength multiplier.

Structure	Static Bending Moment [kNm]	Multiplier	Ultimate Bending Moment [kNm]
Steel	−29,453,568	1.94	−57,139,922
Composite		2.45	−72,161,242

Moreover, the moment-curvature graphic was also plotted to compare the ultimate bending capacity between the classification society rules (ABS/DNV) with the finite element results (see Figure 10). This graph shows the ULS for both types of arrangements and the location each plate starts to buckle as well. As it can be observed, the ULS for the steel and SPS according to the FEA are 11% and 24% higher, respectively, than the ones proposed by the classification society rules, which are more conservative about the estimation. Comparing the values obtained with the same comparison made in [23], they have similar behavior and values regarding the comparison between the FEM and the CS ultimate bending capacity.

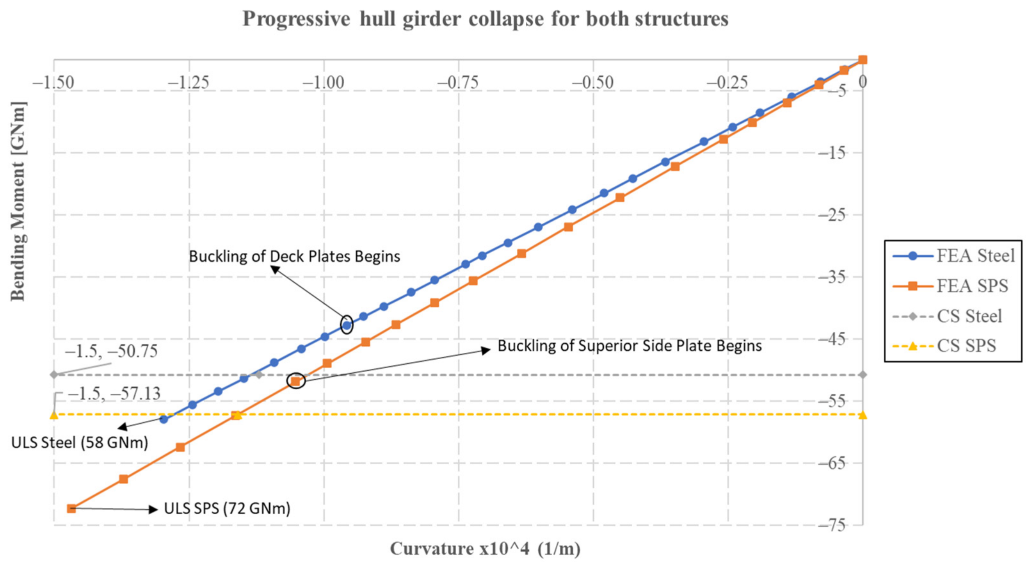

Figure 10. ULS for both designs.

The points circled in the graph indicate the locations where the buckling starts to occur in each plate of the side shell. As can be observed, both arrangements reach the ULS because of the buckling of plates; however, the bottom plates, which were in tension, could support an even heavier load once they did not reach the value near 665 MPa. The main difference between both structures is where the buckling happens.

For the steel design, the buckling happens in the deck plates. This was previously visualized in Section 5, in which the deck plates obtained the highest factor for the buckling and ultimate strength criteria. However, for the SPS design, the region where the plates fail first is the side shell. Similar to the steel ones, they were the ones with the highest values as well for the buckling and ultimate strength criteria. Moreover, their thickness is lower than the deck plates, therefore, their resistance to withstanding buckling is lower. This image phenomenon can be seen in Figure 11.

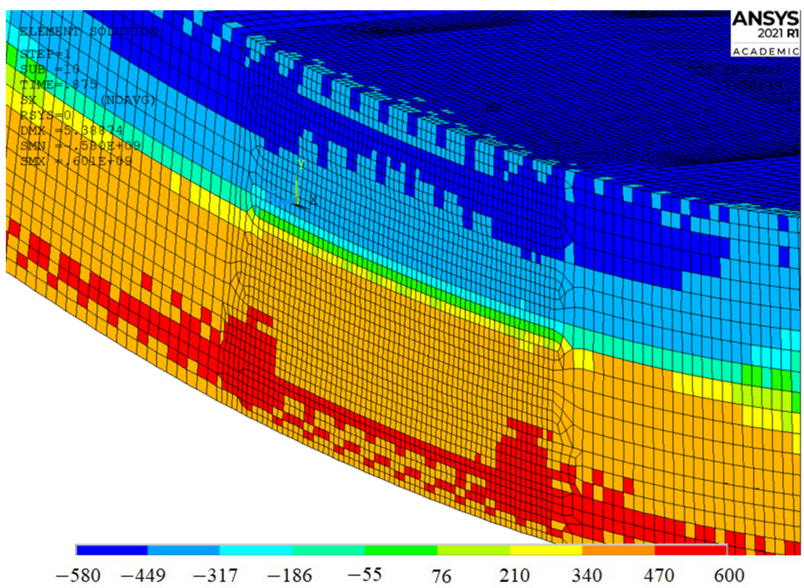

Figure 11. Normal stress at the side shell plates of the SPS design (Unit: MPa).

The last result is the stresses related to the core of the SPS plates. The panel has several criteria regarding the core yield and shear. Figure 11 presents the normal stress at the bottom plates at around 450 MPa. Therefore, using the ratio of the Young Modulus, the yield stress of the core was 1.82 MPa, which is 8% of the yield stress. This resulted also in shear stress of 3.95 MPa and an interface shear stress, which is related to the bond between core and steel plates, of 4.03 MPa, while the allowable ones are 12 MPa and 7.5 MPa, respectively. Therefore, the panel will not collapse because of the core.

7. Conclusions

This work focuses on the research for an initial design and construction of hulls for FPSOs with sandwich plates without stiffeners in the bottom plate and longitudinal bulkheads of cargo tanks. The main idea is to have the walls and bottom of the cargo tanks free of stiffeners to allow remote cleaning and thickness gauging of bottom and bulkhead plates using autonomous equipment.

The initial design of the traditional steel arrangement was made by using the results of this study and the guidelines of the ABS FPI rules [14]. This design was also compared to the DNV rule to check possible changes, and the total strength assessment was made. In general, the design obtained passed all the criteria of yielding (static and dynamic load case), buckling and ultimate strength proposed. The only exception was the deck plates at the static load case, which obtained a factor of 0.62 from the yield stress. This design was considered acceptable because it is close to the maximum safety factor (0.6 for the static load case).

The design of the hull with SPS panels was made by using the steel panels' dimensions and properties with the guidelines of DNVGL [16]. The SPS panels can withstand both static and dynamic load cases as the steel arrangement, but with a lighter structure.

Particular emphasis is given to the construction of the FE model for analyzing the ultimate strength of both arrangements: traditional steel and SPS panels. The static load case was used as a load condition in order to validate the models using as reference the results from beam theory. Although both steel and SPS models achieved results similar to the ones predicted, it is important to note that this analysis was a simplistic one. This is due to the use of the equivalent plate instead of stiffened panels. Thus, the buckling behavior can be slightly different. Additionally, a more refined mesh would be interesting for further analysis.

The FPSO's hull weight was calculated for both types of arrangements, and it was observed that the SPS one was overall 2.8% lighter than the steel one, primarily due to the bottom structure. This happens because the bottom structure has the plates with the highest thickness and with a more robust stiffener than the traditional hull structural arrangement.

Therefore, to summarize, the SPS design demonstrated superior structural performance over the traditional steel one. However, further research in the following areas would be interesting:

- Perform a local ultimate analysis for the SPS plates and stiffened panels with more details. This would provide more insights into the buckling and ultimate strength of the panels.
- Study the efficiency of the fabrication process of the SPS panels.
- Research the financial attractiveness of this new panel both during the building and operation steps in order to know how different kinds of costs vary.
- Research different filling materials and methods for polyurethane in order to have alternatives.
- Research the impact of this new technology during the operational life of the FPSO, converting inspection requirements, maintenance and repair work.

Author Contributions: Conceptualization, B.-Q.C. and P.M.V.; methodology, J.P.S.; formal analysis, J.P.S.; writing—original draft preparation, J.P.S.; writing—review and editing, B.-Q.C. and P.M.V.; visualization, J.P.S.; supervision, B.-Q.C. and P.M.V. All authors have read and agreed to the published version of the manuscript.

Funding: This study contributes to the Strategic Research Plan of the Centre for Marine Technology and Ocean Engineering, which is financed by the Portuguese Foundation for Science and Technology (FCT), under contract UIDB/UIDP/00134/2020.

Institutional Review Board Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Transport Industries Under European Commission. *Best Practice Guide for Sandwich Structures in Marine Applications*; Transport Industries Under European Commission: Newcastle upon Tyne, UK, 2013.
2. Li, R.; Chen, B.Q.; Guedes Soares, C. Design equation for the effect of ovality on the collapse strength of sandwich pipes. *Ocean Eng.* **2021**, *235*, 109367. [CrossRef]
3. Bond, J.; Ferro, A.; Kennedy, S. FPSO side shell impact protection. *Offshore Technol. Conf. Proc.* **2011**, *1*, 622–651.
4. Yoshikawa, T.; Bayatfar, A.; Kim, B.J.; Chen, C.P.; Wang, D.; Boulares, J.; Gordo, J.M.; Josefson, L.; Smith, M.; Kaeding, P.; et al. Committee III.1—Ultimate strength. In Proceedings of the 19th International Ship and Offshore Structures Congress (ISSC), Cascais, Portugal, 7–10 September 2015.
5. Chen, B.Q.; Guedes Soares, C. Experimental and numerical investigation on welding simulation of long stiffened steel plate specimen. *Mar. Struct.* **2021**, *75*, 102824. [CrossRef]
6. Zhang, X.H.; Chen, B.Q.; Guedes Soares, C. Effect of non-symmetrical corrosion imperfection on the collapse pressure of subsea pipelines. *Mar. Struct.* **2020**, *73*, 102806. [CrossRef]
7. Li, H.; Guedes Soares, C. Assessment of failure rates and reliability of floating offshore wind turbines. *Reliab. Eng. Syst. Saf.* **2022**, *228*, 108777. [CrossRef]
8. Li, H.; Huang, C.G.; Guedes Soares, C. A real-time inspection and opportunistic maintenance strategies for floating offshore wind turbines. *Ocean Eng.* **2022**, *256*, 111433. [CrossRef]
9. Paik, J.K.; Branner, K.; Choo, Y.S.; Czujko, J.; Fujikubo, M.; Gordo, J.M.; Parmentier, G.; Laccarino, R.; O'Neil, S.; Pasqualino, I.; et al. Committee III.1—Ultimate strength. In Proceedings of the 17th International Ship and Offshore Structures Congress (ISSC), Seoul, Korea, 16–21 August 2009.
10. Momčilović, N.; Motok, M. Estimation of ship lightweight reduction by means of application of sandwich plate system. *FME Trans.* **2009**, *37*, 123–128.
11. Kennedy, S.J.; Bond, J.; Braun, D.; Noble, P.G.; David Forsyth, J. An innovative 'no hot work' approach to hull repair on in-service FPSOs using sandwich plate system overlay. In Proceedings of the Offshore Technology Conference, Houston, TX, USA, 5–8 May 2003.
12. Det Norske Veritas. Sesam user manual: HydroD—Wave load & stability analysis of fixed and floating structures. In *SESAM User Manual*; Det Norske Veritas: Høvik, Norway, 2014; pp. 1–137.
13. Det Norske Veritas. Sesam user manual: GeniE. In *SESAM User Manual*; Det Norske Veritas: Høvik, Norway, 2012; pp. 1–263.
14. American Bureau of Shipping. *Rules for Building and Classing Floating Production Installations*; American Bureau of Shipping: Spring, TX, USA, 2020.
15. Lloyd's Register. *Rules for the Application of Sandwich Panel Construction to Ship Structure*; Lloyd's Register: London, UK, 2020.
16. Det Norske Veritas. *Dnvgl-Cg-0154: Steel Sandwich Panel Construction*; Det Norske Veritas: Høvik, Norway, 2016.
17. Liu, G.R.; Quek, S.S. *Computational modeling. The Finite Element Method*, 2nd ed.; Elsevier: Oxford, UK, 2014; pp. 1–11.
18. Seo, J.K.; Kim, B.J.; Ryu, H.S.; Ha, Y.C.; Paik, J.K. Validation of the equivalent plate thickness approach for ultimate strength analysis of stiffened panels with non-uniform plate thickness. *Thin-Walled Struct.* **2011**, *49*, 753–761. [CrossRef]
19. Paik, J.K.; Kim, B.J.; Seo, J.K. Methods for ultimate limit state assessment of ships and ship-shaped offshore structures: Part II stiffened panels. *Ocean Eng.* **2008**, *35*, 261–270. [CrossRef]
20. ANSYS Inc. ANSYS Inc. ANSYS Mechanical APDL Element Reference. In *Ansys User Guide*; ANSYS Inc.: Canonsburg, PA, USA, 2011; pp. 1–1416.
21. do Amaral Macedo, D. *Resistência Última de Navios e Plataformas Danificados por Colisões*; UFRJ: Rio de Janeiro, Brazil, 2017.
22. Paik, J.K.; Kim, B.J.; Seo, J.K. Methods for ultimate limit state assessment of ships and ship-shaped offshore structures: Part III hull girders. *Ocean Eng.* **2008**, *35*, 281–286. [CrossRef]
23. Paik, J.K. Ultimate strength of ship hull structures characteristics of ship's hull structures—Chapter 8. In *Ultimate Strength of Ship Hull Structures*, 2nd ed.; John Wiley & Sons Ltd.: Busan, Korea, 2018.