Hybrid Joint Between Steel Deck and Fiberglass Superstructure

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Abstract. In semi-displacement vessels, the reinforced fiberglass composite superstructure, or FRP, is one of the best construction options due to its low weight, shape, and surface finish. A problem with the FRP composite material lies in the joint with the steel hull due to the lack of adherence in the joint between the deck and the superstructure's FRP panels. This research presents a solution for hybrid joints between the deck and the FRP superstructure using a steel tubular structure and laminates with Isoftalic Resin. The design shear stress for the lamination of this hybrid joint has been considered to be 4.55 MPa, according to the recommendation of Lloyd's Register. The analysis initially makes an estimate of the reactions at the hybrid joint based on a 36.80-m ship and then performs a critical layer analysis with the finite elements method. This is followed by an analysis of possible hybrid joints to find the best option for a construction that fulfills design stress. The final hybrid joint presents better results and consists of ASTM B53 steel tubes, Sch40, and uses vertical tubes 2 in. in diameter and 60 cm in height as well as two longitudinal tubes of 1 in. in diameter at 30 cm and 60 cm from the deck, respectively.

Keywords: Hybrid joint · Composite panel · Composite superstructure

1 Introduction

Fiberglass reinforced panels are used in commercial and naval ships for areas where there is no need for high structural resistance, such as interior division panels, stairs, interior decks, etc. Currently, hybrid joints between steel decks and fiberglass superstructures on semi-displacement vessels have not been widely used even though fiberglass-panel superstructures with a balsa core provide a weight reduction of approximately 40% compared to a naval steel superstructure [3].

The development of this type of construction has led various researchers to make proposals regarding hybrid joints.

Salih and Patil [8] mentioned the benefit of using bolts in a hybrid joint, provided it is flexible joint. In their research, Ritter [4] and Hentinen [7] showed the advantages and disadvantages of using hybrid joints with adhesives and described applications on military ships.

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Weitzenböck [5] analyzed hybrid joints using adhesives and bolts, where the bolts were used as an alternative method in case of failure of the adhesive.

In their study, Babazadeh and Khedmati [1] analyzed the effects of the main parameters of a hybrid sandwich joint with adhesive, applying tension loads. The analyzed parameters included the length of the hybrid joint, the thickness of the adhesive, and the thickness of the upper and lower laminates. They concluded that the performance of the bond hybridized with adhesive depends on the geometry of the joint.

In a similar study, Kotsidis et al. [2] used modification in the joint; where the inner end of the steel plate had a bend of length L and an angle θ, concluding that the optimum angle of the bend is 15°, and that the bend contributed to the reduction of flexion stress.

The construction of ships with a mixed superstructure, i.e. with a superstructure above the main deck of with tubular steel and fiberglass panels and an upper superstructure composed only of reinforced fiberglass panels, first began in Ecuador in 2011 [3].

The hybrid joints proposed here consist of a tubular structure welded to the deck. The vertical structure comprises steel tubes 2 in. in diameter, Sch40, with a horizontal stiffening structure composed of a 3 × ¼-in. flat bar at the base welded to the deck and 1-in. tubes spaced 30 cm apart (welder tubes). The number of welder tubes depends on the finite elements analysis.

1.1 Introduction to Finite Elements Analysis

The following assumptions have been made for the analysis of the models using the finite elements method:

- The weight of the superstructure is 9.09 tons.
- The forces to be applied in the proposed hybrid model have been obtained considering the reactions of the ship under critical conditions, namely 30° of heel and 15° of trim. In each case, the design pressures given by Lloyd's Register [6] have been applied.
- There is no contact between the steel tube and the fiberglass panels; however, surface contact has been applied between the fiber laminate of the tubes and the steel tubes.
- The steel structure and the fiber structure do not use the same nodes.
- The edges of the fiberglass panel are simply supported and the steel structure moves in the direction of the applied forces.
- The mesh size is between 1.5 mm and 9 mm, with quadrilateral and triangular elements.
- In the finite element stress results, the occurrence of "hot spots" has been taken into consideration in order to avoid erroneous conclusions.
- ASTM B53 steel is used as the modeling material for the pipes. The following is used for the composite panels: a balsa core of 144 kg/m^3, fiberglass of 450 g/m^3 (Mat 450), bidirectional fiberglass of 400 g/m^3 and 800 g/m^3 (WR 400 and WR 800).

1.2 Behavior of the Hybrid Joint

Critical Zones of the Laminate: To study the hybrid joint between the steel tubular structure and the reinforced fiberglass, a local analysis was carried out on a panel of dimensions 1 m × 1 m with a vertical 2-in. tube and a horizontal (welder) ¾-in. tube. The FRP panel used was of the sandwich type, with a total thickness 37.20 mm; the laminate for affixing the tubes to the panel consist of three layers of fiberglass (Mat450 – WR400 – Mat450) with a total thickness of 2.92 mm.
The loads were applied to the end of the 2-in. tube assuming three possible directions: direction *Z* (F1), direction *X* (F2), and direction *XZ* (F3), with a magnitude of 5 kN (Fig. 1):

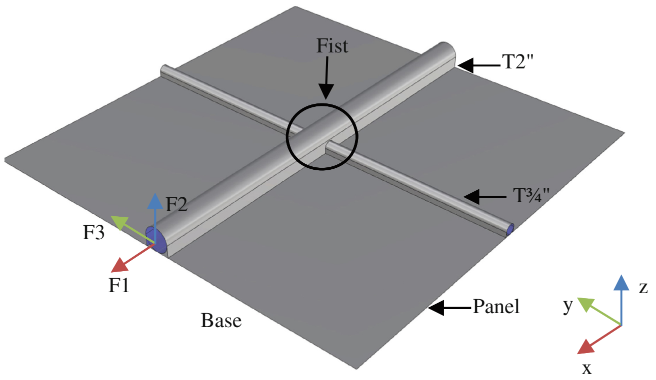

Fig. 1. Analyzed local panel

When analyzing the tubular hybrid joint, two critical zones are present: the fist (laminate at the intersection of the tubes) and the base (laminate close to the area of load application). In both zones, the magnitude of the shear stress increases from the edge of the tubes up to the crown, and finally the contact experiences "boundary bonding."

For the direction *Z* (F1) (parallel to the panel), the maximum shear stress is found in the fist between the vertical and horizontal tubes, as illustrated in Fig. 2. If the applied force is in direction *X* to the surface F2, the maximum shear stress is found at the edge of the laminate in the area where the load is applied, as illustrated in Fig. 3; this stress is considered the most critical condition for the tubular hybrid joint.

The size of the critical zone will depend on the direction of the load and its intensity. Figure 4 shows the stress produced by a direction *XZ* load F3; although the magnitude of the shear stress is lower than in the previous cases, the shear stress occurs at both locations.

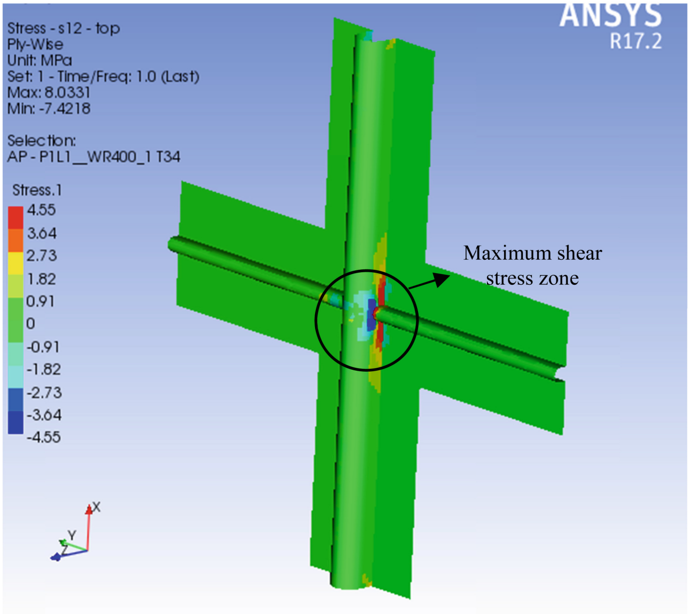

Fig. 2. Shear stress with F1 load

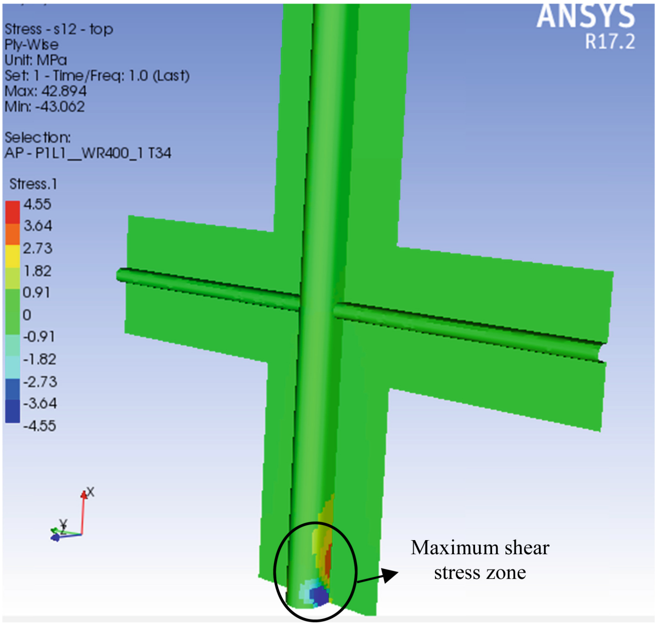

Fig. 3. Shear stress with F2 load

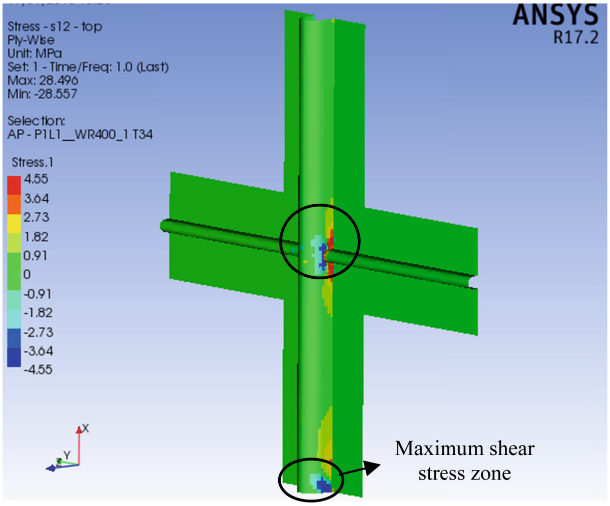

Fig. 4. Shear stress with F3 load

Diameter Variation of Welder Tubes: The results of the variation in the diameter of the welder tubes and the effect on the hybrid joint are presented below. A comparative analysis of the shear stress is presented by varying the diameter of the tube and applying a F3 direction load of 5 kN.

Table 1 shows the comparative relationship of the shear stress at the second fiberglass layer of the tubes (WR400), for the different diameters of welder tube, and the stress in the ¾-in. steel tube, λ_T.

Table 1. Relationship of shear stress to the ¾-in. steel pipe at the second layer, WR 400

Item	Shear stress relationship, $\lambda_T = \gamma_{Ti}/\gamma_{T3/4}$		
	Tube diameter	Fist	Base
1	3/4″	1	1
2	1″	0.983	0.991
3	1 1/4″	0.862	0.873
4	1 1/2″	0.871	0.865
5	2″	0.855	0.844

In Fig. 5 it can be seen that a greater reduction in shear stress is achieved with a 1 ¼-in. steel tube. There is no benefit to using welder tubes with a larger diameter, which would add weight to the structure.

The use of 1 ¼-in. steel tubes is not mandatory; however, it is an option that can be considered for the reduction of shear stress in critical areas of the superstructure.

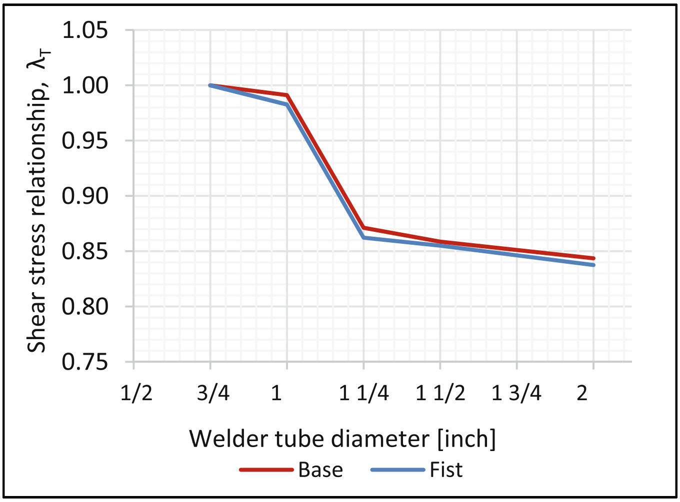

Fig. 5. Shear stress relationship λ_T vs. welder tube diameter

Influence of the Number of Layers in the Hybrid Joint: The laminate supports the entire impact of the loads on the hybrid joint; for this reason it is very important to select a suitable laminate. If this laminate is oversized, the weight will increase.

Table 2 presents several laminate combinations in order to compare the relationship between the maximum shear stress and the maximum shear stress obtained if only one layer of Mat 450 is used, λL. We can see that the greatest reduction in stress occurs in the fist, where using only three layers of fiber reduces the effort by 73% compared to the first layer, while for the base there is a reduction of 54%.

Table 2. Relationship of shear stress to first layer, MAT 450

# of Layers	Shear stress relationship, λ_L		
	Tube laminate	Fist	Base
1	Mat	1	1
2	Mat – Mat	0.442	0.767
3	Mat – WR – Mat	0.274	0.664
4	Mat – WR – Mat – Mat	0.185	0.572
5	Mat – WR – Mat –WR – Mat	0.136	0.484
6	Mat – WR – Mat –WR – Mat – Mat	0.100	0.438

Figure 6 shows the graph of the relationship λL, where it can be seen that for the laminate near the base, the trend after the second layer is almost linear, while the trend in the fist behaves linearly from layer 4 on.

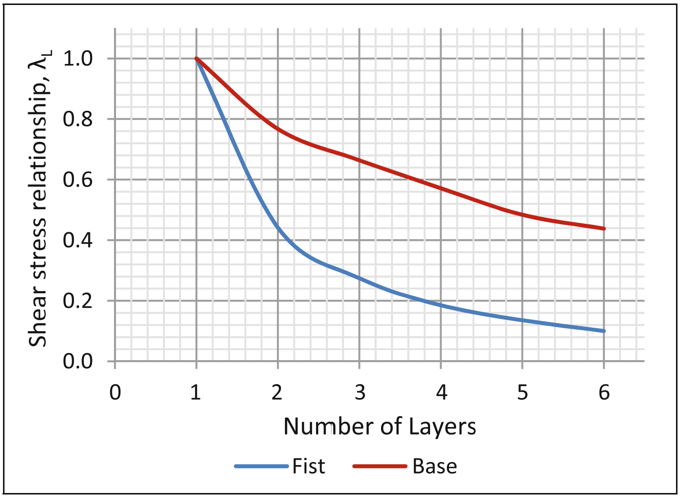

Fig. 6. Shear stress relationship λ_L vs. number of layers

2 Proposed Hybrid Joints

2.1 Study of the Proposed Hybrid Joints

For the study of a typical hybrid joint, two critical areas of the superstructure have been considered, since they are assumed to support greater pressure: the forward bulkhead and the sides of the superstructure. Based on these two zones, a hybrid connection with several geometries is considered. In all cases, the vertical tubes have a length of 60 cm and are joined by a 3 × ¼ in. flat bar at the base. The tested options are:

1. Vertical 2-in. tubes spaced 1 m apart and a ¾-in. welder tube at 30 cm from the deck. All tubes are laminated with three layers of fiberglass.
2. Vertical 2-in. tubes spaced 1 m apart and double ¾-in. welder tubes at 30 and 60 cm from the deck, respectively. All tubes are laminated with three layers of fiberglass.
3. Vertical 2-in. tubes spaced 1 m apart and double 1-in. welder tubes at 30 and 60 cm from the deck, respectively. The 2-in. tubes are laminated with four layers of fiberglass and the welder tubes have three layers of fiberglass.
4. Vertical 2-in. tubes spaced 60 cm apart and double 1-in. welder tubes at 30 and 60 cm from the deck, respectively. All tubes are laminated with three layers of fiberglass.
5. Vertical 2-in. tubes spaced 60 cm apart and double 1-in. welder tubes at 30 and 60 cm from the deck, respectively. The 2-in. tubes are laminated with five layers of fiberglass and the welder tubes have three layers of fiberglass.

Of the tests carried out, options 3 and 5 are the most convenient because less inter-laminar shear stress is produced; therefore, option 3 is recommended for side panels, while option 5 is recommended for the forward bulkhead. See Fig. 7.

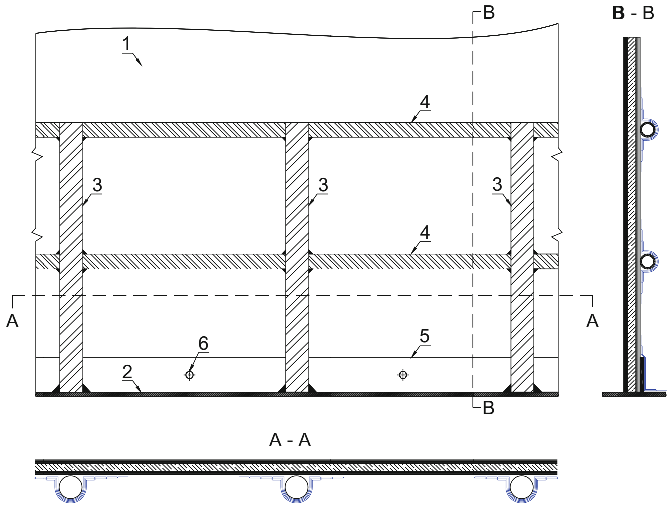

Fig. 7. Tubular hybrid joint

In Fig. 7, the numbers refer to the following:

1. Frontal bulkhead – reinforced fiberglass composite panel, laminated according to Lloyd's Register standards
2. Hull deck, thickness 6 mm – naval steel
3. 2-in. tube – steel Sch40
4. 1-in. tube – steel Sch40
5. Flat bar 75 × 6 mm – naval steel
6. Bolt 9 mm – stainless steel

Hybrid Joint Considerations: For the design of the hybrid joint, the following specifications must be used:

- The laminate of all the tubes must have an overlap in contact with the panel ("boundary bonding"), with a minimum of 25 mm between the layers, following the recommendations of Lloyd's Register [6]. A greater overlap does not improve the laminate.
- The laminate of the 75 × 6 mm flat bar should be two layers of fiberglass Mat 450.
- For the welder tubes it is recommended to use three fiberglass layers: Mat 450 – WR 400 – Mat 450. This is recommended for all zones in the superstructure.
- For the vertical tubes it is recommended to use:
  - Superstructure side: four fiberglass layers, Mat 450 – WR 400 – Mat 450 – Mat 450
  - Superstructure bulkheads: five fiberglass layers, Mat 450 – WR 400 – Mat 450 – WR 400 – Mat 450
- All tubes should be completely welded to the tubes on either side and to the flat bar; for details see [3].

- For the superstructure sides and bulkheads, there should be a vertical tube for each hull-side reinforcement or division and an intermediate reinforcement between them. For the front bulkhead, two intermediate tubes should be located between the reinforcements, depending on the structural scratch. The separation between the beams of the panels of the superstructure depends on the structural calculations made.

Structural Models of Study Areas: In Fig. 8, the loads applied to the superstructure side model are shown. The equivalent loads are generated by a heel of 30° to starboard and a design pressure on the side of 5.16 kN/mm^2.

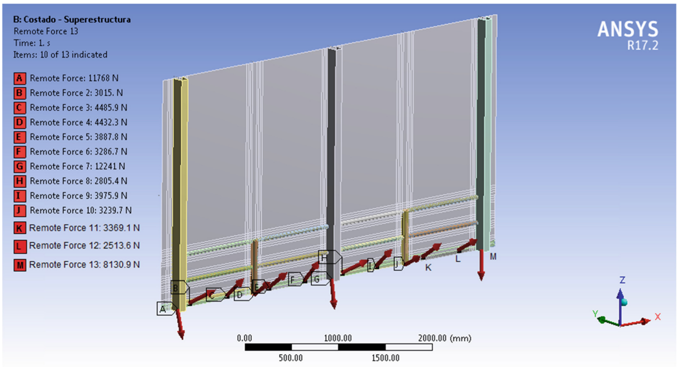

Fig. 8. Structural model – option 3: superstructure side

Figure 9 shows the equivalent loads applied to the front bulkhead model. The loads are generated by a 15° trim and a front design pressure of 10.08 kN/mm^2.

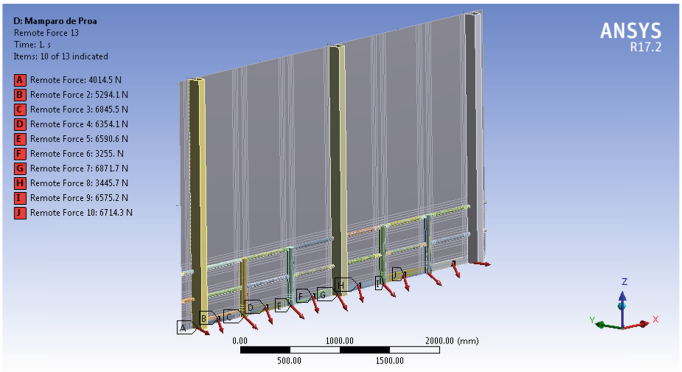

Fig. 9. Structural model – option 5: superstructure front bulkhead

3 Results

3.1 Results for the Superstructure Side Model – Option 3

The results for the shear stress obtained in the proposed model for the superstructure sides are presented in the second layer, as this layer shows greater stress. The maximum stress is generated in the intermediate cuff, with a value of 3.87 MPa, and in the base, with a value of 4.51 MPa.

In Fig. 10 it can be seen that in the fist, the stress starts from the center of the laminate of the 1-in. tube, and its magnitude is distributed approximately 45° towards the "boundary bonding." For the laminate at the base, the maximum stress starts from the corner of the laminate and is also distributed at 45°.

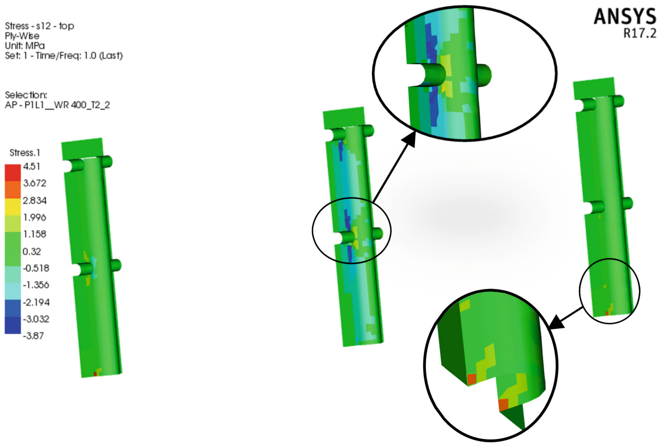

Fig. 10. Shear stress results of the 2-in. tube; second layer – WR 400, superstructure side

The lamination of the welder tubes does not present any significant shear stress. The maximum stress obtained for this case is 3.5 MPa, and occurs only in the area in contact with the fist; however, the average stresses have a value of 0.5 MPa. See Fig. 11.

The aim of the welder tubes and bolts is to contribute to the stiffening of the vertical tubes in order to avoid any possibility of failure.

3.2 Results for the Frontal Bulkhead Model – Option 5

For the proposed model of the frontal bulkhead, the stresses generated in the vertical tube laminate are shown in Fig. 12. It can be seen that the distribution of shear stress along the laminate is different from the previous case due to the forces applied. The maximum stress is generated at the base of the tubes and is distributed along the edge of the laminate to the crown. The maximum value for the stress is 4.11 MPa.

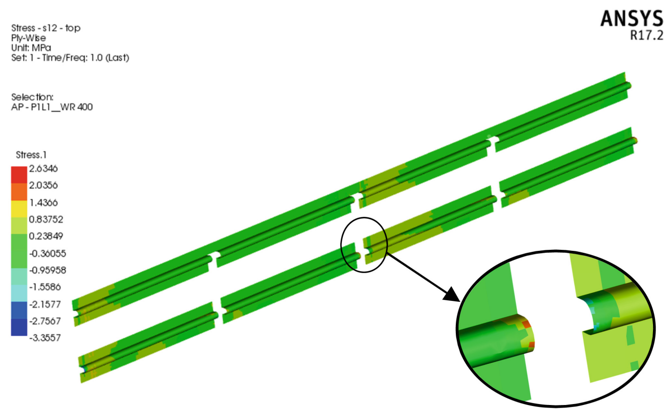

Fig. 11. Shear stress result for the welder tubes laminate; second layer – WR 400, superstructure side

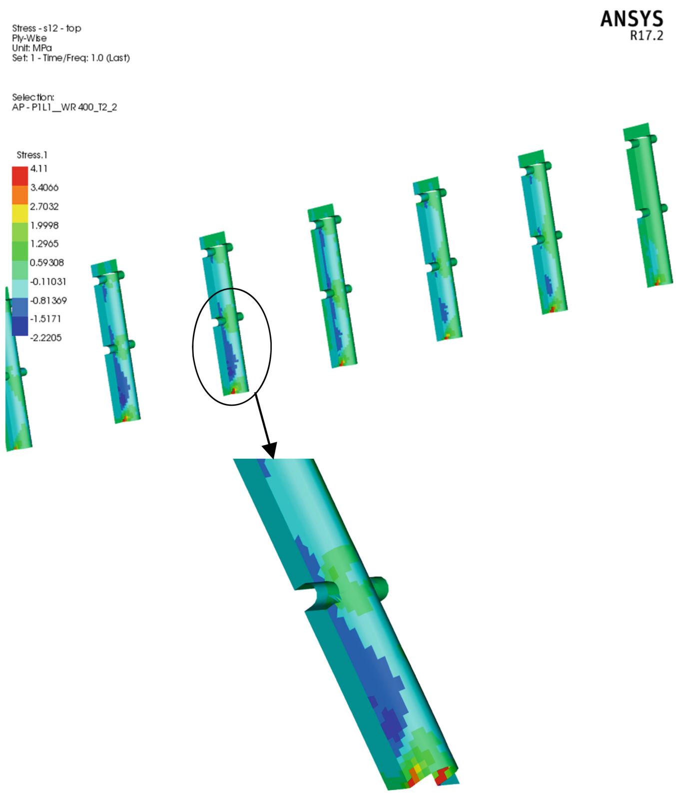

Fig. 12. Shear stress result of laminate of the vertical tubes; second layer – WR 400, bulkhead

4 Conclusion

This joining methodology can be applied to all types of vessels due to its contribution to the reduction of superstructure weight.

The hybrid joints proposed for the superstructure sides and front bulkhead meet the limiting shear stress of the critical layer of 4.55 MPa, as recommended by Lloyd's Register.

4.1 General Comments

The designer has the option to vary the diameters of the vertical tubes and the welder tubes or to increase the number of laminate layers; however, the benefit that would be obtained should be analyzed.

As has been demonstrated in this research, the greatest stress is observed in the vertical tubes. Therefore, it is sometimes convenient to add more fiberglass layers only in the critical areas.

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