ANALYSIS OF HYBRID (BOLTED/BONDED) STEEL-TO-COMPOSITE JOINT FOR MARINE APPLICATION

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Abstract

Any ship using composite materials for structural components will require hybrid connections of some sort, where composite sections are joined to metallic sub-structures. Joints are critical regions in the design of hybrid systems, as failures typically occur at joints and interfaces. Accordingly, this research presents the development of a hybrid steel-to-composite bonded/bolted butt joint.

In the present study, the behaviour of hybrid joint was investigated by numerical simulation. A three-dimensional non-linear finite element model was developed to predict load transfer distribution in the joint and to determine the ultimate static load (in both tensile and three point bending), which would cause the joint failure. In an attempt to more clearly understand the failure mechanisms within the hybrid joint, the bond area was modelled and so evaluated in accordance to Cohesive Zone Modelling (CZM) techniques. The effect of the joint geometry and adhesive material properties on the strength was determined through a parametric study.

1. Introduction

In the marine industry field, reduced hull and superstructure weight directly impacts on reducing fuel consumption. Thus, the introduction of composite materials provides a great potential in that aspect and several others, such as minimizing corrosion or reducing the maintenance and overall operation costs of the vessel. Hence, it is necessary to have a structural joining technology that allows linking a composite material and a metal structural.

Experience has shown that the contemporary use of bonded and bolted joining techniques does not improve the global behaviour of the joint. Bolt-adhesive joints in the maritime industry are not designed for hybrid action where one joining method improves the performance of the other. But, hybrid joints are used in a fail-safe mode, even to compensate the lack of confidence in the long term performance of adhesives. In fact, in case of fatigue failure of an adhesive, the bolt, which is not stressed during service, overcomes to preserve the structural integrity.

On the other hand, hybrid joints are also advantageous when the load acts in different directions, [1]. The adhesive carries shear stress while the bolts carry transverse loads.

Moreover, as mentioned by Anon [1], bolts may help to make a bonded joint survive an exposure to fire. That is, if an accidental high temperature condition occurs, which causes the adhesives eventually soften, the bolt is still able to carry the load.

2. Test case: Hybrid steel-to-composite bonded/bolted butt joint

This work analyses the behaviour of a particular hybrid joint both in tension and in bending; the study is finalized to marine application and more precisely to the joining of particular bow spoilers with the hull of containerships.

2.1. Geometry of the joint and definition parameters

The hybrid joint configuration shown in Fig. 1 is considered.

A sandwich plate is bonded to a steel plate by a vinyl ester resin; the sandwich is built up by four-layers-glass-vinyl ester skins bonded to a core of balsa wood.

A M8.8 bolt is placed in the middle of the straight overlap length. The solution is considered acceptable since literature, [2, 3, 4], suggests that the distance of the bolt from the extremity should be at least four times the bolt diameter; therefore the bolt must be positioned at least 32 mm from the extremity.

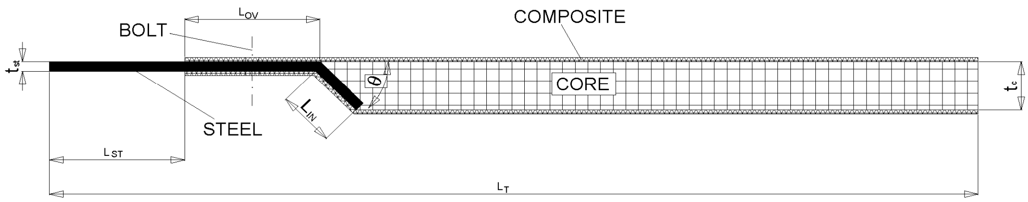

Figure. 1. Joint geometry

The design presented in this document was carried out by means of a comparative study based on the evaluation of the effect of the following geometric variables over the structural performance of the joint:

Case number	Bolt	L overlap (mm)	Joint angle, θ	Lin	Short name
1	No	240	15	0.5	P001
2		240	30		P002
3		240	15	1	P003
4		240	30		P004
5	Yes	240	15	0.5	P005
6		240	30		P006
7		240	15	1	P007
8		240	30		P008

Table 1. Analyzed cases

L_{in}=0.5 indicates that the steel plate covers only half of the inclined part of the joint; otherwise, when L_{in} is 1, the overlap of the steel plate reaches the end of the inclined part.

Dimensions that do not change are:

- overlap length: 240 mm
- overall length of the joint: 550 mm
- thickness of the skins: 2.5 mm
- thickness of the core: 300 mm
- L_{st} length: 80 mm

3. Numerical methods and load cases

3.1. Numerical model

In this work, a numerical simulation based in finite element method (FEM) to find hybrid joint behaviour has been used. The tests were then numerically modelled in a 3D space within both ABAQUS [5] and MENTAT/MARC [6] commercial finite element software. The first software was used in tensile tests whereas the second one was used for bending tests analysis. Main characteristics of the numerical models are listed below:

- Element type: An 8-node linear brick, reduced integration, hourglass control.
- Approximate global element size = 5 mm (*Note: The mesh is refined near the inclined part of the joint, where higher stress concentrations and failure are expected. Moreover, for the three point bending test, a finer mesh is used where the supports and the load roller are placed).*
- *Controlled displacement approach).*
- In order to account for the geometrical and material nonlinearities, the Newton-Raphson method has been utilized together with a line search algorithm.
- Analysis options: automatic step time increment, max TS = $0.1 \cdot d_{fin}$, min TS = $1E\text{-}8 \cdot d_{fin}$, max. number of increments = 2000.

3.2. Material properties

The materials used in the present work are biaxial stitched fabric 813 g/m2 E-glass woven roving (METYX Composites), vinyl ester resin (CRYSTIC VE679PA), 155 kg/m^3 balsa wood core (ProBalsa Standard) and 10 mm thick mid steel. For sake of simplicity the core is modelled as an elastic-plastic isotropic material.

Material properties are listed in Table 2.

	Steel	Composite	Core (Balsa)
Law	Elastic plastic isotropic	Homogeneous elastic orthotropic	Elastic plastic isotropic
Properties	E = 209220 MPa ν = 0.2734 σ_{ys} = 393.4 MPa σ_u = 524.4 MPa Elongation at break = 32.5%	E_{11} = 26400 MPa E_{22} = 25220 MPa E_{33} = 3000 MPa ν_{12} = 0.24 ν_{13} = 0.50 ν_{32} = 0.06 G_{12} = 2200 MPa G_{23} = 1200 MPa G_{31} = 1200 MPa	E = 320 MPa ν = 0.32 "σ_o" = 13.1 MPa (average of tensile and compressive strength of the core) E_T = 6.4 MPa (tangent modulus = 2% of E)

Table 2. Material properties

3.3. Adhesive joints: bonded interfaces.

A Cohesive Zone Model (CZM) is used to model the adhesive behaviour including the debonding phenomenon. CZM is based on the assumption that one or multiple fracture interface can be artificially introduced in structures, in which damage growth is allowed by the introduction of a possible discontinuity in the displacement field. The technique consists of the establishment of traction-separation laws to model interfaces. The CZM laws are established between paired nodes of cohesive elements, and they can be applied directly between two non-contacting materials to simulate a thin strip of finite thickness between them, e.g. to simulate an adhesive bond. This approach is shown in Fig. 2.

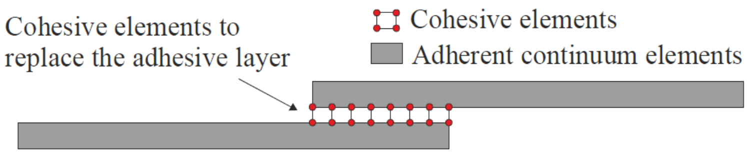

Figure. 2. Cohesive elements to simulate thin adhesive bond between the adherents.

The traction-separation model used assumes initially linear elastic behaviour followed by the initiation and evolution of damage. The elastic behaviour is written in terms of an elastic constitutive matrix that relates the normal and shear stress to the normal and shear separations across the interface.

Once a damage initiation criterion is met, damage can occur according to a user-defined damage evolution law. In this case study, damage is assumed to initiate when a quadratic interaction function involving the nominal stress ratios is fulfilled.

The adhesive layer is most likely mixed mode loaded, i.e. we have a contribution of Mode I and Mode II in the failure process. The damage propagation is studied in terms of energy release rate and fracture toughness.

The overlapping of the elements is forbidden because the particular definition of the constitutive law does not allow the compressive state to influence the behaviour of the cohesive elements.

Since there are three possible interfaces in the joint:
- steel/composite;
- steel/balsa;
- composite/balsa,

Three different bilinear cohesive laws are used. The CZM properties are defined to get the strength limits indicated in Table 3.

Cohesive properties	**Steel / Composite**	**Steel / Core Composite / Core**
Normal stress (MPa)	7.3	3.65
Tangential stress (MPa)	53	26.5
Critical fracture energy for normal (mode I) separation (N/mm)	0.14	0.07
Critical fracture energy tangential (mode II) slip (N/mm)	0.28	0.14

Table 3. Interfaces cohesive properties

In all models, the adhesive layers were modelled using 8-nodes three dimensional cohesive element, with one element with zero thickness.

3.4. Load cases.

The joint is studied in tension and in bending; in both cases. A first load case provides the application of the bolt preload in a unique step of 1 second. The bolt was modelled as a solid body. In order to apply the preload, a touching contact with friction is necessary between the bolt and the joint.

In the tensile test, a pinned constrain (U1=U2=U3=0) is applied at the sandwich edge. A second load case applies a longitudinal displacement of 3 mm. That displacement is applied to the steel edge.

In the three points bending test, the extremities of the joint are free, in conformity with the D790 ASTM standards. The vertical translation is forbidden introducing contacts between the joint and the supports. The latters are placed at a distance of 40 mm from the extremities of the joint. A second load case applies a vertical displacement of 40 mm through 40 steps of 0.05 seconds each; the displacement is applied by the movement of the load roller.

4. Results and discussion

4.1. Joint behaviour in tension

The influence of the bolt effect over the joint subjected to a tensile load is discussed in the following paragraphs. One of the aims of the analyses is to know and understand the failure mechanism present in the hybrid joint.

Note that the ultimate load is identified in the graphs as the load value after which the curves abruptly drop or their slop becomes negative.

4.1.1. Type A specimens (without bolt).

The graph of Fig. 3 represents the behaviour of the joint in terms of Reaction Force vs. Displacement of the specimen at the steel edge.

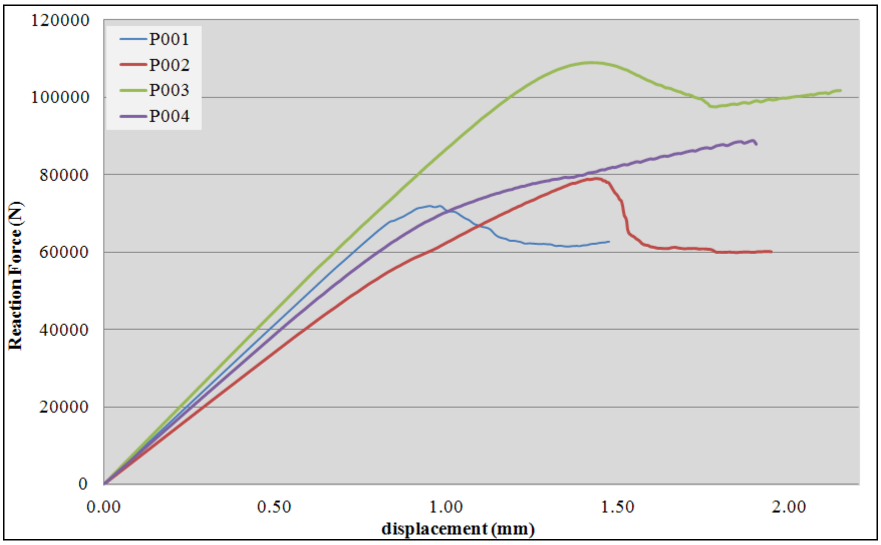

Figure. 3. Reaction force vs. displacement of the specimen at the steel edge.

- *4.1.2. Type B specimens (with bolt).*

The graph of Fig. 4 represents the behaviour of the joint in terms of Reaction Force vs. Displacement of the specimen at the steel edge.

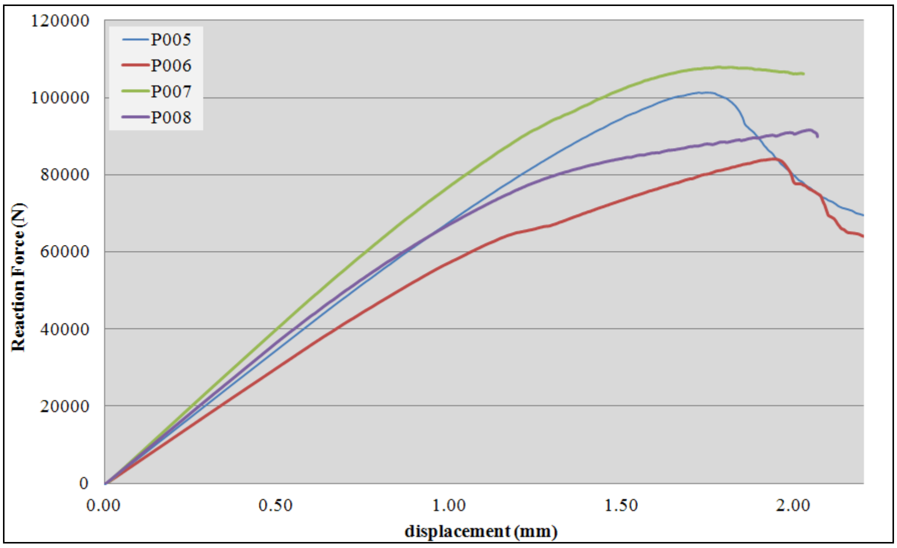

Figure. 4. Reaction force vs. displacement of the specimen at the steel edge.

- *4.1.3. Summary*

Table 4 summarizes the results obtained by FE numerical analysis.

		debonding initiation		debonding effect on stiffness		ultimate load	
		d (mm)	F (N)	d (mm)	F (N)	d (mm)	F (N)
no bolt	P001	0.47	38851.3	0.66	55161.8	0.95	72050.3
	P002	0.52	35804.8	0.75	50337.1	1.43	79053.1
	P003	0.51	45985.4	0.72	63875.0	1.42	108943.3
	P004	0.44	34336.7	0.58	45171.7	1.89	88921.6
with bolt	P005	0.51	35024.1	0.85	58513.6	1.75	101341.9
	P006	0.50	29952.9	0.84	49453.2	1.94	84045.0
	P007	0.45	35703.5	0.70	55899.6	1.78	107969.7
	P008	0.31	22697.9	0.58	42079.9	2.04	91644.3

Table 4. Forces and displacements results for the whole specimens.

4.2. Joint behaviour in bending

The objective of these simulations is to evaluate the influence of the various design variables on the joint performance in bending condition. The performance of the joint are evaluated considering the following key factors:

- deflection of the specimens;
- stiffness;
- onset of the debonding of the composite from the core and the steel plate;
- ultimate load.

- *4.2.1. Type A specimens (without bolt).*

The graph of Fig.5 shows the response of the specimens in terms of Force vs Displacements of the load roller.

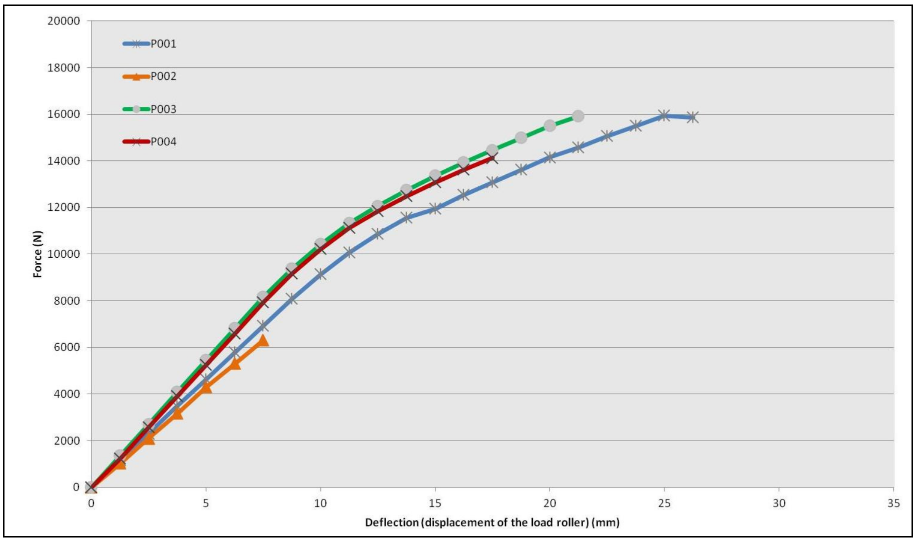

Figure.5. Reaction force vs. deflection of the load roller

- *4.2.1. Type B specimens (with bolt).*

The graph of Fig.6 shows the response of the specimens in terms of Force vs Displacements of the load roller.

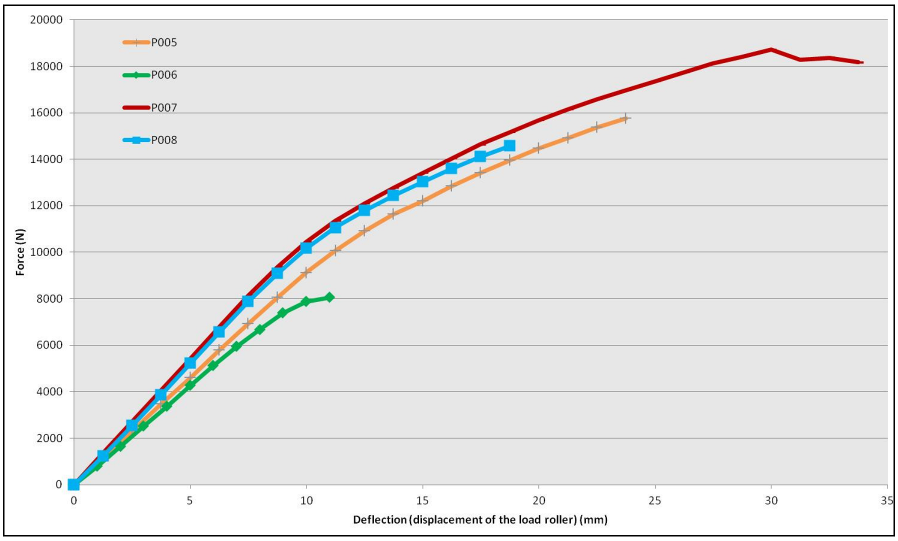

Figure.6. Reaction force vs. deflection of the load roller

- *4.2.3. Summary*

Table 5 shows the onset of the degradation of the cohesive layer and the ultimate load for both each A and B specimen.

Joint configuration	Start of the degradation of the cohesive elements	Ultimate load* (N)
P001	End of the steel plate when the load is equal to 6932 N	11567
P002	End of the steel plate when the load is equal to 3158N	6299
P003	Where the steel plate bends when the load is equal to 6807 N	15907
P004	Where the steel plate bends when the load is equal to 6595 N	14122
P005	End of the steel plate when the load is equal to 6924 N	15747
P006	End of the steel plate when the load is equal to 4268 N	8052
P007	Where the steel plate bends when the load is equal to 11344 N	18707
P008	Where the steel plate bends when the load is equal to 6551 N	14565

Table 5. Degradation and failure loads

4. Conclusions

In this study the structural integrity for a hybrid steel-to-GRP joint has been characterized through a parametric analysis.

Cohesive elements implemented in the commercials finite element softwares, both ABAQUS and MENTAT/MARC, have been successfully used to simulate the thin strip of adhesive of the bonded joint.

The numerical analyses provide insight into the failure mechanism present in the hybrid joint. The linear portion of the Load vs. Displacement/Deflection curve clearly shows the actual joint stiffness before the failure by delamination occurs and how the specimen behaves linearly. The progressive damage model accurately represents the point at which the Load vs. Displacement/Deflection curve becomes significantly nonlinear.

The presence of the bolt does not increase the stiffness of the joint. The bolt only increases the maximum load sustained by the joint.

Overall in tensile, the degradation of the cohesive layer starts where the steel plate bends, at the upper side. In bending, in all joints with L_{in} = 1 (with and without bolts) the degradation starts where the steel plate bends whereas in the configurations with L_{in} = 0.5 the degradation starts at the end of the steel plate.

5. Acknowledgments

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