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Testing and simulation of a bolted and bonded joint between steel deck and composite side shell plating of a naval vessel

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ABSTRACT

This paper describes the large-scale testing and the finite element simulations of the collapse of a steel-composite joint, both bolted and bonded. The joined structures are typical ones of shipbuilding and namely of naval ships. Composite superstructures, beside a valuable weight reduction, may improve the signature features of the ship by embedding installed electronic devices into a composite mast. In the frame of a broader research project, including the electromagnetic characterization of the composite structures, also the structural design and its optimization were exploited, embracing, among other issues, the joining solutions between the steel deck structures to the composite ones of the superstructure side shell. A large-scale specimen of the joint was conceived and collapse tested while, in parallel, design simulations were carried out at different levels of detail. Eventually, a complete description of the collapse of the joint, including the nonlinear simulation by finite element analysis of the progressive failure of the composite laminates of the side shell was obtained and test results were used to validate the numerical models.

Depending on the design stage, various scantling procedures, from a very simplified one to a rather complex and time-consuming numerical analysis, can now be applied to verify the structural behavior of these steel to composite joints as well as to select the most cost-effective solution among several options.

1. Introduction motivation

The a family of integrated masts intended for naval vessels was the subject of a broader research project funded by the Italian Ministry of Education, Universities and Research. An integrated mast includes a box-shaped structure, built with materials suitably transparent to electromagnetic radiation, designed to contain the typical electronic devices of a naval vessel and able to ensure maximum radar coverage and minimum electromagnetic signature. One of the characteristics of this type of mast is that the antennas and some electronic apparatuses are integrated within the structural components to constitute a specific self-standing block, assembled with the remaining part of the ship's structure. Integration concerns the electronic components as well as the mast main structures, requiring all parts to be properly selected and designed so that they can be installed on the ship minimizing interference problems from both the electromagnetic and the structural viewpoint.

To the best of the authors' knowledge, there is a limited number of available publications about hybrid joints in navy ships and even less about bolted/bonded joints.

Mouritz et al. [16] reviewed the application of composites in naval vessels and dedicated a specific section to superstructures and masts. Dow et al. [6] recently reported the state of the art about naval ship construction and dealt with ship masts as well, comprehensively reviewing available literature and other sources and suitably addressing various design aspects.

Integration, in addition to signature improvement, has some advantages such as compactness of the radar components, possibility of a relatively quick change of mast on a ship and reduction of installation and maintenance time. Furthermore, this structure will be easily adaptable to various types of navy ships, being suitable to accommodate the required components according the ship type and size. Not to mention the fact that lightweight materials at top structures contribute to improve the overall performances of the ship in terms of stability, resistance and seakeeping.

The structural joints are usually the weakest elements in structural design. Therefore, it is advisable their enhanced implementation. Part of the research project was specifically oriented to the analysis of the joining problems of integrated masts. The fundamental categories of the joints considered in the project are essentially:

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– Bonded joints, where the load is transferred through glued surfaces;
– Mechanical joints, where the load is transferred through mechanically connected elements.

An overview of pros and cons of the two solutions is provided by Broughton et al. [1]. The bonded joints have relatively high stiffness and limited weight, good fatigue resistance and no corrosion-related problems. Compared to other types of coupling, bonding allows avoiding stress concentrations, which may compromise the efficiency of the joint. Most important, they can be used with rather dissimilar materials, like e.g. metals and composites. Obviously, bonded joints have some negative aspects to be taken into account. The joints cannot be disassembled and are difficult to inspect, so it will be hardly possible to perform regular maintenance. The actual efficiency of bonded joints is strongly related to the thickness of the adherents and to fabrication procedures. Finally, the low peeling strength of adhesive materials should be considered. These limits unavoidably affect the efficiency of the joint from the structural strength viewpoint.

The second type of joint is mechanical and, in comparison to bonding, it presents a few advantages: it is easier to build by a shipyard and it is more easily assembled and inspected. The thickness of the elements to be joined is virtually not limited and structural strength of joined components can be practically restored. However, these advantages are tied to a number of important drawbacks such as stress concentrations, low fatigue resistance, a tendency to corrosion and to a more limited stiffness compared to bonded joints.

The selection of a composite mast during the research project, aimed at saving as much weight as possible, implied that a composite to steel joint was in fact required. The project eventually selected a hybrid joint, where composite and steel structures are joined by bonding. However, in addition to bonding, bolts are added for redundancy in the bonded joint, taking into account the challenging strength requirements of a naval vessel. Moreover, bolts were used to connect the base of the joint to the ship flange in a steel-to-steel connection, making it possible to detach the mast structures from the ship and avoiding the excessive heat input due to welding in areas close to the mast composite structure.

This solution, shown in Fig. 1, has the benefits of a large redundancy, very good stiffness and it is structurally strong enough to withstand the heavy static and dynamic design loads of an integrated mast. Unfortunately, due to confidentiality reasons, it is hardly possible to know configuration details of similar structures. Indeed, extremely limited literature is available about hybrid joints in naval ships.

Research on bonded composite-to-metal structures was carried out in the frame of the EU Bondship and Euclid 3.2.1 programs [17]. While in small crafts and aerospace industry composite structures are widely used, rather high wave loads suggest combining steel or aluminum hulls with composite deckhouse structures for large vessels. One of the few examples is the France's Lafayette Class Frigates (125 mlong, 3500 tons), which have a composite superstructure that is bonded and bolted to a steel hull.

Similarly to the mentioned research Italian project, US Navy recently supported research programs about composite secondary structures such as antennas' masts and deckhouse. Noticeably, a sandwich composite and socket joint structure where the composite wall panel is attached to the deck with mechanical means is used. Most existing designs use bolts in addition to adhesives to attach the vertical composite panel to the metal connecting structure, which is welded or bolted to the horizontal steel deck [12]. Caccese et al. [3,4] supported the US Navy efforts by carrying out wide ranging experimental and numerical analyses on various bolted/bonded joints in different loading conditions.

Recently, a review book chapter about hybrid bolted/bonded joints in maritime industry has been published [19] but very limited applications and even fewer tests were reported. Despite in other industrial fields hybrid bonded/bolted joints are applied, this is a rather novel joining technique in ship and offshore structures. Probably, because of relatively large dimensions as well as complex loading conditions and also because of traditional shipyards building practice and typical structural layouts, making such joints in shipbuilding rather different with respect to bonded/bolted joints in other engineering fields.

Yarza et al. [21] highlight that in the maritime industry hybrid action of bolts and adhesive is used to preserve the structural integrity in case of fire and to support loads in different directions rather than to improve the global behavior of the joint. Unfortunately, they only numerically assessed by finite element analyses small-scale standard tensile and three-point bending joint specimens.

An interesting experimental work was presented by Cao & Grenestedt [5], who compared different joints for composite sandwich/steel hybrid ship hulls, one of them being bolted/bonded. Noticeably, hybrid joint beam specimens were manufactured and tested under bending and shear loads, showing strengths approaching that of the composite sandwich reference specimens.

Hu et al. [20] modeled the progressive failure of bolted single-lap

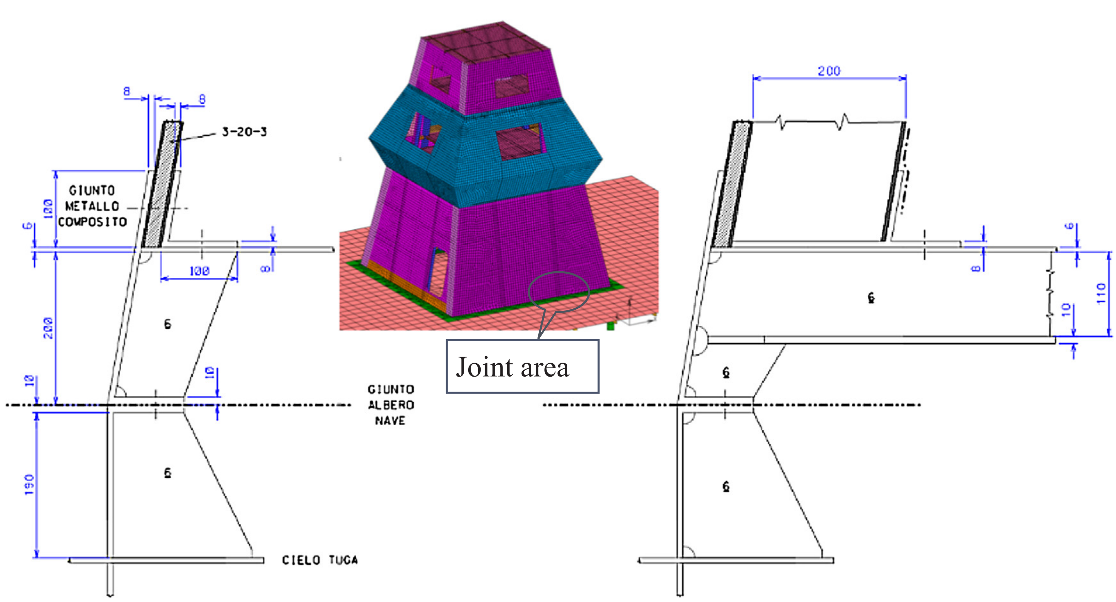

Fig. 1. Designed mast and its joint configuration.