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A comprehensive review on structural joining techniques in the marine industry

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ABSTRACT

Exposure to aggressive environmental conditions and specific loads necessitate precise material selection and manufacturing techniques. Techniques such as overlamination, welding, adhesive bonding, mechanical joining, and hybrid joining are currently used to join different marine structures components. This review groups the published investigations to cover a wide range of geometries, materials, and loading types and organizes them in a chronological context. Comparing joining methods shows that each technique has a considerable potential to be employed in the various marine industry sectors corresponding to the desired application. Besides the significant strength, poor fatigue life is a concerning issue for welding. One of the most crucial challenges in mechanical fastening is drilling holes in composite materials that damages the fibres. Adhesive bonding provides superior advantages such as higher strength to weight ratio and fatigue life, whilst the susceptibility to environmental conditions must be considered. To overcome the drawbacks of each approach, the hybrid joining technique is introduced which combines two different joining methods to achieve the optimum performance. To have the most durable, and reliable structure, major criteria such as the structure application, the fabrication process, and the tolerance of adverse environment must be considered to design the marine structures.

1. Introduction

Over the last decades, progress in the marine and naval industry encourages researchers to improve the structures and increase their efficiency, as well as durability by designing novel approaches and optimization of current methods [1,2]. Conventionally, aluminium and steel are used as the main material for the construction of marine structures. Nevertheless, despite the considerable stiffness of steel and the reduction in weight in aluminium structures, the use of these materials causes concerns such as low resistance to fatigue and electrolytic corrosion [3]. As a result, fibre-reinforced polymers (FRP) have emerged as the most functional material due to the requirement of using corrosion resistance structures. Since the mid-1980, are utilized in various sectors of the marine industry in a variety of components and structures, such as hulls, bulkheads, bearings, propellers, topside structures, different types of vessels, valves, decks, watertight doors, machinery foundation, pipes, ventilation ducts, components for diesel engines and heat exchangers on large warships [4-7]. The composites are thermoset- or thermoplastic-based. The most used composites are carbon fibre reinforced composites (CFRP) or glass fibre reinforced composites (GFRP). Employment of FRP materials results in a significant reduction in structure weight, particularly for topside weight, which not only conduces to increase in payload and speed but also a noticeable reduction in fuel consumption and cost [3,6,7]. Furthermore, vibration damping, noise absorption, and acceptable performance against fire are other remarkable advantages of composite structures, especially in the case of military applications. Nonetheless, the tensile modulus of these materials is considerably low, which makes them vulnerable to deflection especially when the length is high. Therefore, combining the composites with other materials such as steel or aluminium is essential. One of the most used dissimilar pairs used in the marine industry is steel/CFRP, which is usually made by adhesive bonding [8]. The CFRP and GFRP composites have found so many naval applications such as in some propeller structures which are made of CFRPs. One important reason is the reduction of weight which is of great interest in the marine industries. Another usage of CFRPs is in the hull of the cruise boats [9] as well as masts [10]. The main advantage

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of these composites over aluminium is their better damping characteristics. Between 1970 and 1984, sandwich structures consisting of GRP skins with a Polyvinyl Chloride (PVC) foam core were used in the hull of GRP MCMVs developed by Karlskrona shipyard in Sweden [6] as well as the hull structure. However, glass fibres are the most used fibres due to their low price and compatibility with many resins. The cost of glass is 5 times lower than the carbon fibres, but carbon fibres have a higher strength. The application of CFRP is limited to yachts and racers. Fibre-reinforced composites are also used in offshore structures.

Not only the weight reduction but also the durability of the manufactured components is a key factor in structural design in marine applications. Inland, coastal, offshore, and deep-sea water marine structures are frequently exposed to cyclic mechanical loadings including forces and moments caused by environmental factors such as wind, and waves as well as service factors like operations and machinery [11]. Fig. 1 represents the loading conditions that the marine structures usually experience in service. Fig. 2 illustrates various loading conditions acting on a representative yacht.

Exposure to harsh environmental conditions, cyclic fatigue loads, and high temperature (particularly in a tropical environment), dramatically exaggerate fatigue cracking in the components which results in loss of strength and stiffness of the structure [11-15]. These circumstances trigger crack propagation predominantly in zones with high-stress concentrations. Due to the aforementioned points, it is necessary to join metals to polymers. With the objective to shape the panels into a large and complex structure, several components must be manufactured and joined [16]. Commonly, in ship buildings, bulkheads are used to divide the hull into several compartments. Furthermore, to maintain the ship stiffness under different loading circumstances, hulls and bulkheads are employed as the primary structures in the marine industry [5]. In order to connect and transfer applied load from the bulkheads to the hull, various types of joints are used as the connection between the sub-structures [5,17]. As a result, the reliability of the whole structure substantially depends on the strength and durability of the joints [17]. Different types of joints including adhesively bonded, welded, mechanical fastening, and hybrid joints are employed extensively in various marine structural components such as watercraft, submersibles, and offshore structures. Overlamination is widely used in shipbuilding to connect substructures. However, since the hand lay-up method is used to join materials, uniform resin distribution on the fabric is a crucial issue that should be considered by the operator [18]. Nonetheless, manufacturing processes and design requirements necessitate engineers and scholars to employ the most efficient joining methods in the marine and naval industry. As a traditional joining method, welding has been employed in order to join components permanently by quite the same material to form a unit. Superior strength to weight ratio, significant load-carrying capacity, and ability to join dissimilar metals as well as plastics are examples of advantages of different welding methods. Nevertheless, poor vibration sustaining capability, alteration in metallurgical properties as well as residual stress generation due to uneven heating and cooling are several challenges in using this method [19,20]. In addition, in terms of high load cycles, welded joints are prone to fatigue cracking. Another method to join the marine components is mechanical fastening such as bolting and riveting which maintain the mechanical properties of the base material. However, this joining method causes a noticeable stress concentration which consequently leads to fatigue crack propagation as well as a considerable increase in the weight of the structure [15]. Furthermore, galvanic corrosion owing to exposure to saltwater is another concerning issue in using mechanical fasteners [21,22]. The third method to join panels and components is adhesive bonding joints which gain considerable attention. Although by employing this joining method the stress distribution in the structure will be improved, adhesively bonded joints are vulnerable to moisture, high temperature, and UV radiation [23]. As a result, the idea of hybrid joints has emerged in which two joining methods are combined in order to optimize and boost the mechanical performance of the joint by the conjunction of the characteristics of the techniques used. Bolt-adhesive, weld-adhesive, and laser-arc welding are several examples of hybrid joints [24,25]. Due to the fact that failures occur mainly at joints due to the higher stress concentrations, selecting a proper joining method is crucial in order to reach higher strength, reliability, and sufficient durability. The current review paper covers a literature view on investigations conducted by scholars on different joining approaches used in marine and naval industries overlamination, welding, adhesive bonding, mechanical fastening, and hybrid joints. For each joining technique, various effective factors such as material, geometry, manufacturing processes, and loading conditions are considered.

2. Overlamination

Sandwich structures are light versatile composite structures that consist of a low-density core covered by two thin stiff facings. High energy absorption properties, superior stiffness to weight ratios, remarkable ballistic resistance performance are several advantages provided by sandwich structures [26]. Lightweight sandwich structures are used widely in the marine and naval industry. However, one of the significant challenges in the construction of thin-walled structures is joining the panels together as well as panels to other substructures. Hence, in order to increase the fatigue resistance, the overlamination method has been introduced. In general, an overlaminated joint consists of two parts that are connected by lamination [27]. Reduction of the fasteners, assemble cost, the primary structural weight of the structures, and being time-saving are a number of advantages of overlaminated

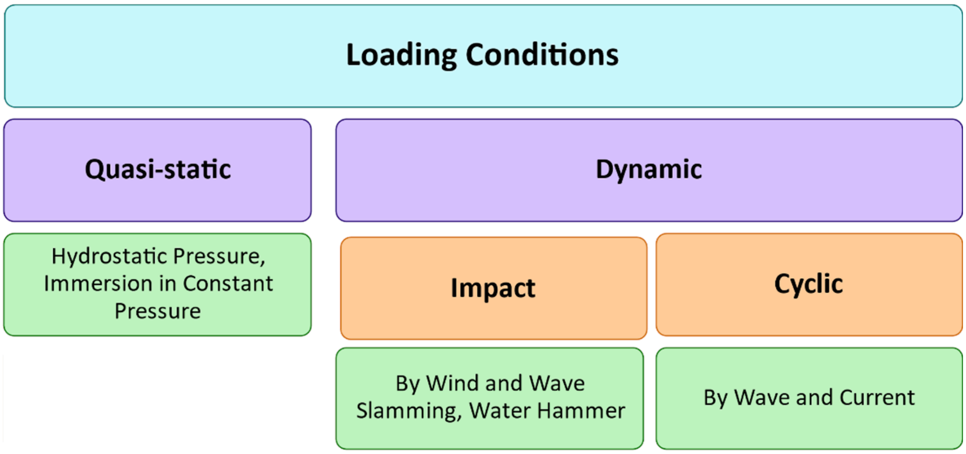


Fig. 1. Loading conditions applied to a marine structure.

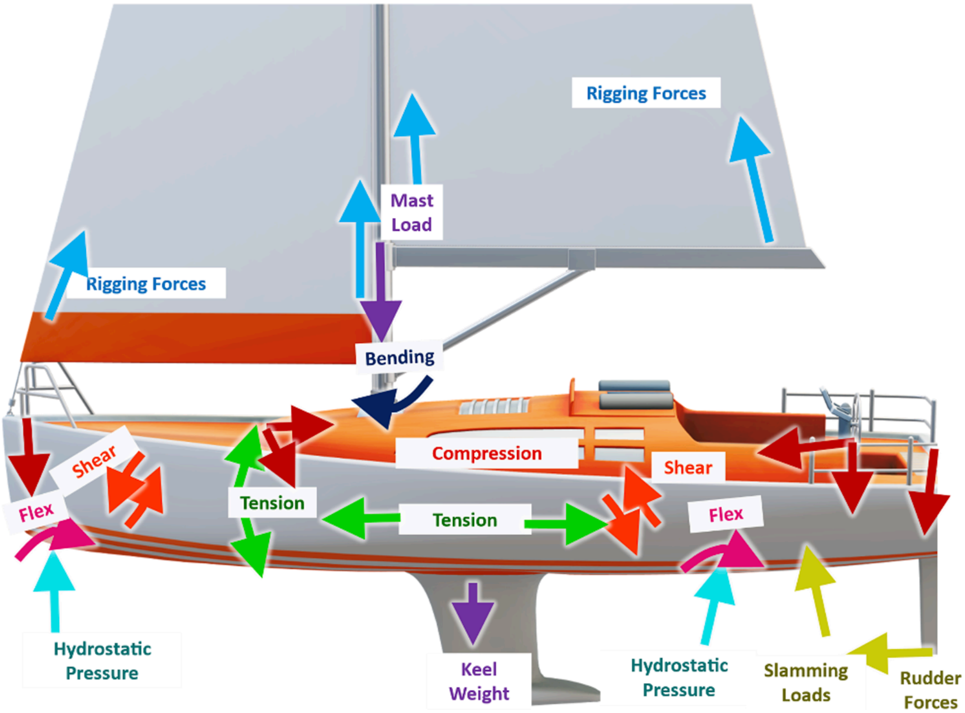


Fig. 2. Schematic illustration of various loads on a yacht.

joints [28]. Fig. 3 shows a sample of overlaminated T-joint.

2.1. Materials

Commonly overlamination methods are employed to joint composite materials. Fig. 4 shows the common sections and materials used in overlaminated joints.

2.2. Process

The hand lay-up process is often used in order to join components by the overlamination method in the marine industry [37,38]. To fabricate composite laminates, a manual lay up of individual dry reinforcement layers (fibres or mat), known as plies, and uncured liquid resin layers are carried out in a specific sequence. In this method, a roller is used to ascertain the homogenous fibre wetting as well as maximum compaction between the layers. Once the laminated composite is cured, it is detached from the mould. Although this method provides considerable advantages such as the ability to manufacture components with a wide range of geometries with the low initial investment, there are several challenges in using this technique such as being nonenvironmental friendly due to the emission of styrene, longer production time, lower production rate, nonuniform quality, and nonuniform distribution of reinforcement [18]. The hand lay-up method process begins with the application of the release agent before the first fabric layer is settled on the mould. In the next step, the resin is applied to the fabric, and to reach the maximum compaction, remove trapped bubbles, and extract the exceeded resins, a roller is used to compress. Finally, subsequent reinforcing layers are hardened at room temperature or through a heat curing process [38].

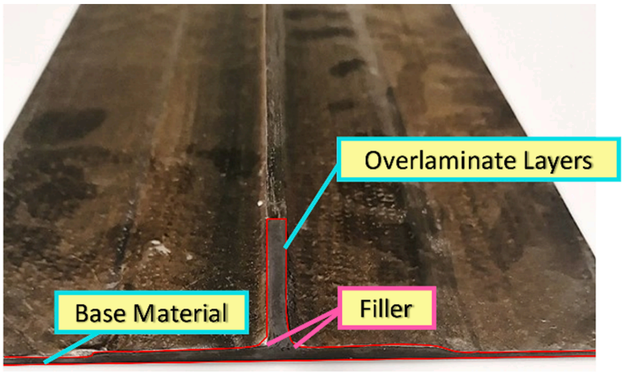


Fig. 3. An overlaminated T-joint.

Another technology to fabricate high-performance composite structures in various industries such as aerospace, automotive, and marine is the prepreg method. The word “pre-preg” is an abbreviation for “pre-impregnated”. In this approach, the pre-impregnated reinforcement layers manufactured with uncured resin are ready to be formed and cured into or on a mould [39]. Vacuum Assisted Resin Transfer Moulding (VARTM) is another method to fabricate composite structures which involves vacuum pressure in order to pull resin through a fibrous preform. In this process, the preform is layered on a single-sided mould, sealed underneath a flexible vacuum bag. Due to the flexibility of the vacuum bag, the fibres are compressed by atmospheric pressure. This vacuum pressure causes the resin to be pulled through the preform. The resin is infused by a resin inlet port which is connected to the mould [40].

Various surface preparation method exists for overlaminated joints such as abrasion, solvent cleaning, or even grinding to ensure that there is no contamination on the surface. Nevertheless, the simple method is peel ply in which typically nylon or polyester fabrics are used to protect the surface and is eliminated just before the manufacturing. The aforementioned fabrics are generally fine weave cloths that are often suggested to enable secondary bonding to be applied so that no further surface preparation is required [41].

In order to manufacture Π joints, which is described in section 2.3.3, flange and web plates are joined with a Π-preform and resin infusion utilizing VARTM. Steel wires are placed so as to obtain a constant adhesive bond-line These spacers were placed strategically such that they did not influence the resulting performance. In order to perform surface preparation, grit-blasting techniques along with using acetone are used.

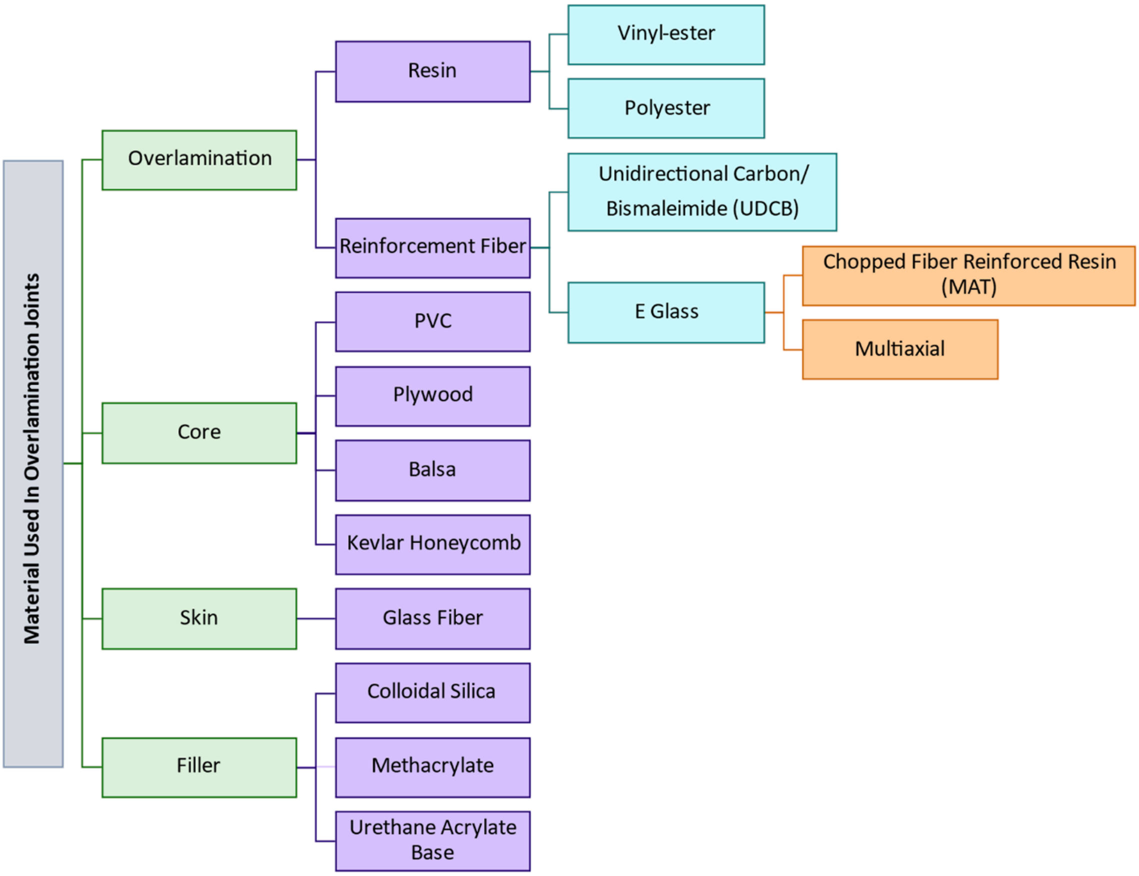


Fig. 4. Different common sections and materials used in overlaminated joints in the marine industry [17,29-36].

To achieve the desired pi-preform dimensions, the aluminium mould is employed which consists of an inlet and outlet pipe-fittings that are located just above the web- location of the Pi-preform and connected to the vacuum pump and the resin-bath, respectively.

To fabricate the sandwich T-joints, Hamitouche et al. [31] utilized the resin infusion technique. In this approach, small grooves are used as spacers to guarantee accurate gaps for the filler. The process begins when all the fabrics and the core are laid-up on a flat table and evacuated using a vacuum bag and then vacuum resin infusion is performed in one shot at room temperature. Next, by the end of the infusion, the pressure is increased so that the panel is allowed to be cured at room temperature before the process of demoulding and post-curing. Finally, to have desirable geometry, the edges of the infused and cured panels are trimmed.

2.3. *Types of joints*

2.3.1. *T-joints*

As mentioned above, ships buildings generally consist of multiple watertight bulkheads employed to divide the hull into some sub-sections. To this aim, commonly, T-joints are used to transfer flexural, shear, and compression loads between the joined deck and bulkhead [5]. Since the hull and bulkhead maintain the stiffness of the structure, the strength and durability of the T-joint dramatically affect the reliability of

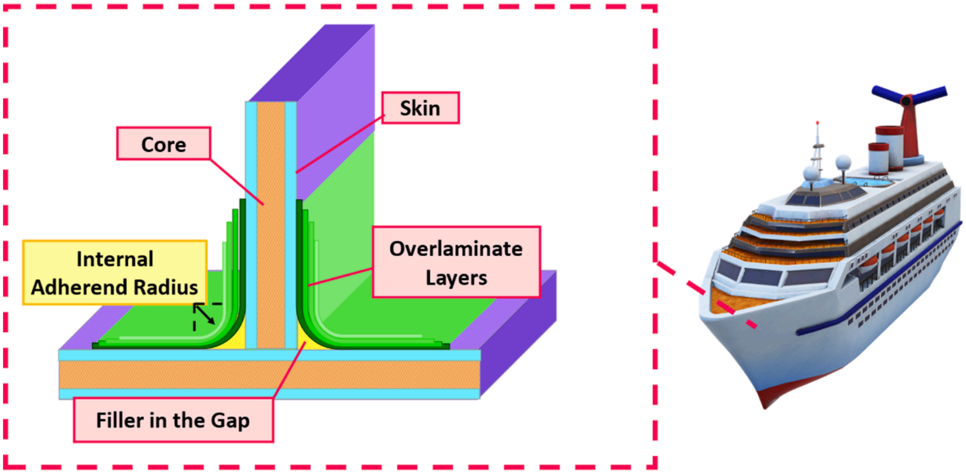


Fig. 5. Schematic configuration of a T-overlaminated joint used in marine structures.

the marine structure. As a result, numerous investigations have been performed on the mechanical behaviour of the T-joints. A typical configuration of an overlaminated T-joint is schematically represented in Fig. 5.

2.3.2. X-joints

In order to connect the end bulkhead of the superstructure to the deck, laminated X-joints are used where the internal bulkhead is located at the same vertical plane below the deck (see Fig. 6). Typically, the X-joints are subjected to alternating tensile and compressive loads in the vertical direction due to the motion of the ship in waves leading to the hogging and sagging bending deformation of the hull girder.

2.3.3. Π -joints

Π joints are one of the typical configurations of out-of-plane overlaminated joints which provides several advantages such as high static strength, good durability, and high damage tolerance. Fig. 7 illustrates a typical configuration of an overlaminated *Π* -joint.

2.3.4. L-joints

Lastly, another type of over-laminated joint configuration is L-joint which is commonly used to connect intersections between the broadside and the upper deck in ship buildings. Fig. 8 shows a typical configuration of an overlaminated L-joint.

2.4. Mechanical performance

Kumari and Sinha [42] examined the influences of transverse stitching and hygrothermal environment at the web–skin interface of CFRP wing T overlaminated joints. They concluded that the additional transverse normal and shear stresses generated by the effects of environmental conditions usually cause the T-joints more prone to failure at the web-skin interface. To overcome this challenge, they recommended transverse stitching at the web–skin interface zone which not only causes enhancement in the joint but also leads to sustaining higher loads in ambient conditions as well as under higher temperature and moisture concentration levels. Najafi and Noorhabadi [43] investigated the effects of various parameters such as core material, overlamination procedure, and fillet shape on the natural frequencies and the mode shapes of the sandwich T-joints having bidirectional E-glass and Kevlar fibres reinforced polyester plates. According to the obtained results, the dynamic behaviour of the sandwich T-joints is substantially influenced by core material. In contrast, it was found that the least effects on the dynamic response of T overlaminated joints are caused by the type of overlamination. Nonetheless, the T-joints with triangular fillet shapes proved to have higher natural frequencies in comparison to those with circular shapes. According to a study carried out by Di Bella et al. [17] on the mechanical performance of adhesively bonded and overlaminated T-joints in ship structures, the enhancement of samples that were made of GFRP composite by overlamination joining method was higher than adhesively bonded joints. Nevertheless, in the case of wood sandwiches, adhesive bonding has better outcomes. Furthermore, in terms of overlamination, their orientation doesn't affect the behaviour of the joint.

Whilst compressive loads cause crushes to the sandwich core within the deck, being subjected to tensile loads leads to pulling the upper face laminate off the deck. Hence, the strength of the laminated X-joints is substantially dependent on the core material [33]. According to the results reported by Hayman et al. [33] since the compressive strength of the foam core material is lower than its tensile strength, in case of being subjected to tensile loading, laminates, as well as core-laminate interfaces, are the critical regions.

Results of an investigation conducted by Qin [28] on overlaminated *Π* joints showed that increasing the thickness of L prepreg and/or filler radius (as indicated in Fig. 7) enhances the strength of the woven composite *Π* joint effectively. A study performed by Zhang et al. [44] proved that there are two zones for progression of damage in overlaminated *Π* joints subjected to tensile load. The numerical and experimental results indicate that damage initiates and propagates in the filler zone and the tip zone.

Zhang et al. [30] investigated the failure mechanisms and final failure loads of composite *Π joints* with different *Π* overlaminates. They observed that damage is more prone to initiate at the spots in and around the fillers which consequently considerably influences the ultimate tensile strength. Hence, both damage initiation and propagation in the filler are significantly dependent on the L and U prepregs. Nevertheless, as the damage propagates through the filler and reaches the filler bottom, the strength of the joints is dependent on the compatibility among

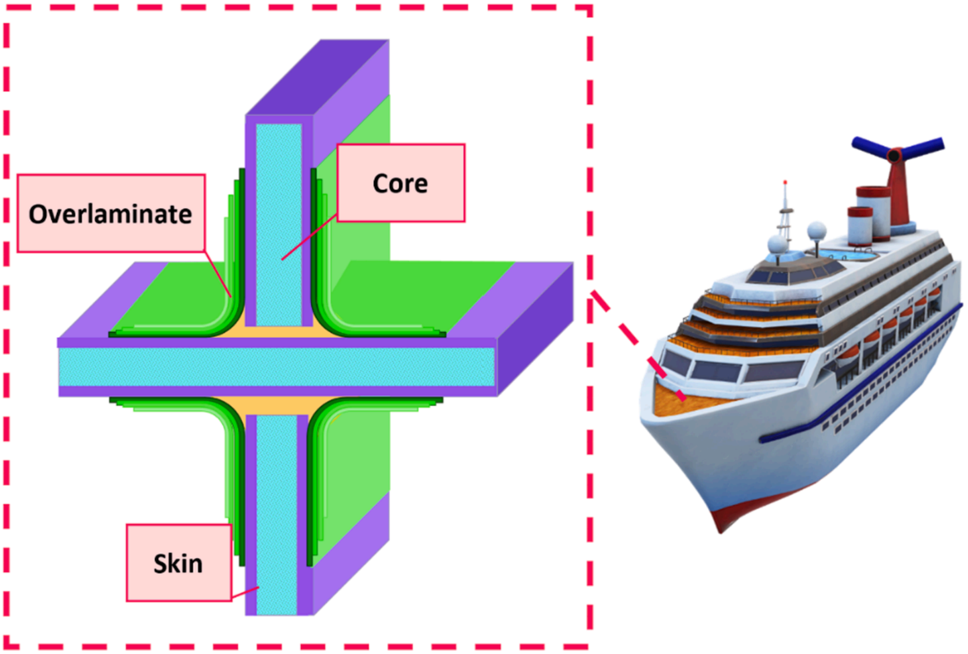


Fig. 6. Schematic configuration of an X-overlaminated joint utilized in marine applications.

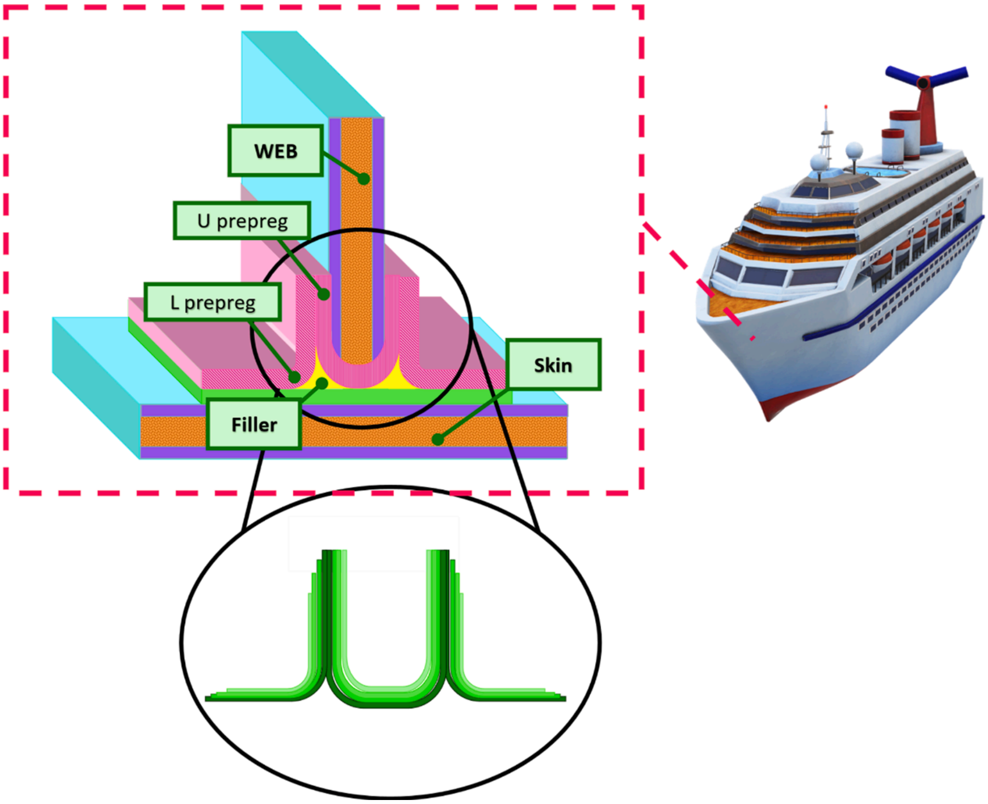


Fig. 7. Schematic configuration of Π -overlaminated joint utilized in marine applications.

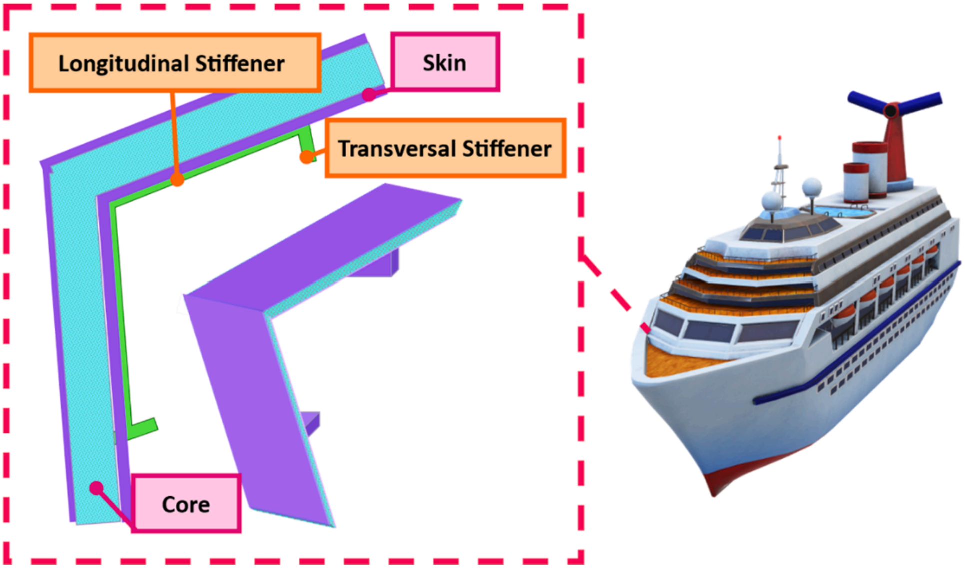


Fig. 8. Schematic configuration of L-overlaminated joint utilized in marine applications.

the filler, L-prepreg, U prepreg, and Base/skin laminates. Moreover, it had been proved that whilst the damage mechanism and the load-bearing are not influenced by the upstanding leg height of the L and U laminates, using a bit long horizontal leg of the L laminate and slightly large fillet radius can enhance the ultimate failure load of composite joints to some extent but without any changes in the damage process. The base laminate has substantial effects on the uniform stress distribution through the filler as well as an optimization of the load transfer path. Finally, it was observed that the layup configuration has a remarkable impact on the failure load of the composite. Kai et al. [45] studied the ultimate tension failure behaviour of GFRP sandwich composite L-joints for ship structures by numerical and experimental approaches for different transitional area radius (R) (45 mm, 90 mm, and 180 mm). Fig. 9 represents the schematic of specimens investigated by Kai et al. [45]. The obtained results proved that whilst for GFRP components, compression strength is generally lower than tension strength, the matrix tension damage can take place much earlier in comparison with the fibre tensile failure. Furthermore, the ultimate tensile strength can also be declined by other failure types such as debonding for samples with the radius of 90 and 180 mm.

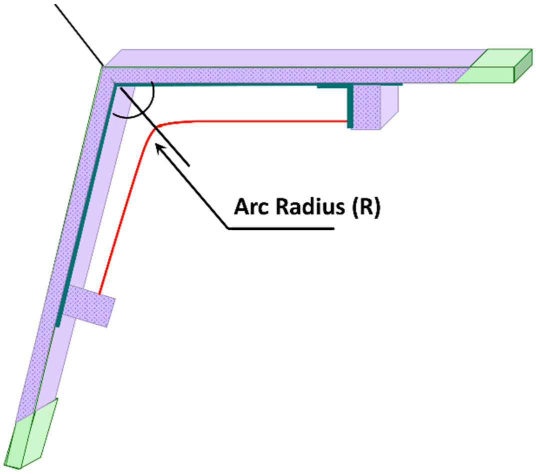


Fig. 9. The L-joint configuration studied by Kai et al. (adapted from [45]).

Failure of composite sandwich L-joint subjected to bending was predicted by Zhang et al. [46]. Based on the numerical and experimental results it was found that increasing the thickness and height of the whole stiffener led to a higher load-bearing capacity. Nevertheless, it causes an increase in the weight of the structure. In addition, increasing the arc radius is more suggested.

3. Adhesively bonded joints

Adhesive bonding is generally employed when the design and manufacturing requirements involve thin substrates, corrosion resistance, particular materials (e.g. FRPs) which cannot be joined by welding, low weight, surface integrity, and minimum stress concentration [47]. In this section, the process, typical types, and mechanical performance of adhesively bonded joints in marine structures are reviewed. Fig. 10 shows several applications of the adhesively bonded joint in the marine industry.

3.1. Materials

An adhesively bonded joint consists of two main parts: adhesive and adherend. Based on the definition provided by Adams et al. [48] an adhesive is a polymeric substance that is applied to substrates surfaces in order to join them and hinder separation. As one of the most prominent benefits of adhesively bonded joints, this method provides an opportunity to join various materials. Nevertheless, adhesive selection must be performed according to the standard/routine experimental results. Fig. 11 shows the adherend materials used in marine applications.

In order to select proper structural adhesive to achieve the highest strength and durability, a range of factors must be considered such as chemical compatibility between adhesive and adherends, fabrication requirements (i.e., surface treatment and hardening process), and service circumstances (i.e., loading and environmental conditions) [49,50]. Generally, structural adhesives are divided into four general categories as provided in Table 1.

Amongst the mentioned structural adhesives, epoxies, methacrylate, and polyurethanes have been employed extensively in marine and naval industries. The largest proportion of adhesives employed in the fabrication of watercraft is dedicated to methyl methacrylates (MMAs) in order to be used as primary bonding such as bonding between the hull and boat frame. Besides this type of adhesive, epoxies are used in the marine industry as well. Whilst epoxies are slightly cheaper than MMAs, using MMAs is more cost-effective as it requires less working time as well as no surface preparation [51].

Recently, silane-modified (MS) polymer has emerged as a new generation of polyurethanes with enhanced properties. They provide benefits including good UV resistance vibrations damping as well as good mechanic properties and acceptable adhesion on various substrates. Due

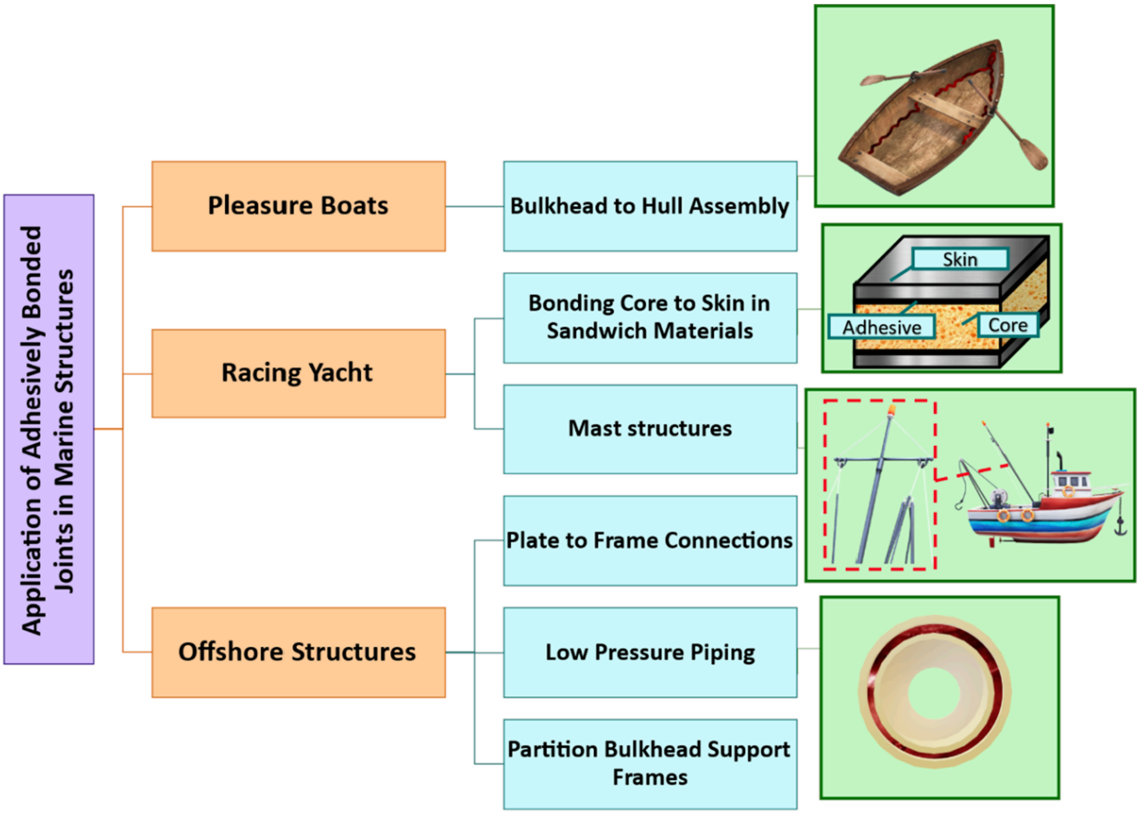


Fig. 10. Application of adhesively bonded joints in the marine industry.

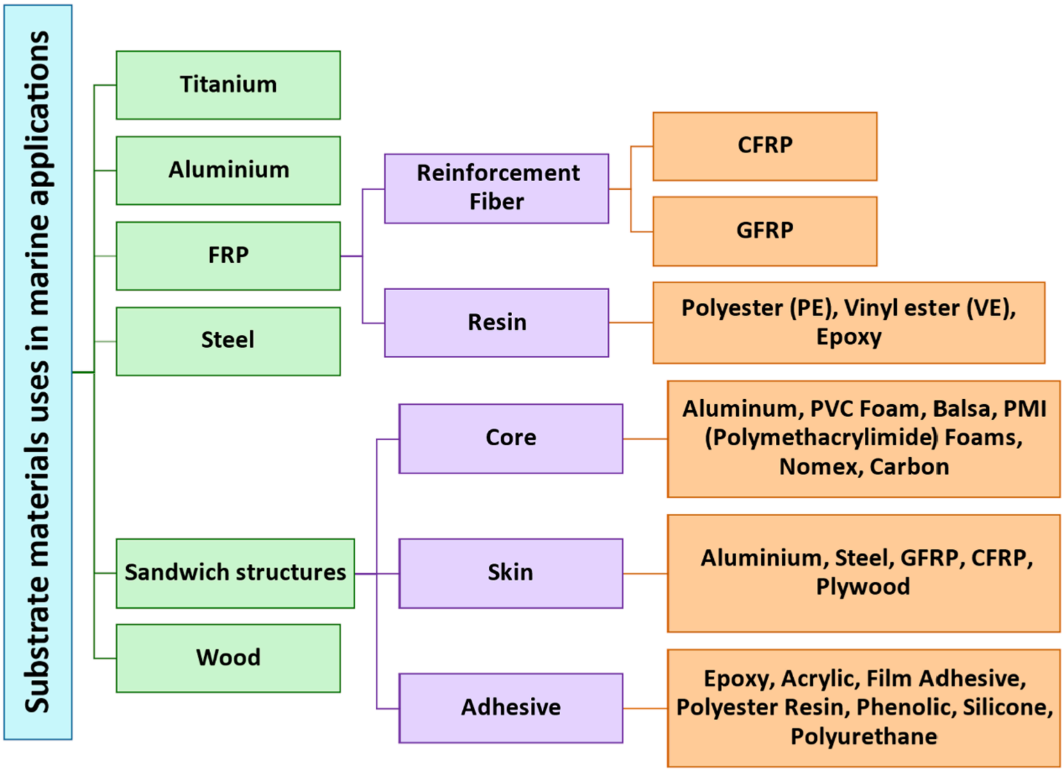


Fig. 11. Substrate materials used in the marine industry.

to the aforementioned advantages, they are recommended for structural bonding operations such as in the teak, porthole, and hull sealing operations [37].

To adhere the FRP substrates to FRP or steel, several adhesives have been used by researchers and engineers. Borrie et al. [14] applied Arald 420 a two-component epoxy-based adhesive to carbon fibre reinforced polymer (CFRP) laminate and steel to investigate the effect of pre-immersion in NaOH solution with various concentrations on the rate of strength degradation. Two-component polyurethane adhesive and a vinylester resin as the most common adhesives to fabricate hybrid structures (defined as a framework that combines two or more materials, usually FRP laminates, metal, and core material) were used by Alia et al. [23] to study the chemical degradation of the aforementioned polymers when they are immersed in natural seawater for different periods. Hollaway et al. [53] used epoxy resin adhesive Sikadur 31 to connect CFRP and GFRP laminates to the steel substrate. Yu et al. [13] employed Araldite 420 adhesive to fabricate CFRP-steel double-lap joints to evaluate the interfacial behaviour of the joints exposed to salt fog spray or high relative RH at the curing stage. Hashim [54] used three different epoxy-based adhesives to adhere steel to composite and steel to steel to examine the adhesive properties and their limitations by stress analysis. He used one-part hot-curing Araldite 2007 adhesive to connect steel to steel substrates, whilst two-component cold-curing Araldite 420 and Araldite 2004 adhesives had been employed to adhere steel to polymeric composites. Jarry et al. [55] applied MA 550, a two-part methacrylate adhesive, to an aluminium plate (alloy Al 6082) and a steel (grade A) plate joined together with an aluminium strap (alloy 5083) to investigate the effect of adhesive properties and adhesive thickness under different ageing circumstances. In another study, Alia et al. [56] utilized two-component polyurethane to bond cold-rolled steel substrates which are typically used in sea applications to investigate the mechanical behaviour of polyurethane adhesive joints subjected to severe marine environmental conditions. Osnes et al. [15] used vinylester resin to study the stress distribution and strength of bonded double-lap steel-composite joints by theoretical analysis as well as experimental testing.

3.2. *Process*

The manufacturing process of adhesively bonded joints consists of six main stages including; adhesive and adherend selection, surface pre-treatment, coating of the primer, application of adhesive on surfaces, assembly and pressing the joint in a mould or use grips to conduct the hardening process, and eventually, adhesive hardening. The most critical stage of adhesive joint manufacturing is the substrates' surface pre-treatment so as to ensure sufficient adhesion between the adhesive and adherends. By increasing the surface tension, roughness to an optimum value, and consequently enhancement of mechanical interlocking, surface pre-treatment causes maximum strength, fatigue life, and durability. In order to select the most suitable method of surface pre-treatment, the properties and type of the adhesive and adherend must be considered by designers. For instance, whilst epoxies require vigorous surface preparation, methacrylates can be applied on the substrates with minimum surface preparation. Due to the less clean environmental condition of a typical shipyard in the marine industry, surface preparation is substantially vital. Commonly, two techniques include simple mechanical grinding using hand-held 'angle grinders' and utilizing peel ply in which a textured polymer sheet covers the uncured laminate and peeled off when in order to provide a clean adherend surface. Furthermore, the surface of the substrate can be cleaned by using a dry cloth and then wiping acetone.

3.3. *Types of joints*

3.3.1. *T-joints*

T-joints have been extensively utilized in various marine structures. For this reason, numerous studies have investigated the strength and durability of T-joints. Fig. 12 illustrates typical marine adhesively bonded joints investigated by scholars. The principal function of a T-joint is the transmission of various types of loads including flexural, shear, and compression between two joining parts [32]. T-joints are the most common configurations in the shipbuilding industry in order to

Table 1
General types of structural adhesives in the marine industry [37,50-52].

Adhesive	Benefits	Challenges	Marine Application
Epoxy	• The capability of adding additives to increase its strength, fire resistance, and toughness Generation of strongest bonds Good durability Become soften but not melt on heating Fill small gaps well with little shrinkage	• Require vigorous surface preparation	• Building and repairing wooden boats Construction of bulkheads, deck cleats, rub rails, gunwales Cargo tanks
Acrylics	• Fast polymerization Good gap filling properties Acceptable toughness Tolerates of contamination and less prepared surfaces Offer flexible bonds providing good peel and impact resistance Providing energy-absorbing bond line Resistance to UV, moisture, and general out-door conditions	• Lower strength in comparison with epoxies Flammable in the uncured state	• Bonding topside and superstructures
Methacrylate	• Provide a unique balance of high tensile, shear, and peel strengths Maximum resistance to shock, stress, and impact across a wide temperature range Does not require surface preparation for joining plastics Providing the opportunity to control cure speed Remain strong and durable under severe environmental conditions Resistance against water and solvents Time and cost-saving Acceptable flexibility Excellent fatigue life	• Lower strength in comparison with Epoxies Slightly expensive compared with epoxies Fast cure rate which limits the perfect positioning	• Bonding of the hull to the deck Bonding of the bulkheads to the side shell of the hull Bonding stringers to FRP hull
Polyurethane	• Good gap filling properties High degree of adhesion to composites A great deal of flexibility and impact resistance Resistant to seawater No additional mechanical fastenings are required	• Low strength Low modulus adhesives Require a primer to bond to metal substrates	• Manufacturing multilayered panels (e.g. bulkheads, superstructures) Thru-hull fittings Hull-to-deck joints

bond the bulkheads to the hull, join panels to the hull, and connect the FRP hull with anti-flood panels [17,57]. Nevertheless, perhaps the most important challenge which researchers and engineers confront is the fabrication of adhesive T-joints as it is essential to maintain the right angle between the web and base parts [58].

According to the experimental investigation conducted by da Silva et al. [61], the failure load of the T-joint is substantially influenced by the base part thickness. Bella et al. [17] performed tensile tests on adhesively bonded T-joints fabricated by wood core and GFRP skins. Based on their results, crack initiates and propagate at the interface between the base and the bulkhead and between the adhesive and the bulkhead. In addition, the failure is mostly prone to occur in adherend in comparison with adhesive. In another investigation, da Silva et al. [65] proved that strength of the T-peel joint increases by increasing the internal adherend radius.

3.3.2. *Corner joints*

Another common adhesive joint configuration in marine structures, particularly in the shipbuilding industry, is the corner joint (known as L-joint). The major role of this type of joint is to transmit flexural, tensile, and shear loads between the two joining parts as well as a reduction in the peel stresses [34,49]. the requirement of adhesive injection for fillet control is one of the encountered challenges in the fabrication of L-joints. This type of joint is commonly used to join the hull to the deck [34]. Fig. 13 illustrates the typical configurations of corner joints studied by researchers.

3.3.3. *Butt-joints*

Fig. 14 represents typical types of bonded butt joints employed in the marine industry. Generally, bonded butt joints are used in the marine industry to fabricate hybrid superstructures which typically consist of multi-materials including metal, composite, and core material. In this case, in comparison to other conventional joining methods, bonded joints provide more integrity in the structure as well as a more uniform stress distribution. Kotsidis et al. [70] conducted tensile static and fatigue tests on bonded butt superstructure joints. They concluded that the bonded samples provide an acceptable strength and good tolerance of load.

3.4. *Mechanical performance*

In general, the mechanical performance of bonded structures depends on three main parameters including; material factors (i.e. adhesive, adherends, and core mechanical properties), geometrical aspects (i.e. span length, adhesive and adherend thickness, etc.), and environmental conditions (i.e. humidity, temperature, UV radiation, etc.).

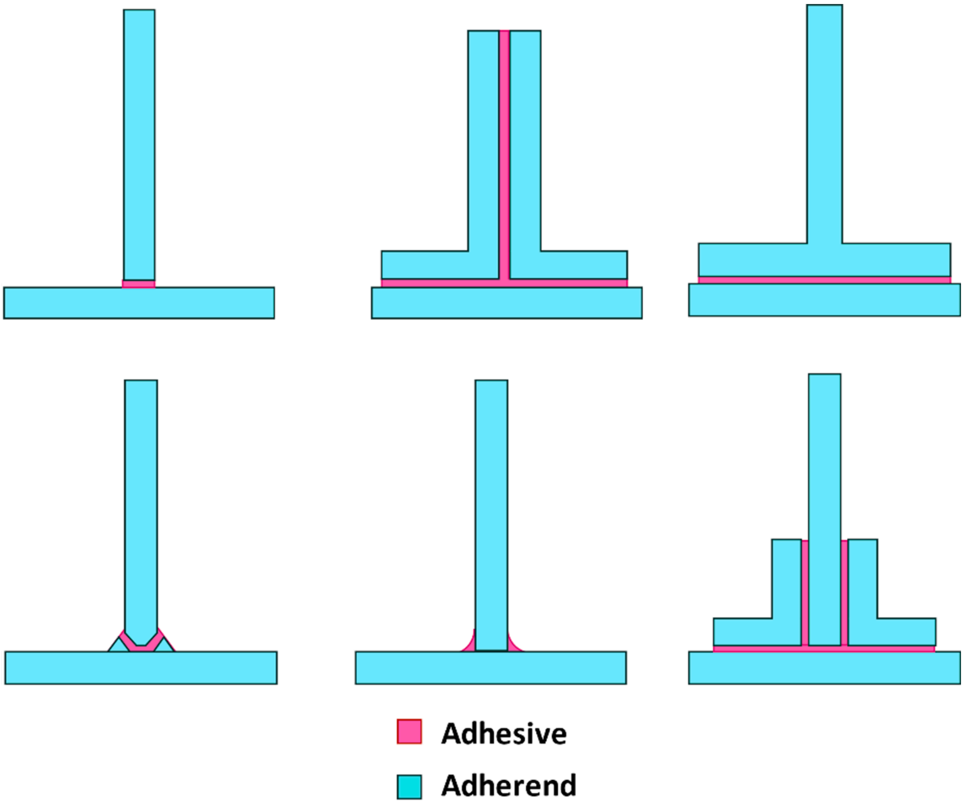


Fig. 12. Typical types of marines adhesively bonded T-joint configurations with sandwich structure substrates (adapted from [58-64]).

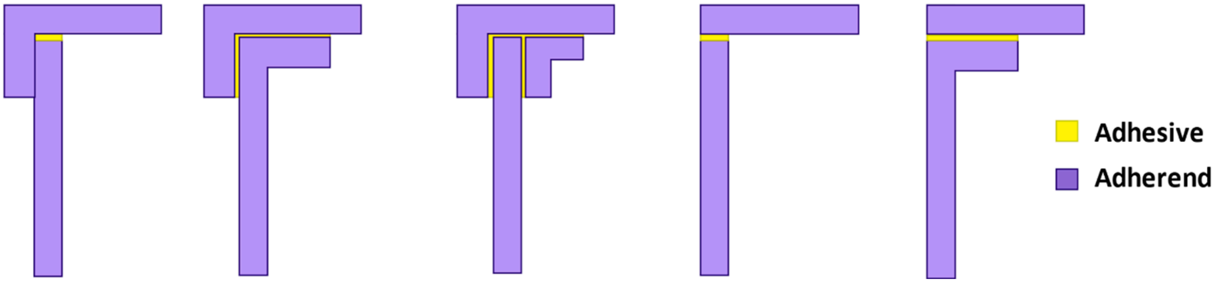


Fig. 13. Typical configurations of adhesively bonded corner joints (adapted from [58,66-69]).

3.4.1. *Effect of material factors*

- Core material

Li et al. [73] investigated the simple and hybrid butt superstructure joints. They used two different materials for the core including balsa and PVC. They found that although the strength of joints with balsa core was considerably higher, the joints manufactured with PVC core were noticeably lighter. Hence, they recommended using PVC core joints for interior substructures which are not subjected to loads as much as exteriors. Khalili and Ghaznavi [59] showed that for adhesively bonded T-joints, alteration in core material considerably affects the failure load.

- ***Substrate material***

Tsouvalis and Karatzas [71] studied the effect of the strength of composite substrates in bonded butt superstructures. They found that the strength of the joints is dramatically influenced by the type of composite adherend. Rudawska [74] compared the results obtained by testing three different types of adhesively bonded joints. Based on the results, titanium bonded joints provide higher strength rather than bonded aramid/epoxy composite joints. Furthermore, it was proven that the highest strength was obtained by hybrid titanium sheet–aramid/epoxy composite joints. Safaei et al. [75] proved that for dissimilar aluminium\CFRP adhesively bonded single lap joints, thermal cycles cause an increase in the residual strains as well as a reduction in the residual static strength of the joints.

- ***Adhesive material***

Arenas et al. [76] compared the shear strength of single-lap adhesively bonded aluminium/ CFRP joints by considering two different adhesive systems including epoxy and polyurethane. They found that epoxy resin provides the highest shear tensile strength whereas the greatest cohesive failure percentage is provided by polyurethane adhesive. Özes and Neşer [77] investigated the performance of bonded single-lap joints fabricated by steel coated with FRP experimentally for two epoxy types. They emphasized that the load-carrying capacity between the GFRP composites and the shipbuilding steel is significantly dependent on the property of the epoxy adhesive. Based on a study

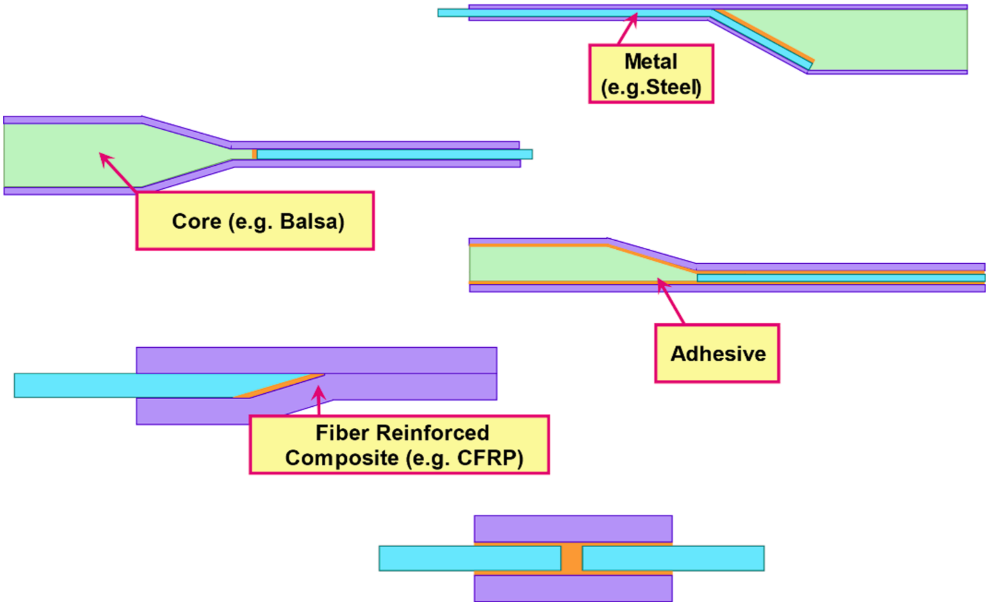
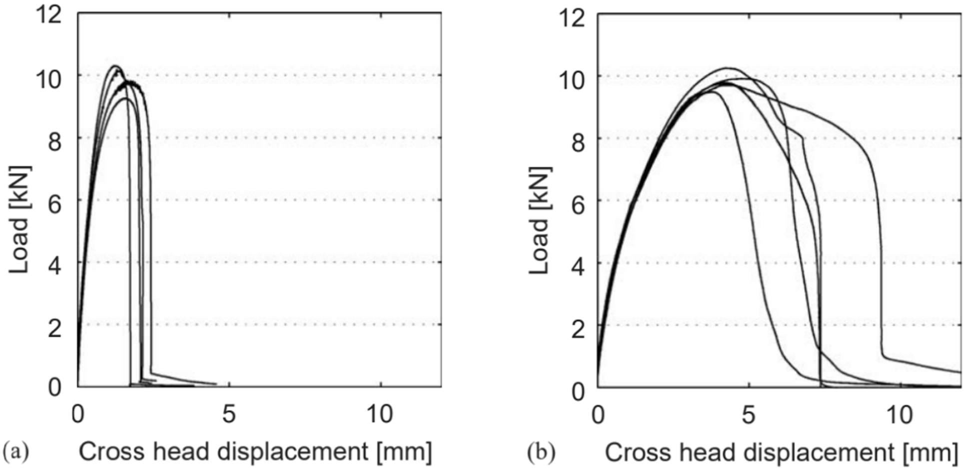


Fig. 14. Typical configurations of adhesively bonded butt joints in marine applications (adapted from [58,71-73]).



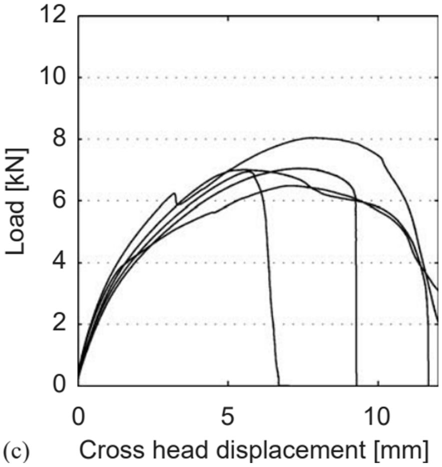


Fig. 15. Typical load–displacement curves of unaged butt strap joints with the adhesive thickness of (a) 1 mm, (b) 5 mm, (c) 10 mm (adapted from [55]).

carried out by Speth et al. [78], the epoxy adhesive bond strength on stainless steel is slightly higher than those manufactured by acrylic adhesive bond on mild steel. Nonetheless, considering hot-wet exposure, acrylic is proved to be more resistant. By elevating the temperature, both adhesives provided low strengths. Being exposed to salt fog, both adhesives were resistant and maintained their strength.

3.4.2. Effect of geometrical parameters

- ***Adhesive thickness***

Generally, for each adhesive joint, there is an optimum value of adhesive thickness in which the fracture energy reaches its maximum value [79,80]. In general terms, the stress concentration at the corners of the joint for thinner adhesive layers is lower than those with higher bondline thickness. Nonetheless, in the case of ductile adhesives, thicker bondline thickness allows better performance [81]. In the marine industry, the adhesive thickness can reach several millimetres which is thicker than aerospace structures. Nevertheless, challenges by applying the thicker adhesive layer over than optimum value such as defects in the adhesive due to the voids and microcracks [82,83], variable hardening circumstances [84], local stress concentrations [84], and reduction in failure load [81,85] must be considered by designers. Jarry et al. [55] considered the effect of adhesive thickness under different ageing circumstances on the performance of the bonded butt joints. They observed a substantial reduction in strength and stiffness of the joints with the increasing adhesive thickness (see Fig. 15). In addition, whilst the descending trend of the strength and stiffness varied linearly with increasing the adhesive thickness, it was non-linear by time.

- ***T-joints***

Based on the results provided by Khalili and Ghaznavi [59] for different angles of the core triangle as can be seen in Fig. 16, **45**° is the optimum angle whilst specimens with 25° were the weakest.

According to Marcadon et al. [63], the failure is affected by the thickness between the shell and the plate as well as the overlap length of the adhesive. Whilst selecting a higher overlap leads to the failure of the plywood, using shorter overlap lengths leads to interfacial damage between the adhesive and the plywood. Fig. 17 shows the T-joint sample tested by the aforementioned author.

3.4.3. Effect of environmental conditions

- ***Temperature***

Temperature alters from −40 °C to over 38 °C in the climate of the marine biome. The ambient air temperature in the machinery space varies from 0 °C to 45 °C [86]. However, the ambient temperature in the marine environment would be higher in the vicinity of the equator where the sea water is exposed to the direct rays of the sun. In addition, the temperature of the exterior components of a marine structure would be considerably higher than ambient temperature when they are exposed to intense sunlight.

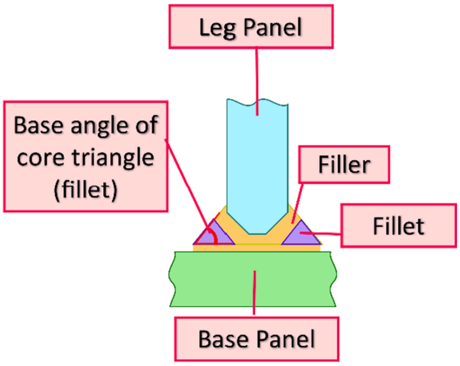


Fig. 16. Schematic of the configuration of the bonded T-joint.

One of the consequences of high temperatures is the thermal expansion due to the mismatch between the properties of different material systems such as fibres, matrix, adhesive layer [87-89]. From the fracture mechanic viewpoint, according to Williams and Marshall [90], increasing the temperature leads to a decrease in the threshold stress intensity factor which causes precipitate the crack propagation. Under given temperature and humidity, Saturated moisture concentration (C_{sat}) is a measure of the moisture absorption capacity. As Fan proved [91], for most polymer materials, as long as the temperature is far below the glass transition temperature (T_g), C_{sat} is only influenced by relative humidity (RH) but not temperature. Nonetheless, C_{sat} is considerably increased by temperatures over the glass transition temperature. Elevating temperature accelerates moisture absorption whereas the maximum amount of moisture absorption remains constant.

- ***Moisture diffusion***

One of the major concerns in the application of adhesively bonded joints, particularly in the marine environment, is the degradation of the joint by moisture intake which substantially affects the mechanical performance of the structure [92,93]. Generally, the process of deterioration by moisture absorption in adhesively bonded joints can occur in three main ways as shown in Fig. 18.

Some adhesives such as epoxies exhibit hydrophilicity behaviour due to the presence of hydroxyl (–OH) groups in their structure [94]. Whilst a hydrophobic film can hinder water molecules' penetration through the surface, the water vapour transmits through the adhesive layer even in hydrophobic materials [91]. In the case of non-absorbing adherends, moisture ingression may not only occur through the bulk adhesive but also the interfacial region between the adhesive and the adherends which results in the adhesive plasticization and swelling [95,96]. By the water penetration through the interface, the moisture causes irreversible damages and ultimately failure of the structure. Moisture absorption by the adhesive prompts the hydrolysis of certain macromolecular functional groups and increases the mobility of the macromolecular chains. It also reduces the T_g of the adhesive which is induced by the plasticization. As a result of plasticization of the adhesive, a reduction in stiffness and yield stress, as well as an increase in strain at break and Poisson's ratio, will be observed [23,97]. Hence, a great deal of research has been conducted on the impacts of moisture on the performance and durability of adhesive joints. Liljedahl et al. [98] performed the cohesive zone model (CZM) approach for adhesively bonded aluminium, composite and dissimilar substrate joints exposed to humid environments. They proved that simultaneous subjection to stress and moisture accelerate the degradation of the joints. According to Fay and Maddison [99], the durability of adhesive joints is considerably influenced by the quality of the surface pre-treatment process. The moisture absorption capacity under given humidity and temperature conditions for most polymer materials does not influence by temperature but relative humidity unless the temperature is higher than the T_g [91]. Degradation is more crucial regarding polymeric composite substrates. Moisture ingression results in dimensional changes, loss of glass transition temperature, and reduction in mechanical properties. Despite the fact that the process of moisture absorption and desorption through the interface of adhesive and adherend occurs rapidly, the moisture diffusion in bulk adhesive progresses slowly. Effective variables on the amount of moisture uptake by a composite laminate are temperature, relative humidity, exposure time, and mechanical load.

Not only being exposed to high temperatures elevate the moisture diffusion in laminated composites but also subjection to wet and subzero temperatures, such as arctic ships, arouse degradation. Furthermore, being subjected to tensile loads causes opening in cavities and

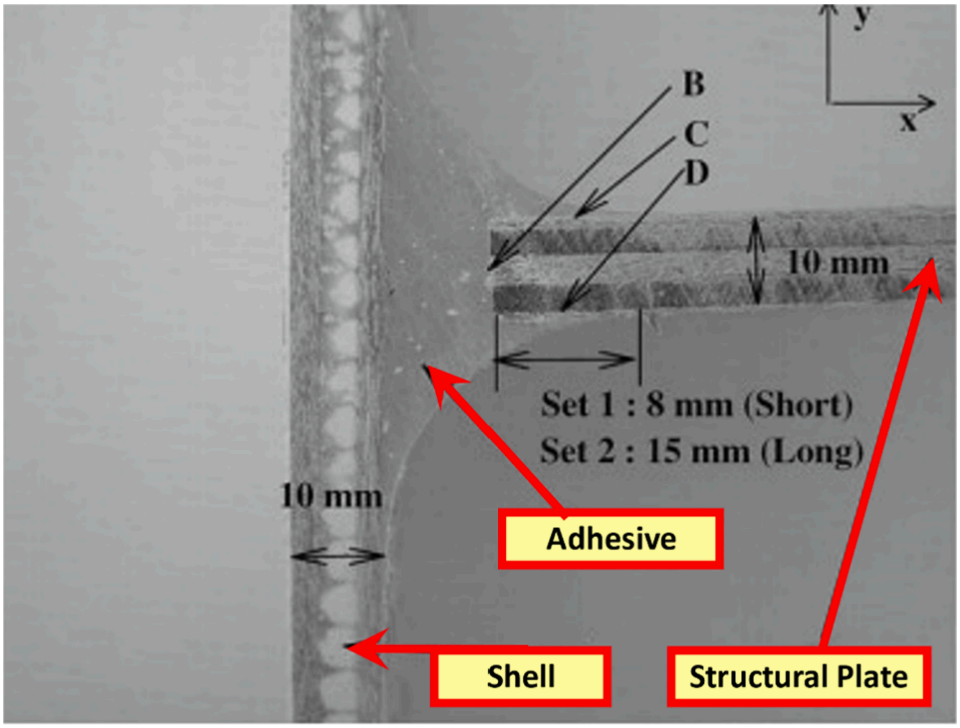


Fig. 17. Geometry of T-joint samples tested by Marcadon et al. (adapted from [63]).

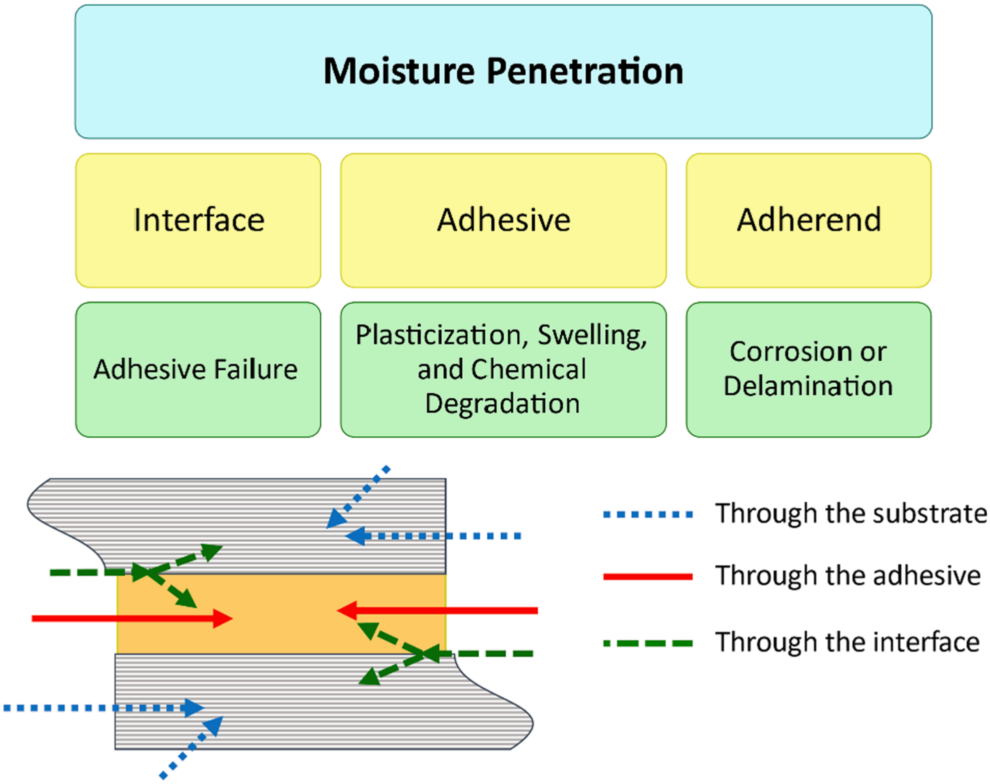


Fig. 18. Principal approaches of moisture penetration in an adhesively bonded joint.

voids which consequently leads to the uptake of more moisture within the polymeric material. In addition to the adhesive layer and polymeric composite, fibres are even vulnerable to moisture and their degradation process speeds up due to the subjection at a higher degree of temperature and humidity. Machado et al. [100,101] investigated the effects of hygrothermal circumstances on the performance of adhesively bonded joints with two different adherend systems including composite substrates and aluminium substrates. They proved that moisture intake causes delamination in the composite substrate as well as degradation in the properties of the adhesive. According to Barbosa et al. [102], the deterioration of the adhesives exposed to moisture is intensified when they are subjected to higher temperatures. According to the literature, whilst the effect of environmental factors such as humidity and temperature on the mechanical performance of adhesively bonded structures is not crucial, the fatigue response of these structures is severely influenced by cyclic loading [92]. Moazzami et al. [103] studied the mechanical behaviour and water absorption properties of the bulk epoxy-based adhesive exposed to cyclic ageing conditions. As their observations show, the subjection of the adhesive to cyclic ageing causes an increase in diffusion constant (D) and maximum moisture constant (M_{max}) of the adhesive. They reported that the elastic modulus and tensile strength are substantially decreased by increasing the number of ageing cycles (see Fig. 19).

Viana et al. [104] carried out double cantilever beam (DCB) tests to evaluate the effects of temperature and moisture on the fracture toughness of the adhesively bonded joints. As Fig. 20**(a) and (b)** illustrate, a significant decline in the mechanical response of the aged specimens was observed as a result of the low interfacial strength after ageing. Nevertheless, salt water specimens yielded better strength in comparison with the distilled water specimens. Furthermore, their results proved that mode I fracture toughness of aged adhesive joints is severely influenced by high temperature.

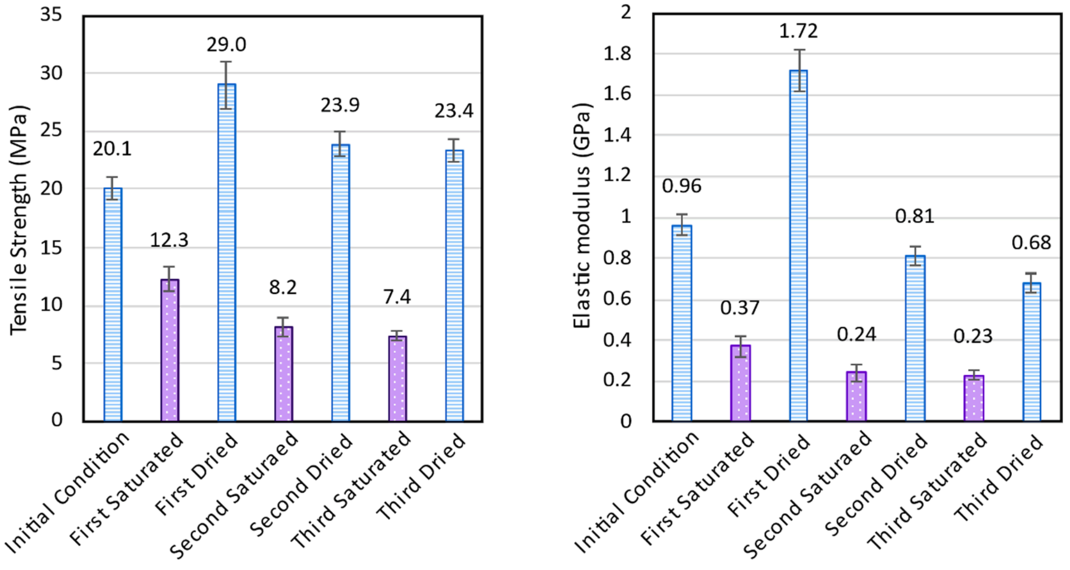
Borges et al. [105,106] reported that whilst temperature influences the mechanical properties of the material considerably, the contribution of humidity leads to a slight drop in stiffness and strength which is due to the relaxation of the polymeric chain promoted by water ingress. Costa et al. [107] studied the effect of cyclic ageing on the rate of water uptake and the drying process in an epoxy-based adhesive considering Fick's law to estimate the water diffusion coefficients for the ageing and the drying steps at different cycles. Based on the gravimetric results, the rate of water uptake and drying is mainly dependent on the level of water uptake of the first ageing cycle. In addition, as tensile test results proved, with each subsequent ageing cycle the maximum water content increases. Furthermore, the adhesive Young's modulus and the tensile strength declined considerably after the initial ageing cycle, whereas all subsequent ageing cycles have a trivial effect on the mechanical properties of the adhesive. Feng et al. [108] investigated the effects of hygrothermal ageing (85% RH, 70 °C) on the mechanical properties of the bulk J-271 adhesive film and observed a decrease of 14.7% and 30.7% in elastic modulus and tensile strength, respectively due to the hygrothermal ageing.

- ***Salt concentration***

Water absorption occurs differently depending on the salt concentration. It also varies whether the material is immersed in water or exposed to a 100% humidity (vapour) environment. Marine structures are mainly exposed to saltwater. Costa et al. [109] provided a comprehensive demonstration of the difference between the process of ingress through the adhesive subjected to distilled and saltwater. According to their observations, the adhesive subjected to saltwater is prone to absorb less water in comparison with pure water. This is due to the larger size of salt molecules compared with the size of adhesive microcavities and voids which results in the hindrance of water diffusion. Hence, the saturation will be reached earlier. In contrast, the size of distilled water molecules is smaller in comparison with the free volume of microcracks and voids which leads to the movement of water molecules across the polymeric network and fills the free spaces before saturation. Alia et al. [56] proved that immersed steel-polyurethane-steel adhesive joints in seawater cause the best performance in service when they are subjected to mode II shear stress. In another study, Alia et al. [23] investigated the chemical degradation of two various polymers including polyurethane and vinylester subjected to natural seawater for different periods of time. The results obtained by scanning electron microscope (SEM) image of the polyurethane adhesive subjected to sea water for 32 days after fracture indicated three zones. The first zone showed the properties of adhesive remain unchanged as absorbed water has not exceeded the critical concentration of water. In the second zone, irreversible degradation of the adhesive due to penetration of water and reaching the critical concentration had been observed. The formation of salt crystals had been indicated in the third zone.

Fernandes et al. [110] characterized the fracture toughness of adhesively bonded joints subjected to distilled water and saturated salt solution tested under mixed-mode loading. They found that the salt solution causes a noticeable increase in fracture toughness in comparison with dry conditions and pure water. Whilst being subjected to the salt solution causes a decrease in T_g, it leads to an increase in adhesive ductility as well as a reduction in water concentration.

- ***UV radiation***



(a) (b)

Fig. 19. Alteration of a) tensile strength and b) elastic modulus for saturated (horizontal striped blue column) and dried specimen (spotted purple column) for different cycles (adapted from [103]). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

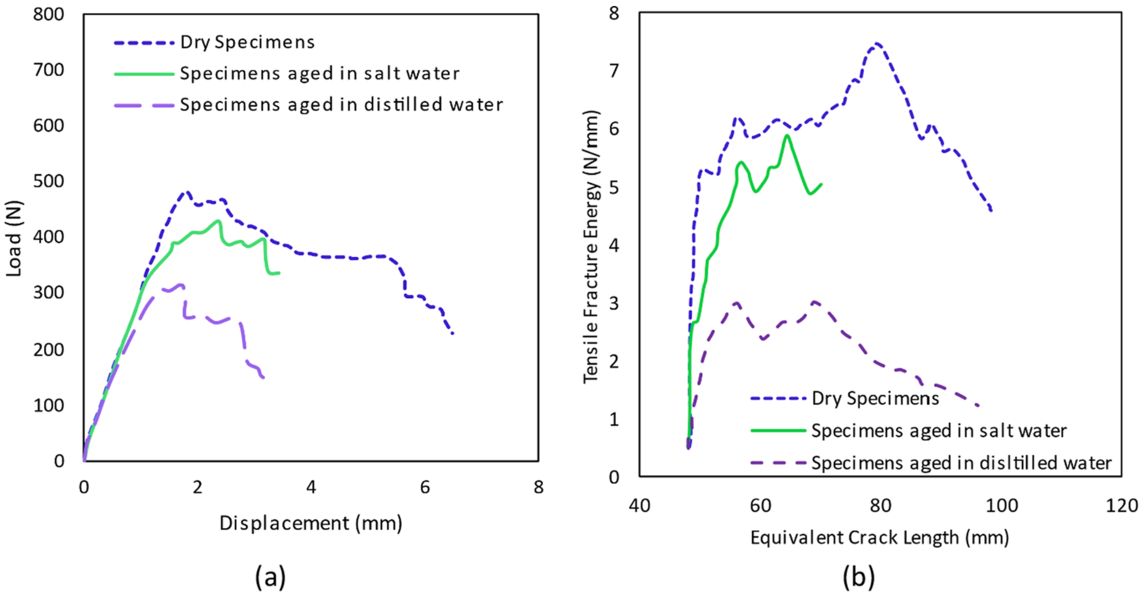


Fig. 20. a) load–displacement and b) R-curves of the dry and aged XNR 6852–1 tested at 23 °C (adapted from [104]).

As a result of the absorption of radiation by polymers, the photo-oxidation process occurs which refers to an alteration in the chemical and physical properties of polymers. Generally, being subjected to sun radiation causes absorption of UV radiation which results in the formation of free radicals within the polymer. This natural phenomenon leads to extensive damages from discolouration to loss of mechanical properties [111]. Usually, the degradation of polymers initiates at the outer surface and then penetrates slightly into the bulk of the material.

4. Welding

Welding processes are usually used to joint metallic materials and the mechanism of joining is the establishment of metallurgical bonding. Fig. 21 shows the application of welding along with the bolting technique in a boat.

Welding processes can be classified into two main groups: fusion welding and solid-state welding. While the solid-state welding processes can be used for all types of polymer composites, the fusion welding processes can only be used for the polymer composites with the thermoplastic matrix [112]. In this state, the contact surface of the polymer is melted, and a joint is established between the two components. When the two similar thermoplastics are welded together, the contact area is unified and no boundary is observed. This method cannot be applied for thermoset materials, as by heating the thermoset it undergoes the T_g above which the material behaves like rubber and by further heating the material degrades without any melting. One of the main applications of the welding processes in the marine industry is the repair of thermoplastic composite materials [113], though they can be used to repair cracked metallic parts by joining composites to metals [114].

The mechanism of joining metals by welding processes is the establishment of an atomic bond (which in this case is a metallurgical bond). When the welding is used for polymer-based materials, the mechanism of joining would be mainly mechanical interlocking, though metallurgical bonding has been reported to exist between specific pairs of metal-polymer couples [115]. The welding processes used to join the polymeric based materials are carried out in lap configuration, especially

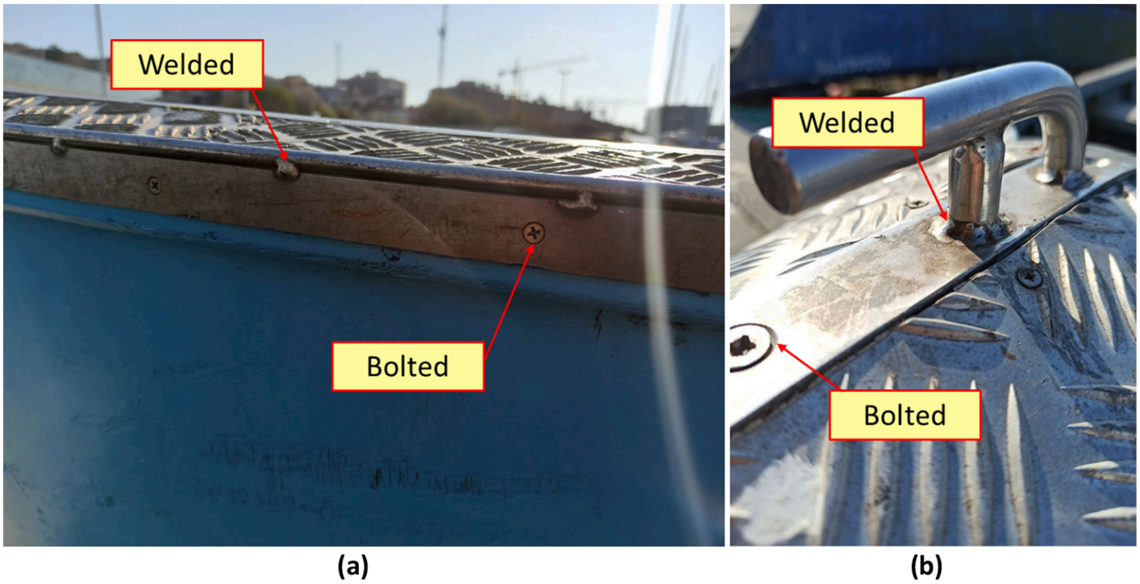


Fig. 21. Application of the welded and bolted joining methods in a) joining of steel gunwale to the wooden hull and b) steel cleat to steel gunwale.

when they must be welded to metals [116,117]. The welding processes are categorized into fusion and solid-state welding processes. In the following the most important welding processes commonly used to join composite materials are discussed. The emphasis is put on the processes which have the potential to be used in the marine industry. As in the welded joints, the mechanical properties are highly dependent on the microstructure, the mechanism of joining in each process, as well as the mechanism of failure of the joints, are discussed.

4.1. Joint configurations

Common configurations of welded joints regardless the substrate materials are illustrated in Fig. 22.

Generally, dissimilar joints between metals and composites need to be performed in lap configuration. The main mechanism of joining in this case is mechanical interlocking which acts effectively in the shear mode of loading. The same applies to the welding of composite-composite, where, in addition to the mechanical interlocking, chemical bonding is the main mechanism of joining. Thermoplastics can be butt welded due to their melting and re-solidification potential [120]. In addition to fusion welding, solid state welding processes can also be used to join thermoplastics in butt configuration [121].

4.2. Processes

As mentioned in the previous section, the diversity in various approaches in welding technique is interesting point which gains various sectors of industries attention. In the current section, typical welding methods to join similar and dissimilar as well as metallic and polymeric materials are demonstrated. Fig. 23 represents various common welding approaches.

4.2.1. Friction stir welding (FSW)

This process uses a tool composed of a shoulder and a pin which rotates inside the material and cause plasticization of the material. The flow of material around the tool causes a joint between the materials. The joining of thermoplastic materials by the FSW process is straightforward and good mechanical properties can be obtained, as these materials can be softened and flowed easily around the FSW tool [122].

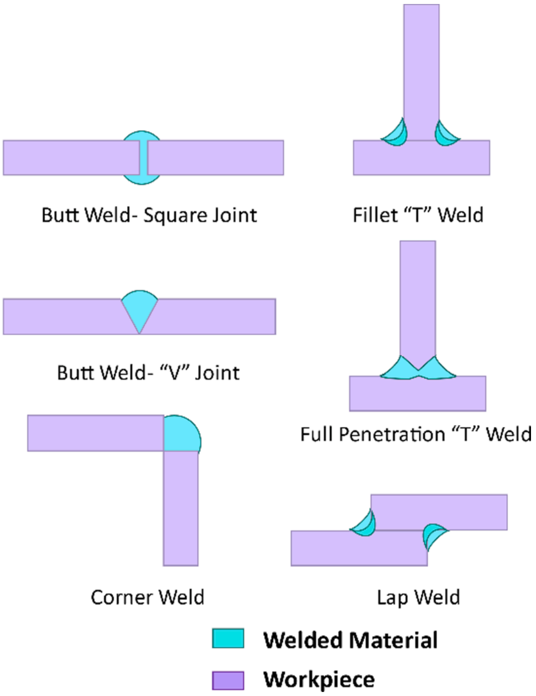


Fig. 22. Typical types of welded joint configurations regardless the substrate material (adapted from [118,119]).

One challenge of thermoplastic welding by the FSW process is the joining of dissimilar thermoplastics. This is due to the different melting points, molecular weight, length of the carbon chain, and flowability of dissimilar thermoplastic materials and hence some modifications are needed to be carried out in order to make these characteristics closer to each other. One modification method is adding aluminium powder into the joint area to make the physical properties of the two polymers more similar [123]. Hajideh et al. [124] used nanopowder of copper between the two thermoplastics to enhance joint strength.

The friction stir spot welding (FSSW) process is similar to FSW with the difference that the tool does not move along a seam. This method is used to join aluminium and PVC [125]. Before welding, the surface of the metal is texturized and then it is placed on the top of the PVS (Fig. 24 **(a)**). The FSW tool rotates at a specific time inside the aluminium which is on top of the PVC and by this rotation, the polymer is softened. Meanwhile, the pressure of the rotating tool pushes the texturized surface of aluminium into the polymer and a mechanical interlocking is established (Fig. 24**(b)**) which enhances the shear strength of the joint between the two materials.

During welding metals to composites by FSW mechanical interlocking plays an important role in the joint strength. Both macro and micro locking promote the joint strengths (Fig. 24**(c) and (d)**) This process has also been used to joint thermoplastic to a thermoset. Lambiase et al. [127] joined polycarbonate and CFRP with an epoxy matrix. In this method the upper part is polycarbonate, and the tool is inserted into this layer. The bottom of the pin ascribes the upper part of the CFRP and extrudes the polycarbonate into the fibres (Fig. 24 (e)). For FSW of CFRP to aluminium, some surface treatments such as surface patterning and micro-arc oxidation are needed [126]. Surface treatment of aluminium caused a considerable increase in both static and fatigue strength in friction stir welded Al/CFRP joints [128].

4.2.2. Ultrasonic welding

Ultrasonic welding (USW) is a welding procedure that uses a mechanical vibration to heat the contact surface up to the melting temperature. This heat in the interface is produced by mechanical vibrations. The mechanical vibration is transformed by a sonotrode which itself is connected to a booster. The schematic of the process is shown in Fig. 25 (a). The contact surface is melted until the vibration is stopped [112]. Welding of the thermoplastic materials by USW is based on fusion and solidification. The pressure of the horn and the contact condition between the horn and workpiece are the main parameters of this process. Weld time and amplitude are other important parameters. This process is vastly used to joint thermoplastic materials and it is used also for joining thermoplastic to thermosets with some modifications in the surface of the thermoset in order to enhance the joint strength [129]. Usually, a spot energy director is used between the workpieces in order to produce a spot welded joint [130].

This process can be used to join thermoplastic to thermoplastic, thermoplastic to thermoset and thermoplastic to metal. When a thermoset is involved in welding, it is of vital importance to keep the heating time as low as possible to inhibit degradation of the thermoset. Ultrasonic welding has the advantage that the welding time can be kept lower than 1 sec [131].

Lionetto et al. [19] used this method to join aluminium to carbon fibre reinforced epoxy composite. The combination of aluminium/CFRP is used in the ship hull structure[132]. As thermoset-based materials cannot be melted and welded, an interlayer of thermoplastic is used between the materials to be joined (Fig. 25 (b)). This thermoplastic is laid on the thermoset surface before curing. After curing these thermoplastic bonds with the thermoset. During welding, this thermoplastic material is melted and displaced out and a direct contact between the surface of the plastically deformed aluminium and composite fibres is

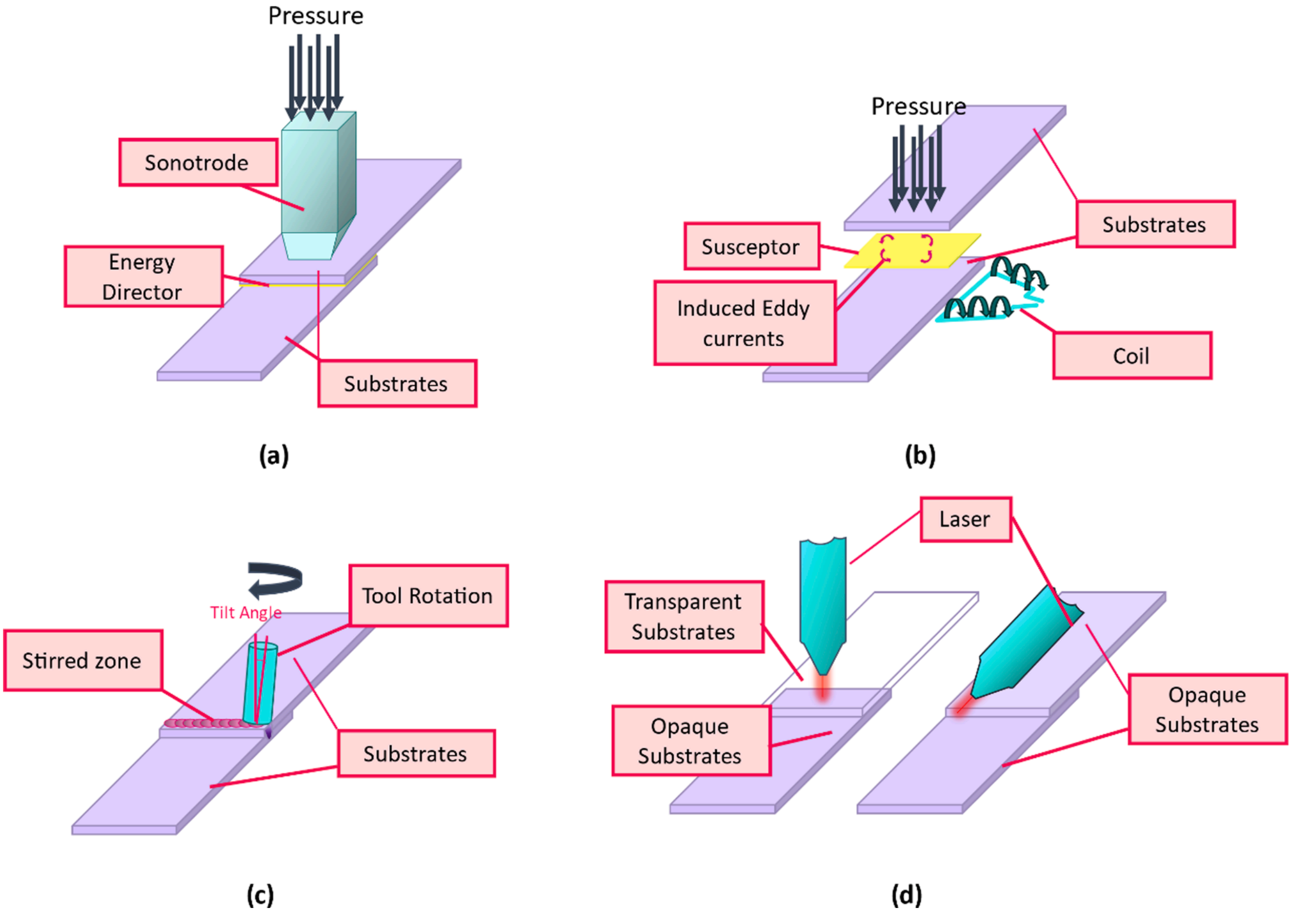


Fig. 23. Typical approaches of welding technique including a) ultrasonic welding, b) induction heating joining, c) friction stir welding, and d) laser welding.

established (Fig. 25 (c)). The joint is established by the mechanism of mechanical interlocking.

The same procedure mentioned above is used to join thermoplastic to a thermoset. In this way, an interlayer is used to prevent any heating of the thermoset (Fig. 25 (d)) [131]. In this way, it is necessary to co-cure the interlayer and the thermoset in order to make sure a good adhesion between them.

4.2.3. Laser welding

Laser welding utilizes a focused beam to provide the energy needed for welding. This process is widely used in marine industries and has a high potential to join dissimilar materials [133]. The main parameters of laser welding are the laser power, the focal point, the pressure, and the welding speed.

Joining of metal to CFRPs (thermoplastic base) is usually made in lap configuration. When the polymer is placed on the top it should be transparent to the laser. In this case, no melting occurs in the metal and the metal is heated by the transmitted laser. This heat is transferred to the polymer at the interface [134] (see Fig. 26**(a)**). When the plastic is coloured and is not transparent to the beam (opaque material), instead of the polymer the metal is placed on top. In this state, only the surface of the metal is heated, and the heat is conducted to the polymer underneath (Fig. 26**(b)**). The main differentiating factor of laser welding of thermoplastics is pyrolysis which leads to gas formation and bubbles in the thermoset [135]. The bubbles expand rapidly and generate a high pressure which establishes a contact between the metal and plastic. However, these bubbles can reduce the fatigue life of the joint [136]. The mechanism of bonding in this state is due to two factors: the mechanical interlocking along with the weak Van der Waals forces and chemical bonding between the metal oxide film and the carbon atoms of the polymer [137]. It is possible to enhance the mechanical interlocking by some methods. Zhang et al [138] showed that pre-treatment of the aluminium surface by the Surfi-Sculpt process before laser welding can improve the joint strength of aluminium-CFRP by more than 4 times. This process produces some protrusion on the surface and enhances the mechanical interlocking.

It is also possible to join thermoset to thermoplastic by laser welding. In this way, as the thermoset cannot be melted, an interlayer should be applied at the interface. The laser beam is transmitted through a transparent thermoplastic and melts the interface[139].

4.2.4. Induction heating joining

Induction heating joining is a process with which heat is produced in the workpieces by induction. The materials that can be heated by this method are steel, stainless steel, aluminium, and carbon fibres. This method can be used to join metals to composites with carbon fibre reinforcements. The combination of steel and composite is a typical joint for the marine industry [71]. The composite structures are extensively joined to steel decks in marine industries [140]. For welding the metal to composite the matrix of the composite needs to be thermoplastic, as it should be melted during the joining process [141]. When the metal is placed near the inductor it heats up and transforms the heat to the composite under forming a layer of melt at the interface. The pressure on the joint area should be controlled as the excessive pressure pushes the melted polymer out and no bonding can occur. The advantage of this process is that it is fast and the joint strength obtained by this method is comparable to other joining methods such as mechanical fastening [142].

The mechanism of increasing the joint strength in this process is not mechanical or surface roughening. The surface treatments used to

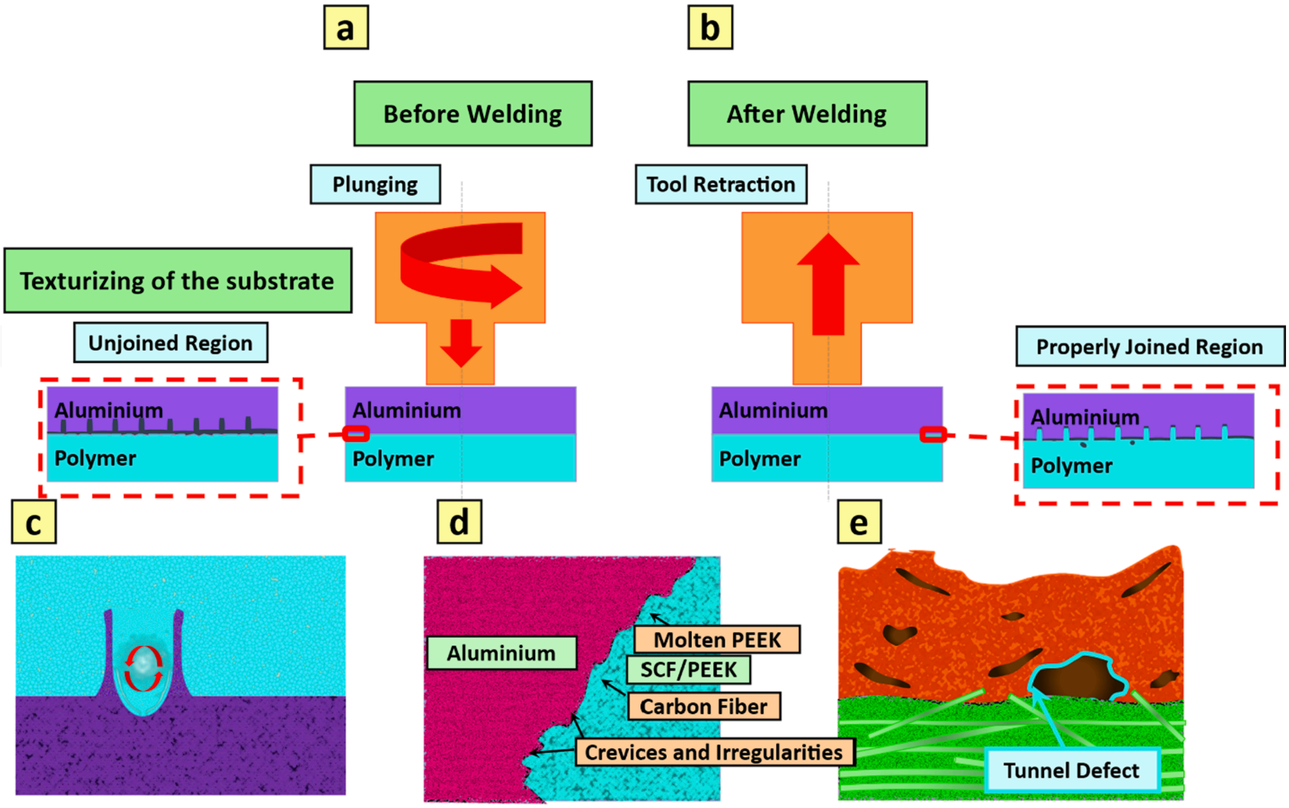


Fig. 24. a) FSSW of aluminium to PVC by using pretreatments on the surface of aluminium before welding. b) The joint after welding(adapted from [125]). c) Macro-mechanical interlocking which is produced by the flow of aluminium into the thermoplastic material SCF/PEEK. d) The micro-mechanical interlocking is due to the infiltration of carbon reinforcements into aluminium (adapted from [126]). e) Extrusion of polycarbonate into the fibres during FSW of a thermoplastic to a thermoset (adapted from [127]).

enhance the joint strength change the chemical and physical properties of the surface. In this state, the polar part of the surface energy contributes most to the joint strength. In fact, surface energy is the most important factor that needs to be controlled to obtain a strong weld [143]. In comparison with other joining techniques, the contribution of mechanical interlocking in this process is lower.

4.3. Mechanical performance of the joints

In marine structures, the aluminium structures that crack under fatigue need to be repaired. Traditionally it is performed by welding a thick insert to the parent material. But in this method, the stress can be transmitted only through the weld bid which causes a high amount of stress concentration. A novel way to overcome this stress concentration is to bond a composite to the parent material by adhesive bonding over the entire area. By this method, the stress concentration is reduced, and the life of the structure is increased with respect to the condition in which a weld is used [114].

The mechanical interlocking at the surface of metal/composite can increase the shear strength of the joint considerably. During FSW of aluminium/CFRP, the plasticized aluminium can entrap the fibres of the composite and establish a mechanical interlocking[144]. The joints made by laser welding to join Al/CFRP contain so many bubbles and these bubbles degrade the joint efficiency. Alongside bubbles, decomposition of the composite at the welding zone may contribute to the decrease of strength[145]. Anodizing the surface of Al can improve the joint strength of CFRP/Al by 8 times[146]. This is attributed to three factors. Enhancement of the surface mechanical interlocking, improving the wettability of the surface of Al with CFRP and formation of chemical bonds between O atoms of CFRP and Al atoms.

In order to have a comparison between the mentioned welding processes, Table 2 and Table 3 are provided. In Table 2 the tensile shear strength of various pairs of materials joined by various welding techniques can be observed. According to Table 2, the strength of CFRP/AA1060 joined by the laser welding technique is considerably lower than the other joints listed in this table. A reason behind this very low strength is the very strength of the aluminium alloy used in this joint. Thus, the micromechanical interlocking that is generated by the aluminium is very weak and soft. Only part of the joint area experiences the micromechanical interlocking. In this area, failure takes place from the aluminium side as a result of its very low strength compared to the composite. In Table 3, the fatigue strength and failure mechanism of some joints are provided. It should be noted that the strength values reported in Table 2 and Table 3 are stated as load or stress (as mentioned in the cited papers) and one has to be careful when comparing these values. The common characteristic of the welding processes used to join composites is a mechanical interlocking at the contact surface between the two materials. A comparison of the values of joint strengths in Table 2 shows that mechanical interlocking yields better joint strength. These techniques are used to join two materials in lap configuration. That is why the surface pre-treatment causes a remarkable increase in the joint strength. Fig. 27 summarizes the welding techniques discussed and also the main mechanism of joining in each process.

Welding techniques can be compared with adhesive bonding in several aspects. As mentioned before, the stress distribution in adhesive bonding is more uniform. One drawback of the welding processes is that the joining can be applied only localized, while by adhesive bonding a wider area can be joined and therefore a higher strength can be obtained. Furthermore, the welding processes influence the base material properties especially the composite materials due to the application of a high temperature and/or pressure. The advantage of the welding process over adhesive bonding is its speed, as no curing time is needed.

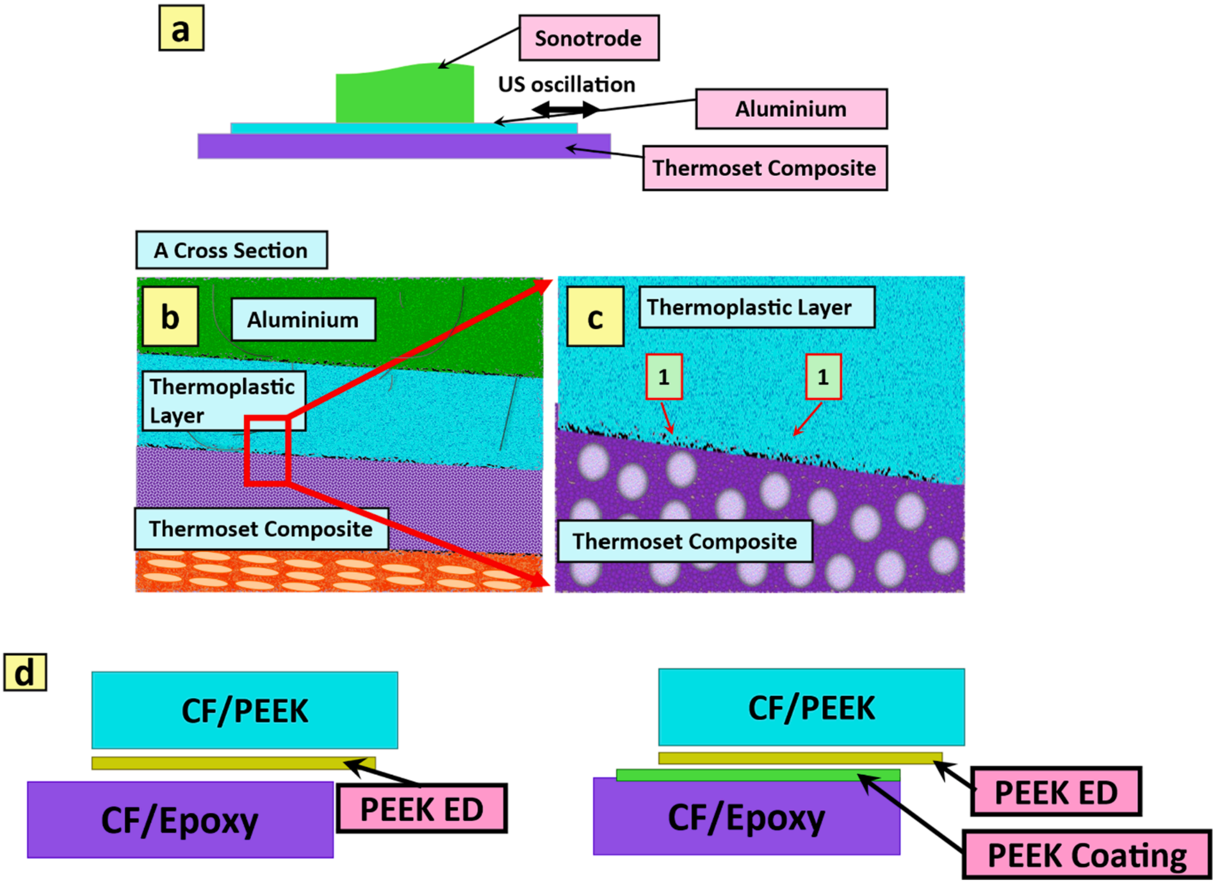


Fig. 25. a) Schematic of ultrasonic welding. b) welding of aluminium to thermoset using an interlayer. c) The established direct contact between the surface of the plastically deformed aluminium and composite fibre (adapted from [19]). d) Schematic view of welding between a thermoplastic and a thermoset using an interlayer co-cured to the surface of the thermoset (adapted from [131]).

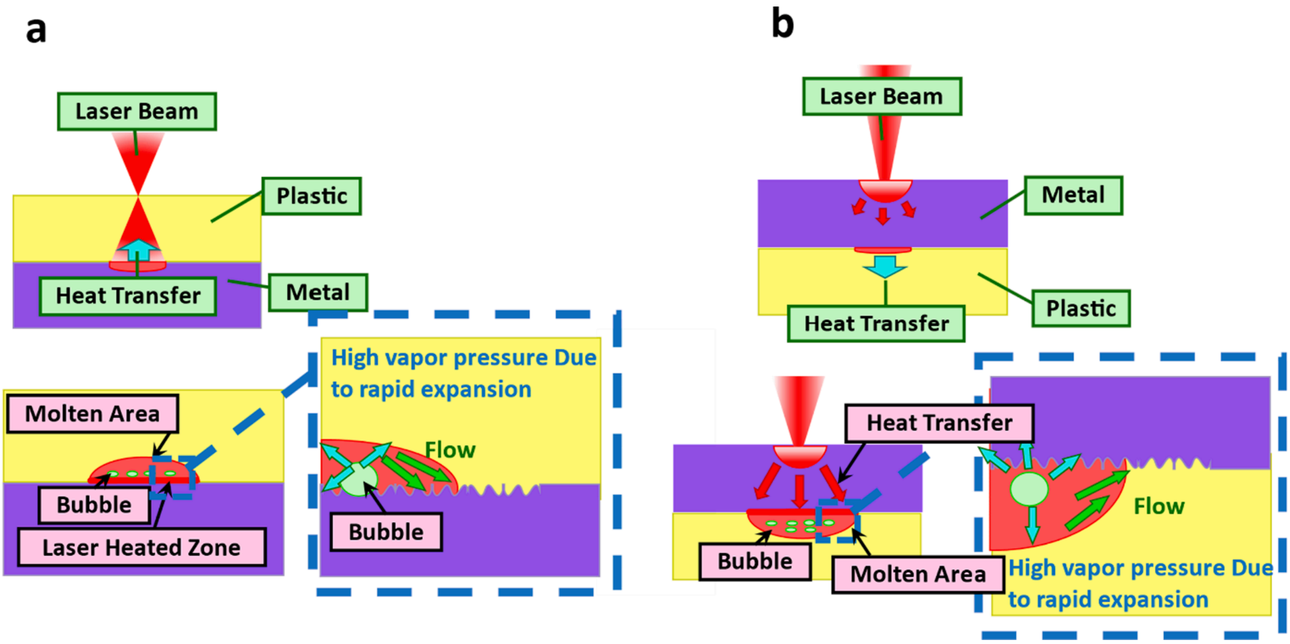


Fig. 26. a) laser welding of a transparent polymer to a metal. b) laser welding of a coloured polymer to a metal. In this state, only the surface of the metal is heated, and the heat is conducted to the polymer underneath.

Table 2
A comparison between different welding techniques used to join various types of composites.

First material	Second material	Joining technique	Joining mechanism	Joint strength MPa	Ref
CF/epoxy	AA5754	Ultrasonic spot welding	Mechanical interlocking	34.8	[19]
CF/PPS	CF/PPS	Ultrasonic spot welding	intermolecular diffusion	38	[130]
CFRP	AA1060	Laser welding	mechanical interlocking and diffusion	5	[147]
CFRP	AA7050	Laser welding	Mechanical interlocking	39	[138]
SCF/PEEK	AA2060	FSW	macro/micro-mechanical interlocking and the chemical bond	34	[126]
CFRP	AlMg6	Induction welding	Chemical bonding	14	[143]
CFRP	AA6061	Laser welding with pretreatment	Chemical bonds and mechanical interlocking	40	[146]
CFRP	TC4	Laser welding		2052 **N**	[145]

Table 3
Fatigue characteristics of the joints made by various welding processes.

First material	Second material	Joining technique	Failure mechanism	Fatigue strength (1 million cycles)	Ref
AA5182	polypropylene-reinforced 40 wt-% carbon	FSW	Interfacial and cohesive	1.5 kN	[128]
Titanium	polyethylene terephthalate (PET)	Laser welding	Stress raiser around the bubble	0.2 kN	[136]
Aluminium	CFRP	FSSW	Debonding and breakage of fibres	2 kN	[148]
CFRP	CFRP	Ultrasonic spot welding	Cohesive failure	4 MPa	[149]
CFRP	CFRP	Ultrasonic spot welding		10 MPa	[150]

Moreover, the weight added to the structure is lower than adhesive bonding as a minimum overlap is sufficient to establish a joint.

4.4. *Environmental effects*

One important advantage of the welding processes is that in most cases they do not need special surface preparation, though in some cases it improves the joint quality. Several investigations have been performed on the behaviour of composites under sea water. It is well known that the saturation of the composite with moisture degrades the mechanical properties of the composites [151]. However, the behaviour of the welded structures made of composites needs further investigation. The welding processes are aggressive to the composites local structure and therefore the welding procedure may affect the local sensitivity of the composites to the sea water. Aluminium in contact with carbon fibres shows a galvanic corrosion, as carbon acts as a cathode and no passive layer can be formed on the surface of carbon [152]. Crevice corrosion is another form of corrosion that takes place when aluminium is in contact with carbon fibre [153]. In the case of adhesive bonding, it is observed that immersion of adhesively CFRP materials in saline water degrades the adhesive performance [154]. This can change the fracture mode from fibre breakage to cohesive failure [155]. Another environmental factor is sun exposure which needs to be investigated for welded joints, as previously was performed for adhesive joints [156].

5. Mechanical fastening

Suitable geometries and materials selection are key to achieving a reliable composite structure [157]. Mechanical fastening is based on the joining of components in an assembly using an integral feature or a supplemental device, resulting in two types of mechanical connection: integral mechanical attachment, where the substrates are joined together without any additional joining elements; and mechanical fastening, where substrates are joined with additional fasteners such as rivets and bolts/nuts [158]. For FRP composite materials, the design of bolted joints presents a number of challenges due to a vast possibility of combinations of materials and fibre patterns, complex 3D stress and strain distribution and the existence of failure modes that may not exist in typical metallic bolted joints [37]. Fig. 28 shows the factors which are considered in the design and application of mechanical joints in large ships.

Examples of mechanical fasteners are nails, bolts, rivets, pins, screws, and snap-fit fasteners. Regarding integral mechanical attachments, these can be categorized into two domains: designed-in and processed-in. Typically, the following integral mechanical attachments can be employed in FRP composites: Tongues and grooves, Flanges and shoulders, Ears and tabs, Bosses and lands and Moulded-in inserts [158].

5.1. *Process*

Generally, mechanical joints are the ones that need less preparation and skill [158]. Holes in FRP composites are generally manufactured employing methods such as drilling and countersinking [158]. A vast

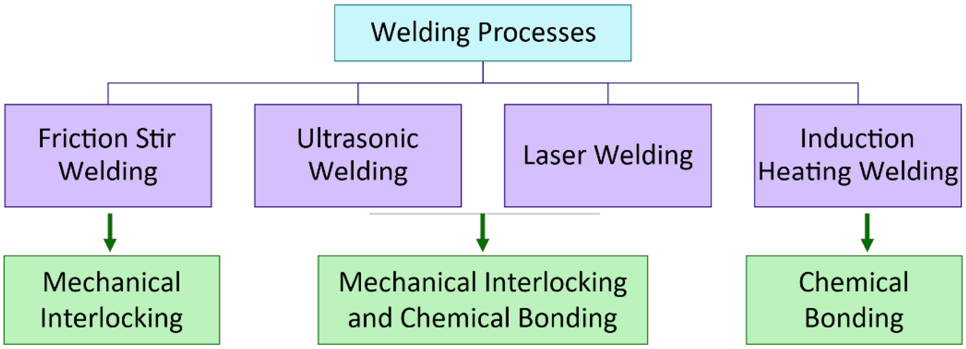


Fig. 27. Classification of welding processes used for joining composites and the main joining mechanisms involved in each.

Fig. 28. Consideration regarding the application of the mechanical fasteners in the large ships.

majority of mechanical joints require an overlap, where two mating members are overlapped and a hole is created for the bolts or rivets to be inserted [37]. The threads created in the composites when screws are employed are not strong in shear, and, therefore, metal inserts are generally used [37]. The presence of holes leads to an increase in stress concentration unless the fastener is “interference fit” (when the diameter of the hole is slightly smaller than the fastener) [158]. Also, another way of decreasing stress concentration around the hole is by integrating fibres orientated in different directions in this area. Nevertheless, even the most carefully designed joints can only achieve about 50% of the strength of the basic structure [158].

The mechanical fastener selection must consider the compatibility with the composite materials and, for shipbuilding applications, with the marine environment [157].

There are numerous advantages of the mechanical joining methods compared to the traditional joining techniques such as no thermal/ structural transformation of workpieces and easy mobility, and some disadvantages may include the temporary joint and early failure of joints under the dynamic loading conditions. For shipbuildings, in order to replace the conventional welding methods used for metal materials, several joining by forming techniques such as mechanical clinching and self-piercing rivets are used. Table 4 provides information regarding the compatibility between the material of mechanical fasteners and substrate material.

5.1.1. Hemming

Hemming is a forming operation in which the edges of the sheets are deformed or folded over another part for achieving a tight fit (see Fig. 29). There are typically two types of hemming processes (a) Conventional die hemming – the flange is folded over the entire length with a hemming tool and (b) Roll hemming -where the hemming roller is guided by an industrial robot to form the flange.

A typical hemming process involves the three steps bending of the sheet to 90^0, hemming at $45^{0,}$ and folding at 180^0 as shown in.

Table 4
Fastener Material Compatibility [159].

Structural Materials Being Joined	Fastener Material		
	Preferred	***Acceptable***	***Prohibited***
Aluminium to Aluminium	Anodized Aluminum	Titanium A286	Cadmium Plated Steel
Titanium to Titanium Austenitic Stainless Steel Nickel Base Alloys	Titanium	A286 Inconel 718	Alloy Steel Aluminium Aluminium Coated Fasteners
Titanium to Aluminum	Titanium	A286 Inconel 718	Aluminium Aluminium Coated Fasteners
Carbon/Epoxy	Titanium	Inconel 718 A286	Aluminium Aluminium Coated Fasteners

The quality of the hemming joint is a strong function of the formability of the applied sheet and its bend radius. In general, for aluminium sheets, the bend factor is around 0.4–0.5 for a good tight fit between the sheets.

The study on the 6014-T4 aluminium sheets [160,161] by hemming process shows the reduction in the plastic strains and increased uniform elongation at the interlock regions. The joint strengths are less compared to the riveting or clinched joints. This type of joint has quite a few structural applications compared to the other mechanical joining methods and are quite popular with the combination of adhesives (hybrid joining).

5.1.2. *Clinching*

Another method to assemble two sheet metals or sheet metal to CFRP components is clinching, also known as the press joining method. To be described straightforwardly, the process begins when the punch applies a force onto the sheets and pushes them locally into the die. Next, the vertical downward movement of the punch causes the deformed sheets to touch the bottom of the die. Additional progress of the punch compels the base materials to flow radially and form a button shape which results in the mechanical interlocking generated by sprung segments of the die assembly. This phenomenon leads to the maintaining of the sheets tightly together. Eventually, the punch is discharged [162]. The process of clinching is schematically illustrated in Fig. 30. The formation of the mechanical interlock in the clinching process is significantly affected by a multitude of parameters as well as the interaction of these factors. Amongst the effective parameters, the diameter of the punch as well as the force of the punch, materials, and friction of the two sheets, are the most influential factors to mention [163,164].

According to the experimental and numerical investigations

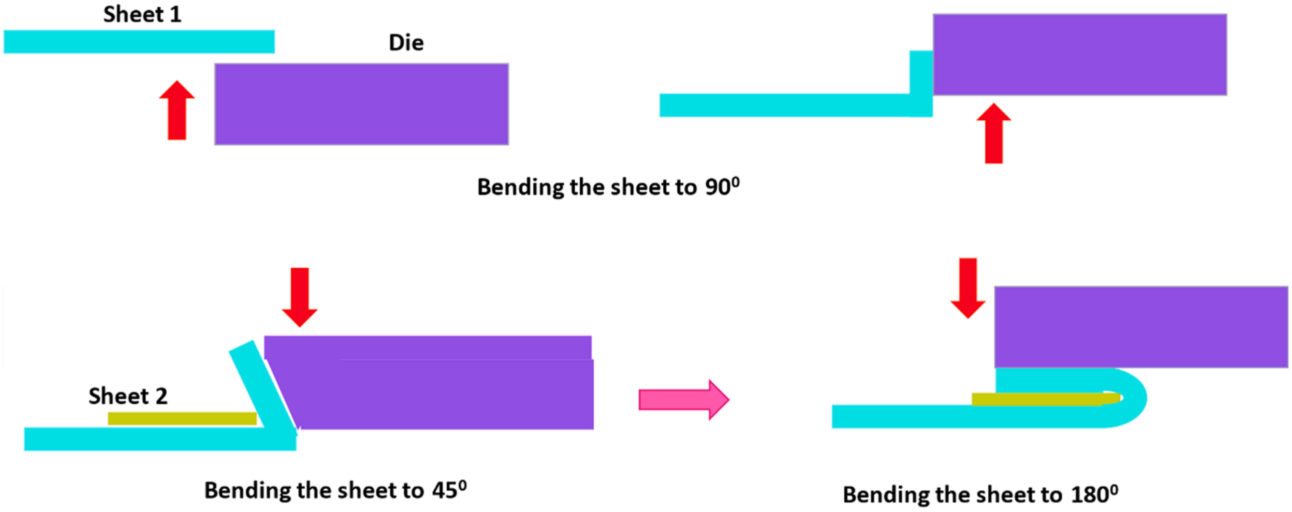


Fig. 29. Hemming process-tight fit by bending the sheets.

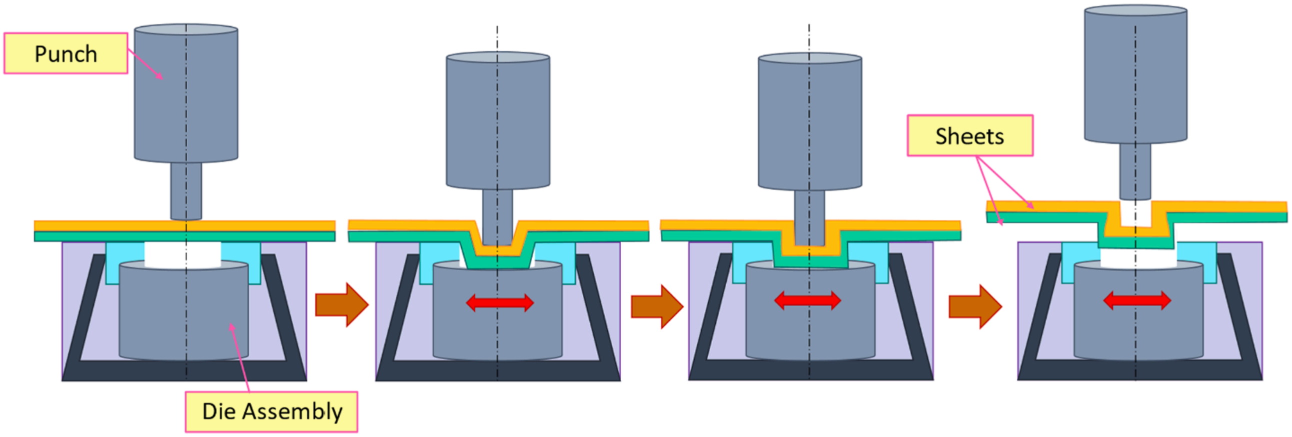


Fig. 30. Schematic process of clinching.

conducted by Chen et al. [165] on the combination of the flat clinching process and the material-forming technology, enlarging the punch diameter causes an increase in the neck thickness as well as the interlock length. These effects could ultimately enhance the quality of joining. Furthermore, based on the obtained results, the reliability of the joint will be excelled by increasing the forming force due to the better mechanical interlocking [166]. Lambiase and Cheol Ko [167] verified the appropriateness of mechanical clinching to manufacture hybrid CFRP–aluminium joints using extensible dies considering various clinching tools geometries. According to the geometrical and morphological analysis on the punch geometry and damage on the clinched joints, increasing the punch's taper angles results in smaller undercuts as well as major damage in the CFRP, which ultimately causes a reduction in the mechanical performance of the joint. Likewise, enlarging the pin diameter not only leads to an increase in the undercut due to the greater material flow, but also results in greater delamination in the CFRP laminates.

In comparison with spot welding, clinching does not require electricity hence this approach can be used to join polymers or plastic-metal composites with no electrical conductivity [168,169]. Furthermore, reduction in joining costs, decreasing the processing time, and no demand for surface preparation are other advantages of this approach. Nevertheless, some limitations such as the necessity to use deformable materials as well as inducing cracks in the vicinity of the punch-sided and die-sided sheets due to the severe deformation must be taken into account [168]. To increase the deformability of the materials, the heat-assisted clinching process has been introduced in a way that heat conduction causes a reduction in materials yield strength which increases the ductility of the materials and decreases the required load to perform the clinching process. Hence, this method can be employed to join thermoplastic composites to metals. Despite the benefits of this technique, clinching is mainly employed in automotive, appliance, aircraft, and electrical industries as a suitable replacement for spot welding [162].

5.1.3. *Rivets*

Rivets are non-detachable mechanical fasteners that are used as an additional element for the joining of parts. In the context of the multi-material joining the self-piercing rivets are widely popular in the automotive and marine industry.

Self-piercing riveting can be classified as a single-step cutting-riveting joining process where the prior formation of holes used in conventional riveting can be eliminated [170,171]. It is classified as a high-speed mechanical fastening technique for the point joining of two or more material layers. Depending on the type of rivets used in the application, SPRs are classified as semi-tubular (half-hallow) and solid rivets.

Self-piercing rivets pierce and fasten the components to be joined in one operation as shown in Fig. 31, eliminating the need for pre- holes and alignment, minimizing distortion, etc. The process can be used on a wide variety of materials including aluminium, steels, magnesium, FRPs, dissimilar combinations, etc.

5.1.4. *Screws and bolts*

Bolted and screw and nut joints are used for the joining of the parts with the use of screws/bolts. For the structural joints, one of the quite popular methods used in the industries is the flow drilling screws where the screw is forced into the workpiece causing plastic deformation and resulting in the permanent joint.

In the flow forming (drilling) process (FDS), a tapered, but unthreaded punch rotating at high speed is forced down to pierce through the metal. The sheet metal heats up and is momentarily softened [170,171]. Thus, a collared hole is formed by plastic deformation. A thread can then be tapped into the cylindrical hole. Stainless steel sheet metal screws are most often used for joining aluminium alloys as shown in Fig. 32.

According to an investigation on the optimum bolted joints for hybrid composite materials conducted by Hoon Oh et al. [172], increasing the clamping pressure on the bolted joints leads to an increase

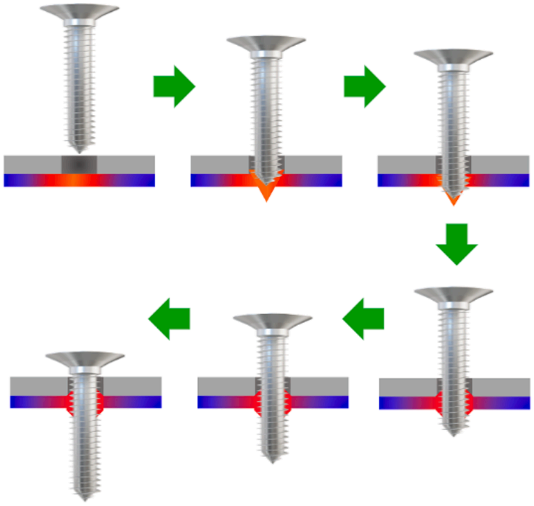
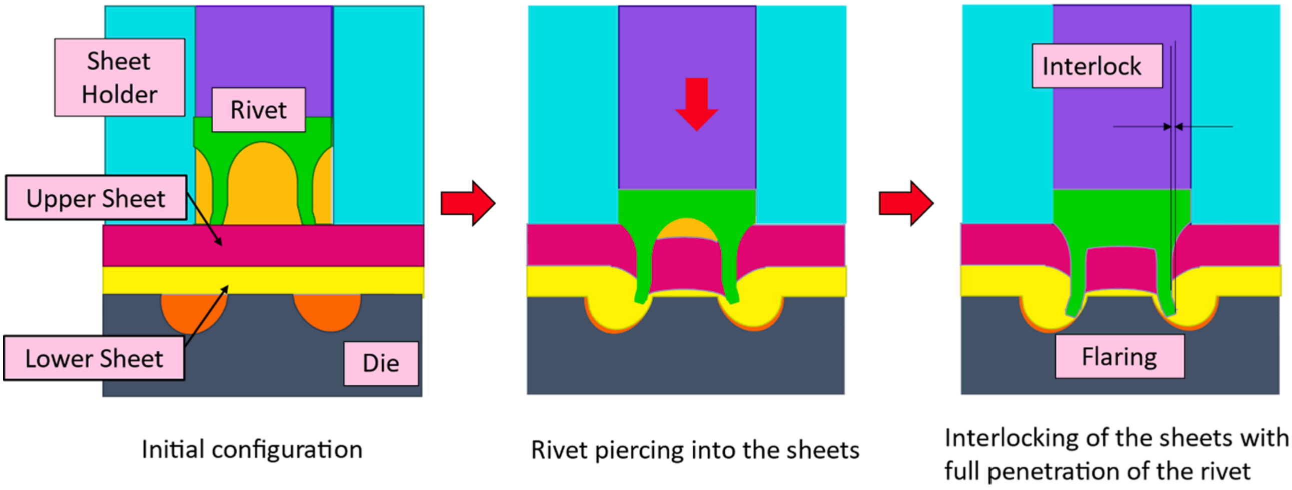


Fig. 32. Process steps of flow drilling screws.



Initial configuration
Rivet piercing into the sheets
Interlocking of the sheets with full penetration of the rivet

Fig. 31. Stages in self-piercing rivets joining.

in the strength of the joint until it converges to a plateau (see Fig. 33).

McCarthy et al. [173] investigated the effects of bolt-hole clearance on the stiffness and strength of composite bolted joints using the single lap joint configuration. According to their results, enlarging the clearance causes a reduction in the joint stiffness whereas ultimate strain increases.

According to a study carried out by Sayman et al. [174] on the failure analysis of the bolted FRP laminated composites, bearing strengths of the joints are substantially influenced by the magnitudes of applied preload as well as geometrical factors. The geometrical parameters include the edge distance to hole diameter ratio (E/D) and the plate width to hole diameter ratio (W/D). Accordingly, the results revealed that increasing the W/D and E/D ratios cause an increase in the joint strength. Furthermore, the stacking sequence of the plates is another effective parameter that must be taken into account. According to their observations, cross-ply $[0, 90]_s$ laminates proved to have a better mechanical performance in comparison with other stacking sequences. Fig. 34 shows one of the applications of using bolted joining technique in a boat.

5.2. Mechanical performance

5.2.1. Corrosion

One of the main considerations in the selection of mechanical fasteners in marine applications is corrosion compatibility. Whilst corrosion is not a substantial issue for glass or aramid fibre reinforced composites, it is proved to be a crucial challenge when carbon fibres are used since this type of reinforcement can act as a cathodic in contact with metals like aluminium and steel. To overcome this issue, titanium and its alloys (especially Ti-6Al-4 V) are used extensively due to their superior compatibility with carbon fibres. Nevertheless, it should be pointed out that titanium fasteners are expensive and heavier than aluminium fasteners which leads to a considerable increase in costs and weight of the structure.

In order to avoid corrosion and increase the weight of the structure, composite fasteners such as carbon fibre/polyimide, carbon fibre/PEEK, carbon fibre/carbon composites are introduced. Nonetheless, along with the aforementioned advantages provided by composite bolts, they are prone to confront shear failure under static tests as well as lower durability under cyclic loading which leads to lower fatigue endurance in comparison with titanium fasteners [175].

5.2.2. Sea water influence

Due to the extensive application of FRP composites in marine applications, numerous investigations have been conducted on the study of the mechanical performance of bolted joints when they are subjected to saltwater. The strength of glass/epoxy specimens with two pinned holes after immersion in seawater for 24 h had been investigated by Ozen and Sayman [176]. In the aforementioned study, whilst some of the pins were unloaded, the others were loaded by 3 Nm and 6 Nm torque. The strength of the specimens without torque preload diminished dramatically by 90% after the immersion, whereas almost no drop was observed for the samples that were preloaded by both torque values [176]. According to the provided justification, immersion of specimens in water causes an expansion in samples. Hence, when the expanded specimens were assembled into the holes, internal stresses generated in the samples may decrease the failure load. The mechanical performance of glass/epoxy composite subjected to bearing test after exposure to salt-spraying, foggy conditions for 30 and 60 days in order to assess the induced alteration in the failure mechanisms and the consequent decrease of the joint mechanical responses with unaged samples had been studied by Calabrese et al. [177]. The results showed that the conditioning induced moderate reduction by a maximum of 28% of bearing strength for hole diameter of 8 mm and edge distance of 14 mm. Additionally, the conditioning caused no change in the failure mode.

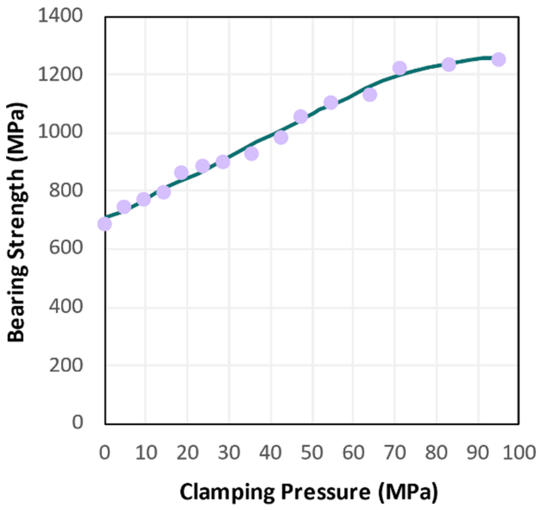


Fig. 33. Bearing strength regarding the clamp-up pressure (adapted from [172]).

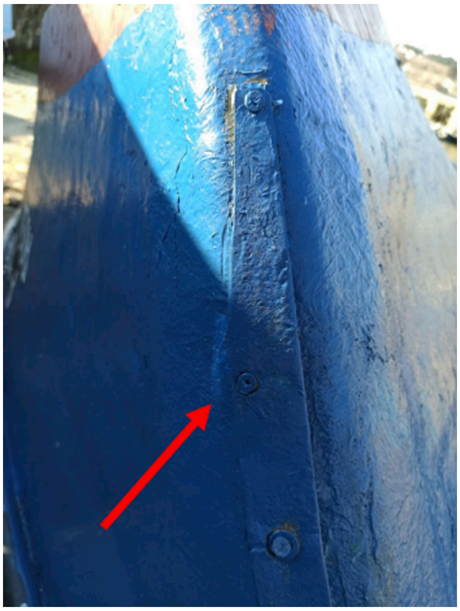


Fig. 34. Application of the bolted joining method in joining steel to the wooden part of the bow.

5.2.3. Fatigue

Giannopoulos et al. [178] carried out static and fatigue bearing tests by considering various tightening torque values. In the mentioned study, samples were fabricated from carbon/epoxy prepreg unidirectional tape with a quasi-isotropic lay-up. They reported that increasing the bolt pre-tightening leads to an increase in the allowable static stress and consequently an apparent increase in the fatigue life. Mariam et al. [179] studied the fatigue behaviour of the single lap joints by performing tensile-shear fatigue tests at the stress ratio of 0.1. In addition, for different levels of stress amplitude S–N curves were obtained. Based on the results, the fatigue life declined dramatically with the stress level. The combined influences of seawater ageing along with fatigue loading on the bearing response as well as failure mechanism of the CFRP/CFRP single-lap bolted joints had been investigated by Zhang et al. [180]. To this aim, fatigue loads followed by static bearing tests were applied to the unaged and aged bolted joints which were immersed in artificial seawater (3.5% NaCl solution) at 50 °C for 7 months. They observed that whilst the degradation of load-bearing capacity with increasing the ageing time followed an exponential trend for samples that were just exposed to seawater ageing, it followed a linear degradation for specimens that were subjected combination of seawater ageing and fatigue loading. In addition, the degradation level is substantially higher for mechanical joints under combined seawater degradation and fatigue load. Jiang et al. [181] investigated the mechanical response of dissimilar CFRP and aluminium sheets joined by the electromagnetic riveting (EMR) method considering three approaches including the slug rivet (SR), round head rivet (CFRP sheet I contact with the round head side, RC), and round head rivet (Al sheet in contact with the round head side, RA). Based on the results, the locking mode, as well as the discharge energy, had a substantial influence on the performance of the joint. Furthermore, fewer microvoids and consequently higher strength were observed in the case of the RC joint. In another research, Jiang et al. [182] studied the fatigue behaviour of aluminium/CFRP/5182 joints riveted by the EMR process. The experimental results revealed the remarkable effect of the driven head dimensions on the fatigue property of the tested joints. Increasing the diameter of the driven head to the shaft diameter ratio (D/D0) caused an increase followed by a decrease in the fatigue life. Furthermore, according to the failure analysis, damage through the joint occurred in three main ways including failure in the rivet, failure in the aluminium sheet, and failure in the CFRP and aluminium sheets as influenced by driven head dimensions and the stress levels. In another study carried out by Jiang et al. [183], the fatigue properties of electromagnetic riveted joints with various rivet dies under pull-out loading were examined. A significant effect on the pull-out fatigue performance had been observed by the rivet dies. As a result of the restriction caused by special rivet dies on the radial flow of the material in the driven head, this type of rivet die was proved to provide a higher fatigue life rather than a flat die. Furthermore, as fracture analysis showed, there were two main failure modes for the joints under pull-out loading including rivet manufactured head and upper sheet fracture.

6. Hybrid joints

As demonstrated earlier, each type of joint including welded, adhesively bonded, and mechanical fastening has limited performance especially when these structures are subjected to harsh marine environmental conditions (i.e., temperature and humidity) and cyclic fatigue

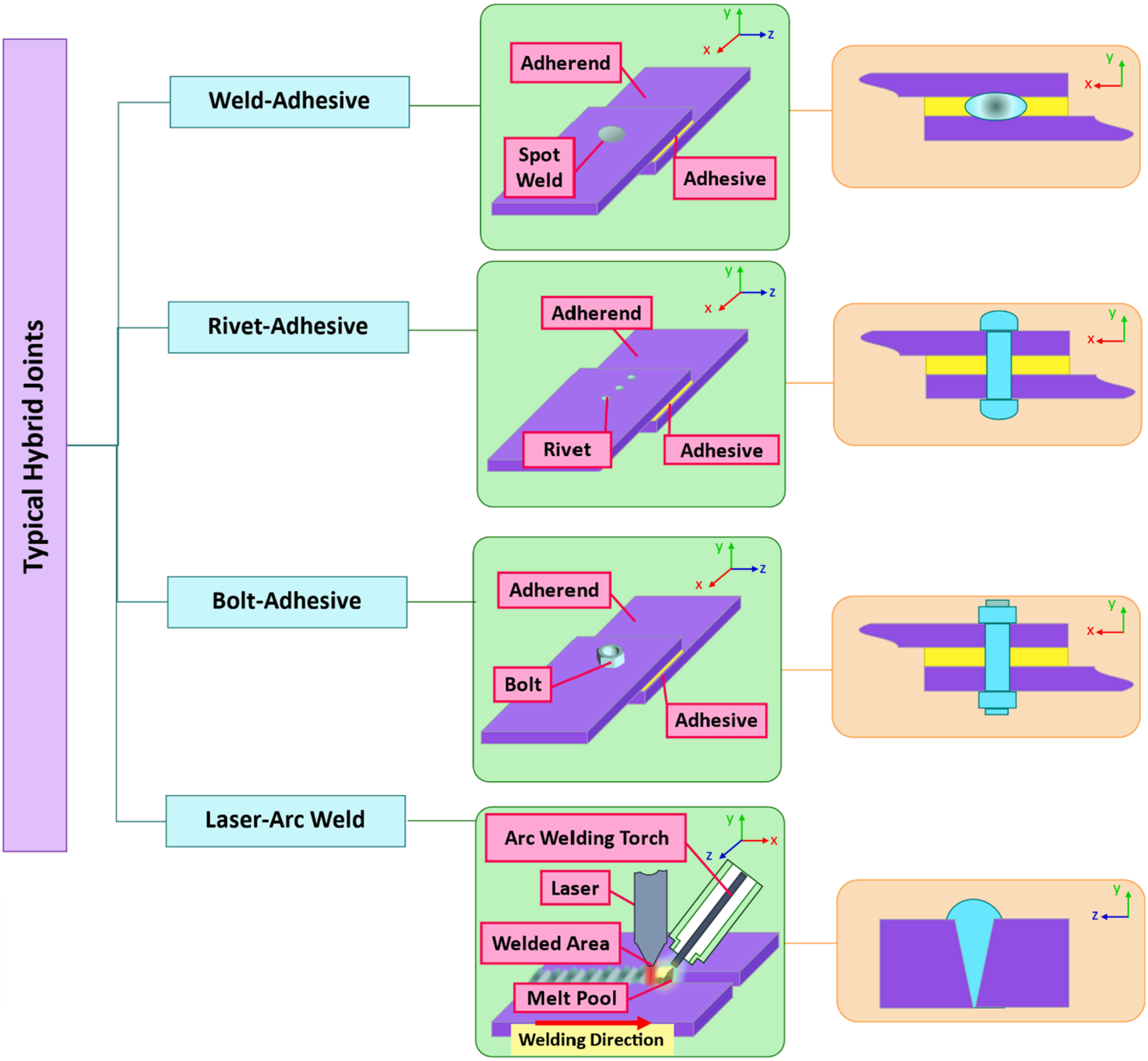


Fig. 35. Various hybrid joints configurations in the marine industry.

loads. For instance, in the case of welded joints, poor fatigue resistance has been a concerning issue while humidity can significantly change the performance of bonded joints. Applying mechanical fasteners such as bolts or rivets requires substrates to be punched or drilled to form holes that not only conduce to local stress concentration but also cut the fibres in FRP laminates. In addition, utilizing mechanical fasteners causes an increase in the weight of the structure [184,185]. In terms of adhesively bonded joints, these structures are prone to irreversible damages and instantaneous failure by subjecting to adverse environmental conditions (i.e., temperature, radiation, and humidity) due to the susceptibility of the polymeric adhesive. Furthermore, the stress concentration at the ends of adhesive joints precipitates premature failure, particularly in the case of FRP substrates. To overcome these concerning issues and raise the durability and efficiency of structures, the hybrid joining method has been proposed [186]. In general terms, the employment of hybrid joints leads to a substantial increase in the strength, reliability, and durability of the structure. According to surveys [187], using hybrid joints increases the strength of the joint by a factor of 1.5 to 3 compared with adhesive joints.

6.1. Types of joints

Fig. 35 illustrates several types of adhesive hybrid joints used in the marine industry.

6.1.1. Hybrid weld-adhesive joint

The hybrid weld-adhesive method incorporates two joining approaches including adhesively bonding and welding in order to achieve the advantages of both methods. This joining method has been initially developed by the former Soviet Union in 1957 for the AN-24 planes in order to be employed in the fabrication of transport aircraft. However, later it was developed for other industrial applications including marine structures [188-191]. Utilizing hybrid weld-adhesive joints, the welded part provides high peel resistance and acceptable strength while benefits such as uniform stress distribution, high fatigue life, and vibration resistance are offered by adhesively bonded parts. Other advantages of the application of hybrid weld-adhesive joints are higher fatigue-resistance in comparison with weld or adhesive joints due to the lower stress concentration, possibility of utilizing the fully automated process in order to manufacture hybrid weld-adhesive joints, reduction in fabrication costs, enhanced environmental durability, and enhanced energy absorption [188].

6.1.2. Hybrid rivet-adhesive joint

As mentioned before, hybrid joints have been recommended in order to obtain a combination of advantages of each joining method. Generally, there are three types of hybrid rivet-adhesive joints including adhesive joints reinforced by a small number of rivets, rivet joints where the adhesive fulfils a gasket, rivet joints where the adhesive fulfils joints in which both adhesive strength and rivet strength play a part [187].

The most significant advantage of hybrid rivet-adhesive joints is the simultaneous generation of stiffer and stronger joints [188]. In addition, this connection method provides other noticeable benefits such as flexibility in selection adhesive in comparison with weld-adhesive joints, higher mechanical strength in comparison with adhesively bonded joints, enhanced corrosion resistance compared with rivet joints. One of the naval applications of hybrid rivet-adhesive joints is for hull/vessel joining [188].

The hybrid rivet-adhesive joining method is widely employed in the shipbuilding industry for sealing purposes, particularly when the sealant strength is insufficient. In such circumstances, the rivet acts to sustain the load whilst the sealing is performed by silicone or polyurethane [192].

6.1.3. Hybrid bolt-adhesive joint

Perhaps the most applicable hybrid joint in the marine and naval industry is hybrid bolt-adhesive joints. Despite the hybrid weld-adhesive and hybrid rivet-adhesive joints, the combination of the adhesive and bolt method is not for hybrid purposes. Therefore, each joining method does not improve the performance of the other. otherwise stated, the bolt which is not stressed during service will be in charge of load-bearing and preserve the structural integrity as soon as adhesive fails, and it plays a backbone role in maintaining the adhesive layer [193]. From another point of view, the incorporation of the bolt and adhesive methods provides an opportunity for the joint to endure multi-axial loading in such a way that the adhesive layer carries the shear loads whilst the bolts bear transverse loads [193,194]. Furthermore, one of the most concerning issues in the marine and naval industry is the structures' durability to tolerate high temperatures and fire. As mentioned earlier, adhesive joints have poor resistance against high temperatures. To overcome this issue, in hybrid bolt-adhesive joints, the bolts bear the load in the case of failure of the adhesive layer [193]. Due to the fact that the long-term performance of adhesively bonded joints has been a major challenge, utilizing bolts along with adhesive joints can ensure the durability of the joints.

6.1.4. Hybrid laser- arc welded joint

The use of hybrid laser-weld joints was introduced by Steen et al. [195] in the late 1970 s. The results of their investigations observed clear advantages of combining a laser beam and an electric arc for welding. They proved a remarkable increase in welding speed, penetration depth and process stability could be obtained by hybridization due to the synergic influences of the laser beam and eclectic arc in the same weld pool [196]. In 2001, the Meyer Werft, one of the largest and the most modern shipyards globally, started to use hybrid welding as an exclusive welding method for butt joints and long fillet welds between the deck plating and bulb profiles [157]. In this method, arc welding and laser welding are simultaneously utilized in a common interaction zone.

6.2. Process

6.2.1. Hybrid weld-adhesive joint

The process of manufacturing adhesive joints and welded joints has been explained earlier. Nevertheless, in order to fabricate hybrid weld-adhesive joints, generally, there are two different methods including the Flow-Through method and the Weld-Through method which are illustrated in Fig. 36. As can be seen, whilst in the Flow-Through method, the process begins with welding, in the Weld-Through method the first step involves applying adhesive. Therefore, the Flow-Through method is more applicable in the case of low-viscosity adhesives so that the adhesive flows smoothly in blank spaces. It should be pointed out that, in the Weld-Through method using a thermoplastic adhesive, it is necessary to ensure a suitable heat transfer and not to change it irreversibly through the adhesive hardening process. On the other hand, typically thermoset adhesives show a better resistance to harsh environmental attacks which makes them more suitable for marine applications. Although various types of welding methods can be applied to fabricate these joints, typically, spot welding is the most common welding approach [188,199]. Table 5 brifly shows the advantages and disadvantages of the hybrid laser-arc joining technique.

6.2.2. Hybrid rivet-adhesive joint

Generally, in order to fabricate hybrid rivet-adhesive joints, three techniques have been suggested represented in Fig. 37. Similar to the Flow-Through method for fabrication hybrid weld-adhesive joints, in the Flow-In method to manufacture hybrid rivet-adhesive joints low-viscous adhesives should be applied on substrates. This technique is employed in order to enhance the strength of rivet joints. In order to achieve the maximum mechanical properties of adhesive, the Rivet-Through Uncured Adhesive technique is the optimal method. Moreover, due to the presence of rivets, the polymerization process of the adhesive is performed properly because a more suitable adhesive

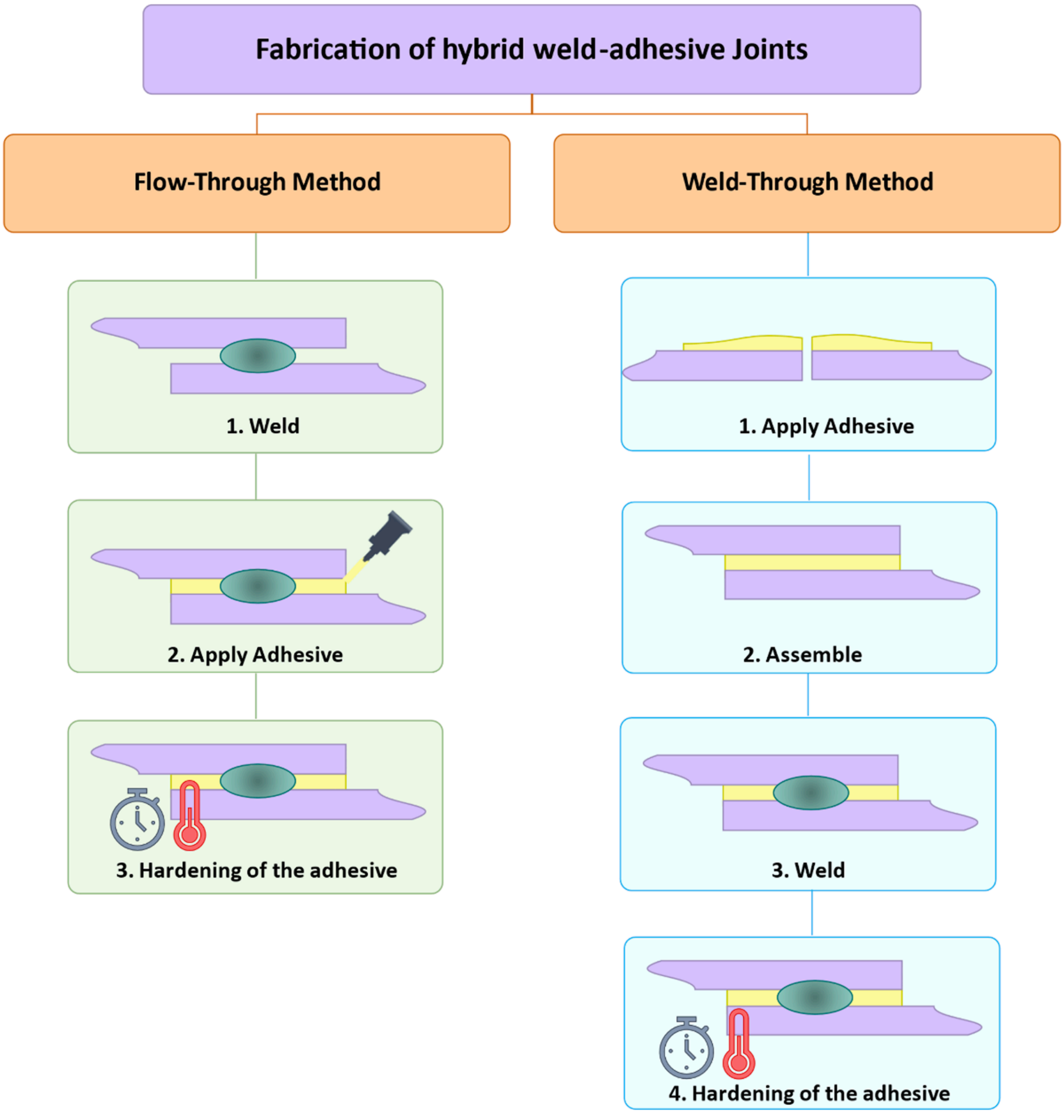


Fig. 36. Various fabrication processes of hybrid weld-adhesive joints.

Table 5

Advantages and disadvantages of hybrid laser-arc joining method (adapted from [197,198]).

Advantages	Disadvantages
■ Production of the narrow and deep weld pool Higher welding speed Reduction in the heat input and the chances of thermal distortion in welded parts	■ More expensive than arc welding Very poor electrical efficiency for most of the laser systems Poor gap bridging ability Requirement of high precession in workpiece fit-up and edge preparations Complex application for highly reflective materials like aluminium, copper, gold, etc

thickness controlling mechanism is employed by fixing the substrates with rivets. Lastly, the Rivet-Through Uncured Adhesive (RTUA) technique is less recommended as it provides disadvantages similar to the adhesively bonded joints. Nevertheless, there is a possibility to repair or increase the strength of pre-existing bonded joints [188]. It should be borne in mind that the mechanical response of the adhesive including the stiffness and strength, is dramatically influenced by the curing temperature as well as the curing duration. Partial and incomplete curing will result in a low strength of the joint and eventually lead to a catastrophic failure of the structure. Hence, in the selection of the joining methods, the compatibility of the adhesive with the joining process must be taken into account.

6.2.3. Hybrid bolt-adhesive joint

The schematic of the process of fabrication of hybrid bolt-adhesive joints is illustrated in Fig. 38. After pre-treatment of substrates which has been explained previously, the adhesive is applied to the adherends. Due to the requirements of controlling the adhesive layer thickness, similar to simple adhesive joints, utilizing adhesive scaffolds, beads, or shims. Having been assembled, the adhesive must be cured at room temperature or in the oven based on the datasheet provided by the producer. The next step begins with drilling a hole with the proper diameter in the specimen before the bolt is assembled to the sample. If it was needed to perform the drilling step prior to bonding, it is mandatory to insert a pin in the drilled hole during the curing process so as to ensure the hole alignment.

A number of applications of hybrid bolt-adhesive joints in the marine industry are provided in Fig. 39.

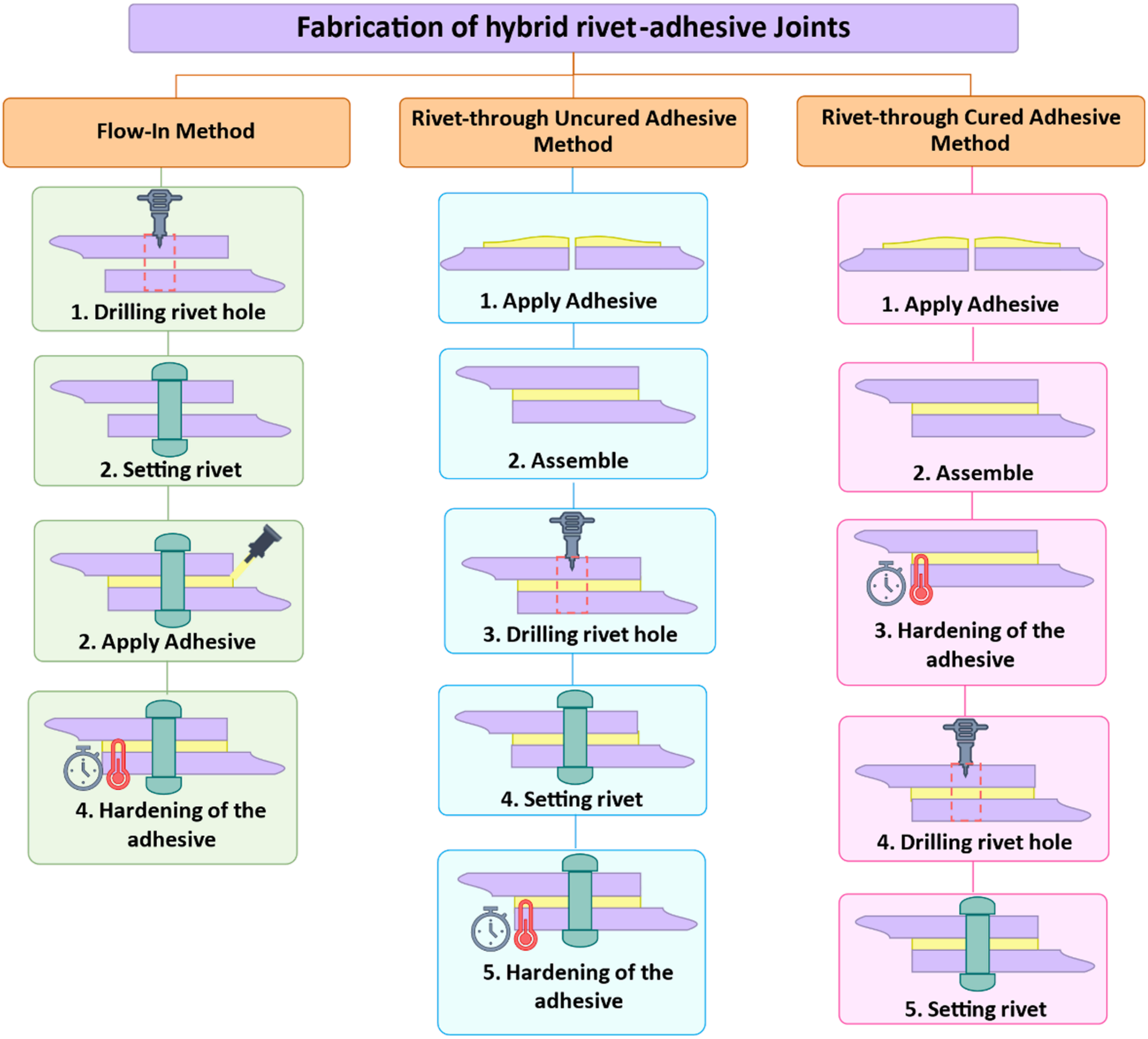


Fig. 37. Three different manufacturing processes of hybrid rivet-adhesive joints.

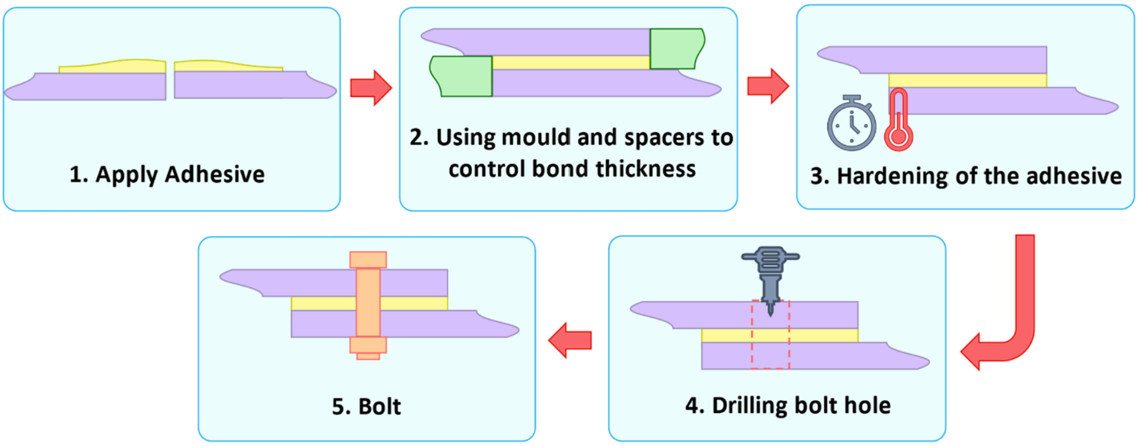


Fig. 38. Manufacturing process of hybrid bolt-adhesive joints.

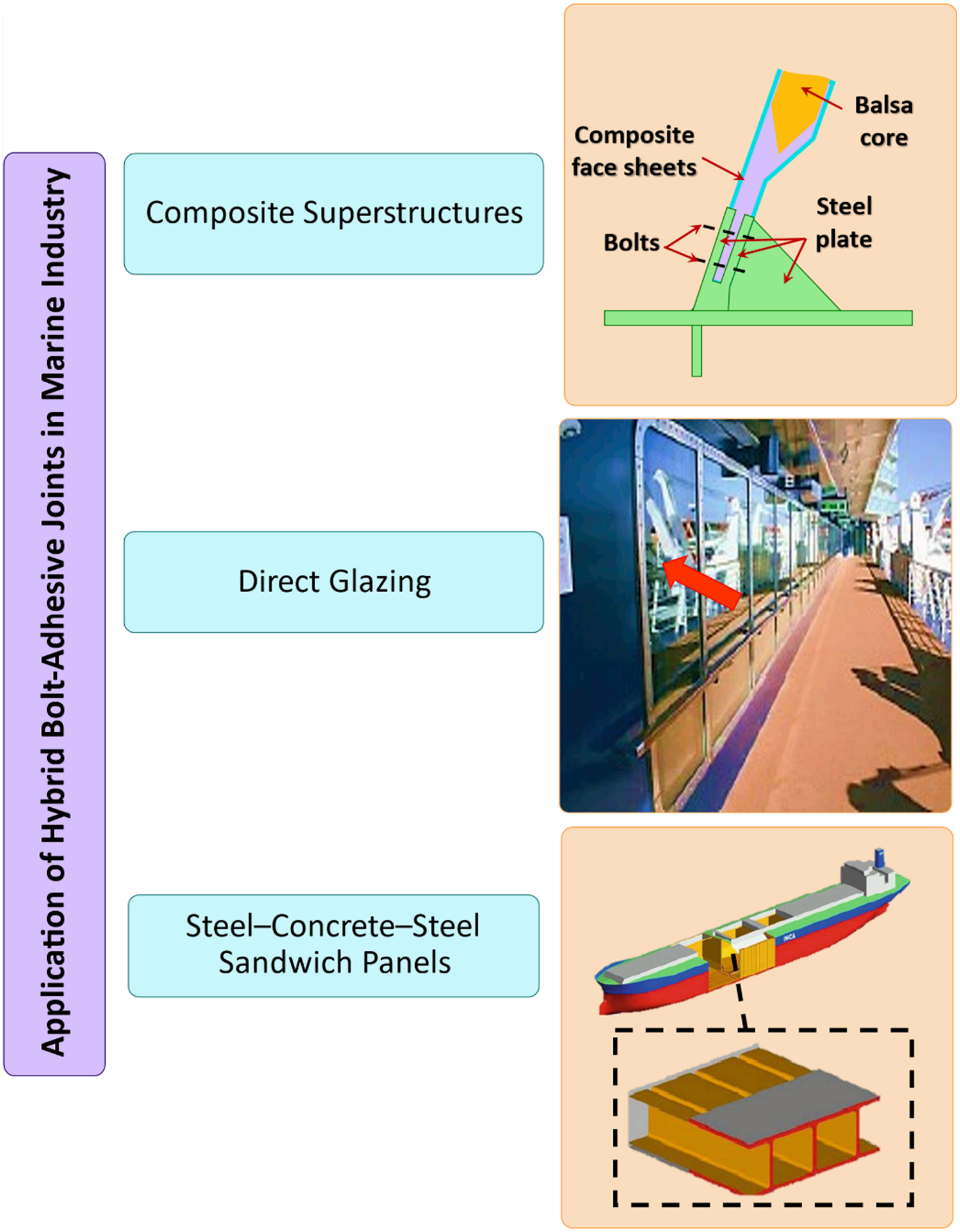


Fig. 39. Applications of hybrid bolt-adhesive joints in the marine industry (adapted from [188]).

6.2.4. *Hybrid laser-arc welded joint*

In this method, the synergic action is provided by a high-power laser beam, and an electric arc performs welding. The laser is utilized to conduct a deep penetration welding. The configuration of shape and size of the weld bead and the strength of the weld are regulated by the dynamic interaction of laser irradiation, electric arc, and the filler droplet. Fig. 40 illustrates the scheme of the hybrid laser-weld process. As can be seen in Fig. 41, by performing the hybrid laser-weld process, two zones are generated, including the arc (upper zone), which resembles a semi hemispherical ‘cup’ shape and the laser (lower zone), which resembles a finger. In this process, the primary heat generated by the laser beam interacts in the same weld pool developed by the secondary heat source generated by the arc welding process [189,200,201].

6.3. *Mechanical performance*

The fatigue behaviour of the jointed single lap joints with three different methods including spot welding, adhesive bonding, and hybrid weld-adhesive bonding had been examined by researchers [202-204]. Their results proved that employing the hybrid joint method has a remarkable influence on the endurance of the hybrid joint compared with conventional spot-welding. Nevertheless, as Sam and Shome reported [202], the fatigue behaviour of hybrid weld-adhesive joints was lower than adhesive bonding only. Based on an investigation conducted by Chang et al. [205] utilizing a computational model to study the fatigue and fracture behaviour, whilst the application of the adhesives in joints connected by spot welding has a considerable effect on the joint fatigue performance, the implementation of the weld spots in an adhesively bonded joint detriments this parameter. Fig. 42 illustrates the fatigue testes results of three different joining techniques. According to the results, the fatigue strength of weld-adhesive joints was substantially greater than that of the spot-welded, whereas it was slightly lower than the adhesively bonded joints.

Somervuori et al. [206] investigated the fatigue performance of the hybrid weld-adhesive and spot-welded joints under corrosive conditions of 3.5 wt% NaCl solution at the temperature of over 50°C. according to

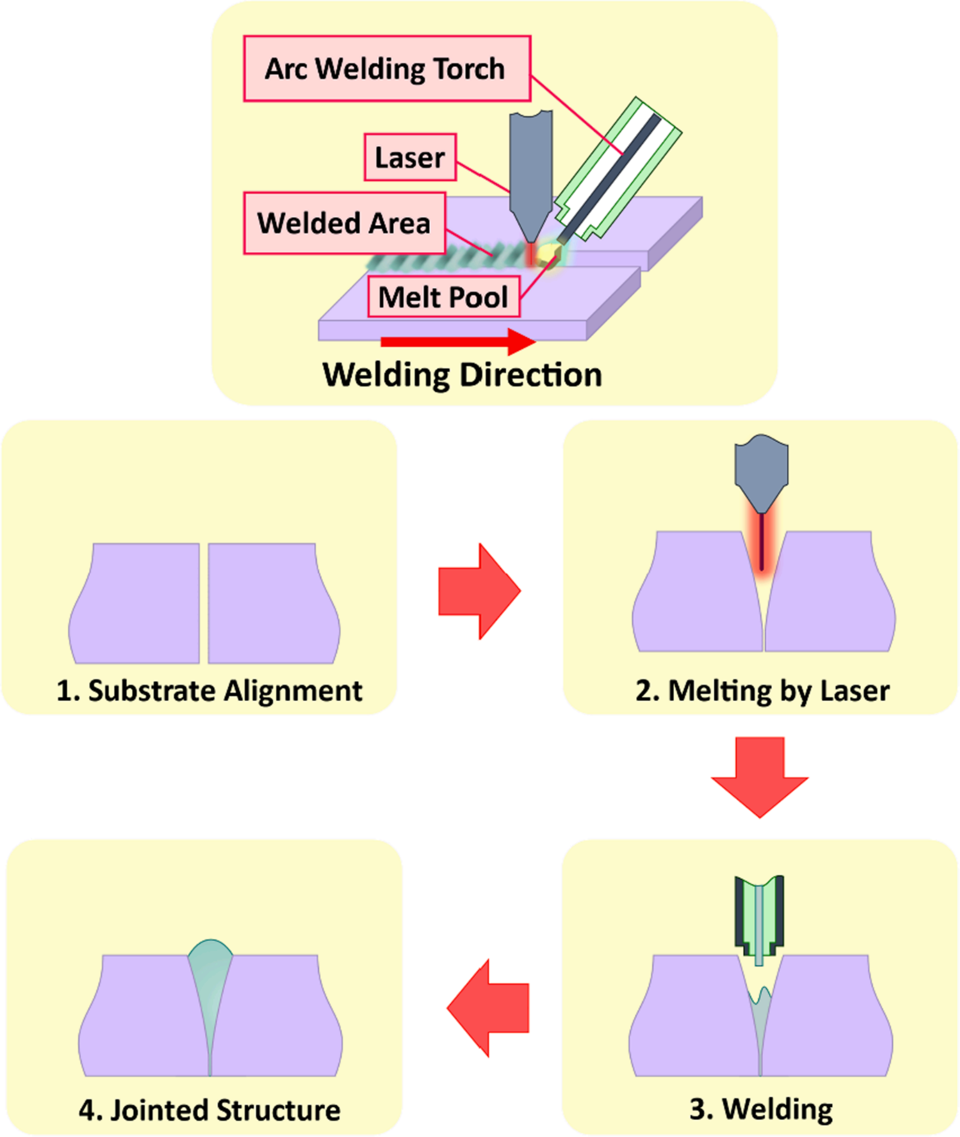


Fig. 40. Joining process of hybrid laser-weld joints.

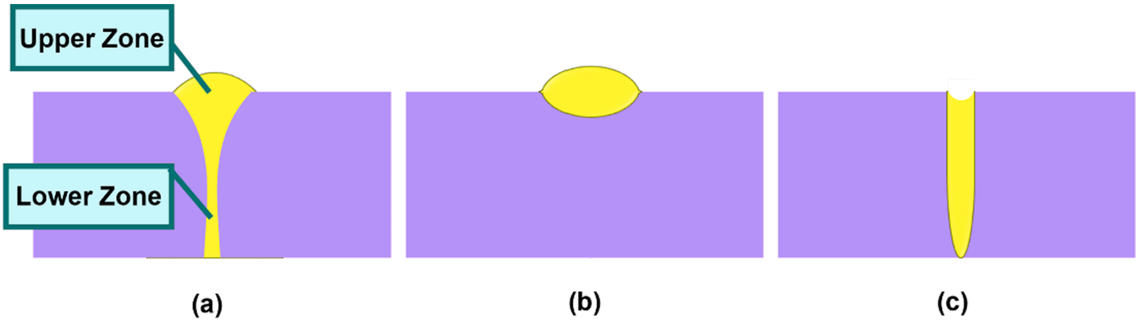


Fig. 41. Configuration of a) hybrid laser-arc welding, b) arc welding, and c) laser welding.

their results, the fatigue performance of hybrid joints was significantly higher, whereas under corrosive circumstances the difference between the fatigue strength of hybrid and simple weld joints decreased.

According to an investigation conducted by Imanaka et al. [207], fatigue cracks propagated more gradually in hybrid rivet-adhesive joints than in adhesive joints after crack initiation. Sadowski et al. [187] analysed the effects of rivets' layout geometry on the hybrid rivet-adhesive joints response to mechanical loading. They found that energy absorption to the final failure of the hybrid joints is 1.7 times higher than simple adhesive joints and also 1.4 higher regarding simple rivet joints. Furthermore, the tensile strength of the hybrid joint is about 3% higher than the simple adhesively bonded joint and almost 112% higher than the simple rivet joints. As the results show, the rivets' layout geometry has a considerable influence on the strength of the hybrid joints

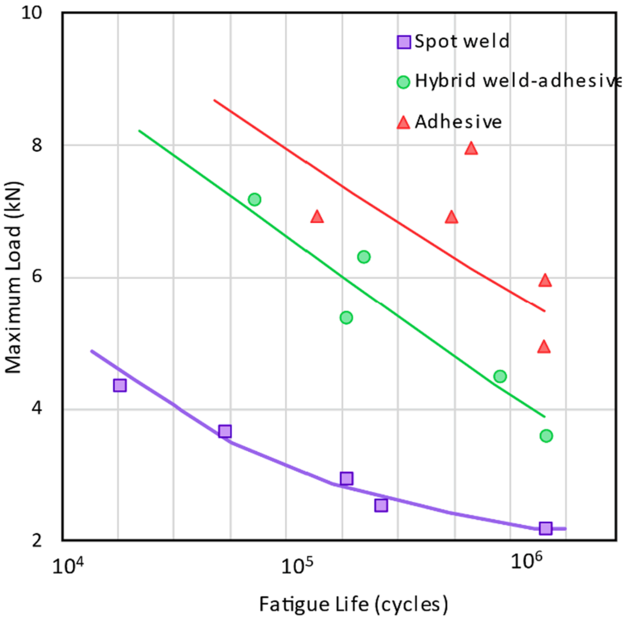


Fig. 42. Fatigue test results for three types of joints including spot welded, adhesive bonded, and hybrid weld-adhesive joined (adapted from [205]).

whereas this influence is negligible on the strength of simple rivet joints. Jiang et al. [208] examined the efficiency of the hybrid self-piercing riveting bonding technique on the mechanical properties and failure behaviour in comparison with simple riveted, and bonded joints. In the aforementioned study, the digital image correlation (DIC) approach was employed to analyze the strain of the sheets during the test. According to the obtained results, significant coupling effects can be achieved by combining the electromagnetic self-piercing riveting and adhesive bonding such as increasing the failure displacement and energy absorption compared with simple joints (see Fig. 43).

Several studies have been conducted on the investigation of the mechanical performance of hybrid bolt-adhesive joints. For instance, Chan and Vedhagiri [209] studied the effect of geometrical parameters as well as the adhesive property on the performance of hybrid bolt-adhesive single lap joints both numerically and experimentally. In the mentioned investigation, CFRP laminates were used as adherends and two bolts had been applied in the overlap region. Their results evident that, although the bolts did not engage actively in load transfer before the initiation of failure, they had a considerable effect on the reduction of the stresses at the edge of the overlap. Kweon et al. [184] carried out experimental research to evaluate the strength of carbon composite-to-aluminium double lap joints manufactured with two different types of adhesive materials including film and paste. The results proved that the hybrid joining method is not effective unless the strength of the bolted joint is higher than the strength of the bonded joint. Zhang et al. [210] conducted a compression shear test on CFRP/CFRP composite bonded–bolted hybrid single-lap joints at 800 °C. Based on their outcomes, in comparison to the adhesively bonded joints, the shear stress gradient of the adhesive layer increased whereas the peel stress gradient decreased. Moroni et al. [211] assessed the influence of the material, geometrical factors and environmental conditions on the static strength, stiffness and energy absorption of hybrid weld-adhesive and bolt-adhesive joints. According to the results, for weld–adhesive joints an increase of strength, stiffness as well as higher energy absorption had been observed in comparison with simple spot-welded joints. Moreover, hybrid weld-adhesive joints proved to be more dependent on temperature and ageing compared with adhesively bonded joints. In the case of hybrid-fastened joints, in comparison with hybrid weld-adhesive joints, the effect of adhesive joints was more substantial. As the authors justified, this could be due to the lower relative stiffness of the rivets which transfer the load on the bonded area. Hence, the design of the adhesively bonded joints in hybrid fastened/adhesive joints is more crucial. In addition, a noticeable enhancement in the mechanical response regarding the fastened joints had been observed. Nevertheless, the effects of temperature and degradation for hybrid joints is the same as simple bonded joints. Lopez-Cruz et al. [212] evaluated the influence of several effective parameters quantitatively on the mechanical response of hybrid joints including the adherend thickness, adhesive modulus, adhesive thickness, clamping area, and bolt-hole clearance. According to the results, hybridization had a remarkable influence on the strength of hybrid bolt-adhesive joints in comparison with adhesive bonding and bolted joints since the presence of the bolt postpones the crack propagation through the joint (see Fig. 44).

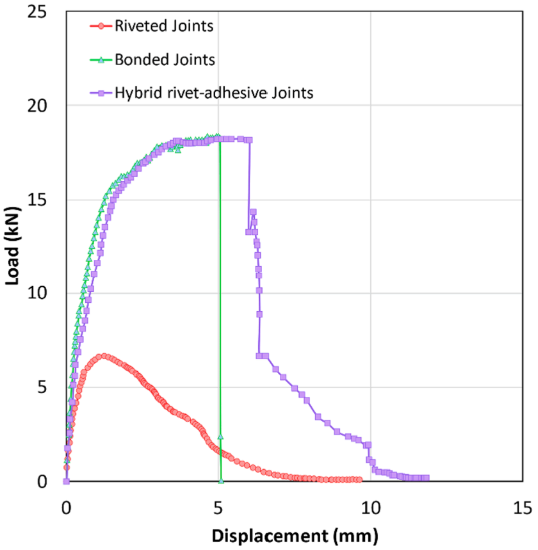


Fig. 43. Typical load–displacement curves of various joints including riveted, bonded, and rivet-adhesive joints (adapted from [208]).

7. Discussion (Benefits and Challenges)

In the above section, various typical joining techniques in the marine industry have been explained. Hence, in the current section, the benefits and challenges of each method have been generally and qualitatively compared. To this aim, the comparison is performed considering various major criteria.

7.1. *Manufacturing prospect criteria*

Nowadays, various manufacturing corporations are forced to lunch novel designs of products due to the shorter life cycles and higher demands of the customers. Therefore, factors which control the manufacturing process are very crucial in order to obtain swift, economical, and qualified product. As mentioned before, mechanical fastening, adhesive bonding, welding, and hybrid joining are typical joining methods that are currently widely used in the marine industry. Nevertheless, as a manufacturer, different factor such as tooling cost, diversity in material to be joined, the requirement of an expert technician or any pre-procedure needed before joining are important considerations in the design and manufacture of the structures. In terms of tooling cost, materials, energy cost, and the requirement of the accurate machines the techniques of welding, hybrid joining, and overlamination are exorbitant in comparison with other methods. Amongst available methods, mechanical fastening methods are generally more cost-effective in comparison with others. Considering prospect such as cost of machines, materials, and technician are governing factors in decision of manufacturer to choose the optimum joining method. Obviously,

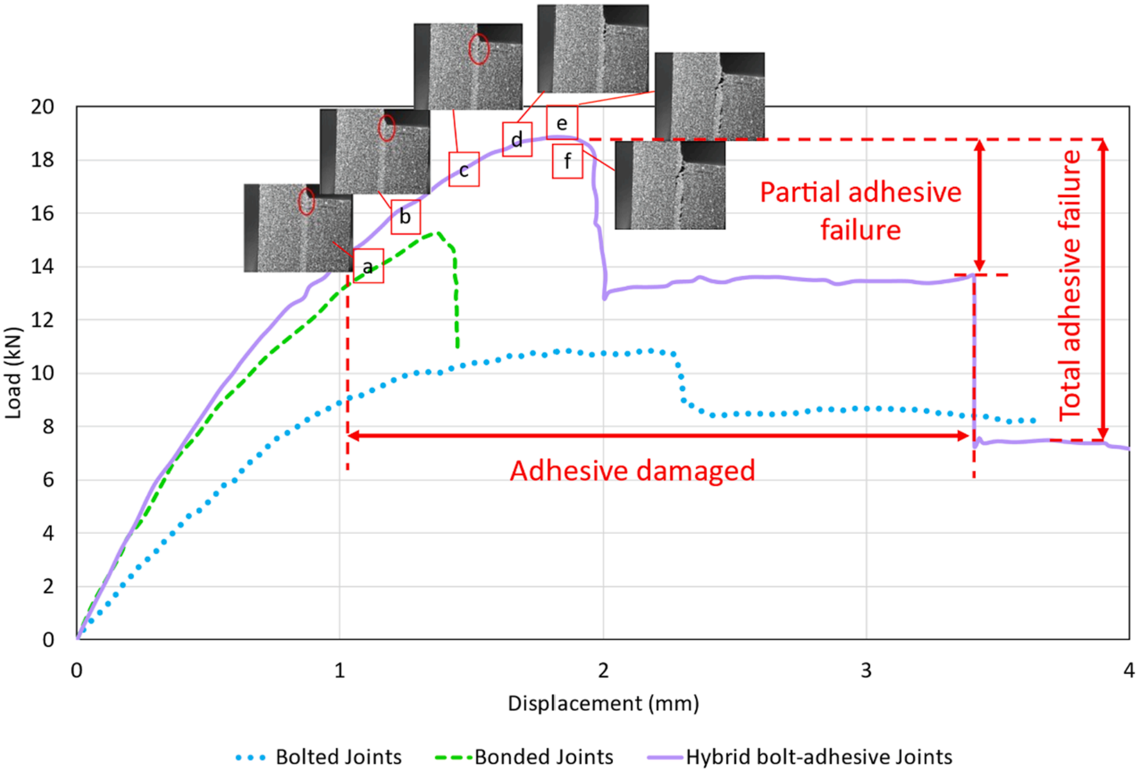


Fig. 44. Typical load–displacement curves and failure process of various joints including bolted, bonded, and bolt-adhesive joints (adapted from [212]).

costs attributes to welding machines are considerably higher than other methods such as mechanical fastening. It should be pointed out that even in the case of other joining techniques, the expenses related to material, drilling machines (mechanical fastening), surface preparation machines and pressing machines (adhesive bonding method), must be taken into account. Another important factor is the skill and experience of the technician. Amongst the available joining methods, welding and overlamination require a high skilled technician to perform the joining precisely and with high quality. It should be pointed out that in the case of welding of composites, the technician needs to perform welding with the optimized welding parameters to be sure that the highest strength is obtained with the lowest damage to the fibres due to the generated heat. As mentioned earlier, one of the important factors in obtaining a high strength joining is surface preparation. This requirement is very vital in the case of the techniques which is based on adhesion. This manufacturing step is time-consuming and also introduces an extra cost to the manufacturing process. In addition, using some surface preparation techniques such as anodizing or plasma can be significantly challenging when it comes to large structures and panels. Another preliminary criterion to be considered is the substrate material in the selection of joining technique. Generally, adhesive bonding is the most unlimited technique in joining various types of materials including metal and polymers. In terms of welding, using this method is possible and limited to thermoplastic materials. Although utilizing mechanical fastening is not time and cost consuming, due to the drilling, this method is not highly recommended for fibre reinforced materials. Consequently, this limitation is extended to the hybrid adhesive bonded-mechanical fastened joints. Lastly, in terms of overlamination, this method is usually applied to fibre reinforced polymers. Lastly, another important factor is the time needed for structure to be used in service from the manufacturing process. Since welding and mechanical fastening are swift processes, the structure can be employed in service conditions instantaneously. Nonetheless, in the case of other types of methods in which adhesion plays the role of joining, the time required for the structure to be used in service conditions is dependent on the curing time of the resin or adhesive. In some cases, the curing time of adhesives can take even weeks. Hence, generally, being time-consuming is one of the most important challenges in using adhesion based joining methods. One of the most important advantages of adhesive bonding over welding processes is the lower level of residual stresses associated with bonding. In some cases, it is needed to do some post-weld heat treatments to reduce the residual stress. This may compensate for the curing time needed in adhesive bonding. This is beside the distortion which may take occur during welding processes. Table 6 represents a qualitative comparison between the aforementioned factors in manufacturing considerations.

7.2. Inspection/repair criteria

As mentioned earlier, since marine structures are subjected to severe environmental condition and various cyclic loads, these structures are highly vulnerable and hence requires structural damage detection during their service time. Therefore, the possibility of damage identification and repairability are crucial to the industry. Furthermore, in the next step, considering the propagation of the damage in the structures, the possibility of the dismantling of the damaged part to repair is a very important factor in time and cost-saving. Considering a large structure, joints are very susceptible to damage since they are transferring the loads between various components. Hence, in the case of damage, it is more cost-effective for the industry if the damage occurred in the joint can be detected and repaired without the requirement to replace the whole structure. Amongst various joining techniques, usually, damage detection in the case of the mechanical fastening method is easier than other methods. Acoustic emission (AE) analysis using a piezoelectric sensor, active thermography, phased array ultrasonics, and shearography is a number of non-destructive evaluation (NDE) methods to damage identification and structural health monitoring in composites. In the case of welded joints, damage detection is more difficult with respect to mechanical fastening. Visual Inspection, liquid penetrant, magnetic particle, eddy current, ultrasonic/acoustic emission and

Table 6
General characterization of various joining methods considering manufacturing prospect criteria.

Concerning Prospect	*Method* **Welding**	**Adhesive Bonding**	**Mechanical Fastening**	**Overlamination**	**Hybrid Joining**[*]
Manufacturing					
Tooling cost	High	Medium	Low	High	High
Substrate materials	Limited	Unlimited	Limited	Limited	Limited
Skill required for technician	High	Medium	Low	High	Medium
Requirement of surface preparation	Not required or very simple and fast	Required	Not required	Required	Required
Time to reach service condition	Short	Medium to long	Short	Medium to long	Medium to long

[*] In this table, hybrid joints are defined as joints where a combination of adhesive bonding and mechanical fastening (or welding) techniques is used.

radiography are the most common non-destructive tests to detect defects in the welded joints [213]. Nevertheless, in the case of the joining based on adhesion, defect detection is more challenging due to the lack of reliable non-destructive evaluation (NDE) methods through the overlap [214]. Amongst NDE methods, visual inspection, ultrasonic testing, acoustic emission, x-ray radiography, shearography, and infrared thermography are the most common techniques for quality assessment of bonded joints focus on detecting defects like cracks, voids or porosity in the adhesive layer [215,216]. Considering a damaged structure, it is very crucial for the industry and engineers to separate the damaged part without introducing of any damage into other components and the whole structure. Amongst the aforementioned methods of joining, adhesively bonded joints and mechanically fastened joints enable the possibility of dismantling the damaged part. Nevertheless, in the case of adhesive bonding, disassembly of the damaged part is dependent on the type of adhesive. While it is typically not possible to disassemble the thermoset adhesive joints, the thermoplastic-based adhesive joints can usually be dismantled by heating the entire adhesive area. In case of welding, the repair can be performed without dismantling and instead the damaged part can be removed and re-welded (this is not possible in all cases). Table 7 summarizes the general properties of different joining methods with regard to inspection/repair criteria.

7.3. Strength and durability criteria

Perhaps the most effective criteria to the industry in order to select a joining method is strength along with the capability of withstanding of severe environmental circumstances. The benefits and challenges of different joining techniques considering strength and durability criteria are qualitatively compared in Table 8. Regarding the strength to weight ratio, generally adhesive bonding shows promising strength in comparison with other joining techniques. Antelo et al. [217] compared the performance of welding and adhesively bonded joints in a real structural representative component in the agricultural industry. Experimental and numerical investigations revealed that adhesive bonding could be a suitable replacement for welding in structural applications. According to their results, even in the case of the reduced overlap by 70%, the static strength of the bonded joints was higher than the welded assembly. Delzendehrooy et al. [218] compared the static strength of the bonded, bolted, and hybrid bonded-bolted steel joints considering various bolt sizes. According to their obtained results, the effect of the adhesive on the strength of the hybrid joints in the case of lower bolt sizes is more significant rather than higher bolt sizes. Furthermore, the results of durability tests represented that in the case of leaking, higher bolt size and drilling area diameter leads to higher water uptake and consequently higher reduction in the strength of the joints. In terms of stress concentration, generally, adhesively bonded joints and overlaminated joints act better rather than other joining techniques, particularly mechanical fastening. In terms of mechanical fastening, especially in the case of composites, due to the requirement for drilling (e.g., bolt or rivet) or considerable deformation in microscale and mesoscale in the case of clinched joints, significant stress concertation would be generated in the deformed or drilled area. Furthermore, the requirement of drilling or deforming leads to various failure and damage mechanisms in the vicinity of the processed area such as fibre breakage, fibre buckling and matrix cracking. In previous sections, various joining techniques for welding thermoplastic composites and polymers has been demonstrated. These techniques are based on heat generation which leads to binding and diffusion. In the case of fibre reinforced composites, excessive heat generations cause fibre damage and fibre burn as well as matrix burn (e.g., laser welding) or matrix flow from the overlap under the impact of the solidifying force (e.g., ultrasound welding) are possible challenges in welding process which ultimately leads to irregular welded joint. Irregular stress distribution and consequently irregular stress concentration are destructive mechanisms of failure in an irregular welded joint. Marine industry requires structures having high fatigue endurance since they are constantly exposed to various cyclic loading (e.g., tides). The superior performance of adhesively bonded joints in fatigue endurance and vibration absorption, as well as uniform stress distribution, are encouraging advantages that must be noted by designers. As Jones and Williams [219] demonstrated, high rigidity to the structure and consequently enhancement in the fatigue properties of the structure is provided by high strength/modulus adhesives. Based on their achieved results, whilst the fatigue properties of hybrid welded-bonded structures are similar to adhesively bonded structures, higher fatigue strengths were obtained regarding bonded compared to spot-welded structures due to the re-distribution of the stresses in the joint.

Finally, to all the engineers and designers in the marine and naval industry, the durability of structure in harsh environmental conditions has been a concerning issue to select the best joining technique. As mentioned earlier, susceptibility of the adhesion based joining methods to environmental factors such as high temperature, humidity, and

Table 7
General characterization of various joining methods considering inspection/repair criteria.

Concerning Prospect	*Method* **Welding**	**Adhesive Bonding**	**Mechanical Fastening**	**Overlamination**	**Hybrid Joining**[*]
Inspection/Repair					
Damage detection	Medium	Difficult	Easy	Difficult	Difficult
Repairability	Difficult	Difficult	Easy	Difficult	Difficult
Dismantling	Not applicable	Dependent on the adhesive	Applicable	Not applicable	Not applicable

[*] In this table, hybrid joints are defined as joints where a combination of adhesive bonding and mechanical fastening (or welding) techniques is used.

Table 8
General characterization of various joining methods considering strength and durability criteria.

	Method				
Concerning Prospect	**Welding**	**Adhesive Bonding**	**Mechanical Fastening**	**Overlamination**	**Hybrid Joining**[*]
Mechanical Performance					
Strength to weight ratio	Medium	High	Low	Low	Medium
Stress concentration at joint	Medium	Low	High	Low	Medium to high
Fatigue endurance	Medium	Good	Low	Good	Medium
Vibration absorption	Low	High	Low	High	Medium
Tolerance of Environmental Conditions					
Tolerance of high temperature	High	Low	High	Low	Low
Tolerance of humidity	Moderate	Low	Low	High	Low
Tolerance of saltwater	Low	Medium	Low	Low	Low

[*] In this table, hybrid joints are defined as joints where a combination of adhesive bonding and mechanical fastening (or welding) techniques is used.

saltwater is a limiting characteristic in the selection of a suitable joining methods. In this state, welding is more promising in comparison with other methods, especially adhesive bonding. Nonetheless, the tolerance of adhesively bonded joints in saltwater is preferable compared with other methods. Obviously, developments in manufacturing of novel and more durable adhesives and resins will results to provide potential advantages in marine and naval industry due to the higher resistance of the adhesion-based joints to intense environmental circumstances.

Since the focus of the current investigation is on the development of the application of composite joints in the marine industry, perhaps joining based on adhesion, particularly adhesive bonding would be a potential option to be employed rather than other joining techniques. Obviously, the future applications of this technique require further progress and development in both polymer technologies (manufacturing of durable, fast curing, and strong adhesives) as well as the structural manufacturing procedures by using enhanced and advanced machines to perform bonding swiftly and accurately.

8. Conclusions

Using suitable and efficient joining methods which maintain the integrity, reliability, and durability of the structure is a concerning issue that must be considered in joining components in marine structures. In the current review, a comprehensive study was carried out on the different joining techniques used by researchers in marine applications. To this aim, various important aspects from the manufacturing viewpoint (e.g., materials selection, process, etc.) to mechanical performance emphasizing the effects of marine environmental circumstances were considered. According to the literature and feedback from the industry, the overlamination method is extensively applied in the marine industry but it is mostly limited to composite materials. In addition, this method is cost and time consuming and requires expert fabricators. On the other hand, considerable advantages provided by welding such as high strength to weight ratio, low vibration absorption and low fatigue life are noticeable challenges that welded structures are faced with. Furthermore, whilst structures that are joined by this method can be instantaneously used in the service condition, tooling cost and requirement of expert technician are major problems. In the case of mechanical fasteners, whilst they have easy manufacturing procedures, issues such as non-uniform stress distribution, susceptibility to environmental conditions, and low vibration absorption, as well as fatigue life must be considered. Adhesively bonding can be considered as an optimum method to bond various parts of marine structures. In this method, it is possible to join different materials and obtain desired strength and flexibility corresponding to the type of adhesive. Even though vulnerability to elevated temperature and moisture is a concerning issue, these joints can be operated excellently when they are subjected to saltwater compared with other methods. Hence, it is recommended to employ this joining technique for structures that are exposed directly to saltwater. Finally, as pointed out before, the hybrid joining method is suggested to cover challenges regarding simple joining methods. Nevertheless, it is important to choose the optimum combination of two joining techniques based on the most required criteria. For instance, in the case of optimization of time and strength, hybrid laser-arc welding is recommended whilst hybrid bolted-bonded joints are more cost-efficient.

To sum up, to design the most efficient joints to be used in the marine industry, criteria such as mechanical performance, manufacturing process, endurance against environmental conditions, and the specific application of structure must be considered. Further experimental and numerical investigations must be conducted to evaluate and compare the performance of the available joining techniques especially for the hybrid joining method.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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