Science and Technology of Bolt-Adhesive Joints

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Abstract This chapter addresses bolt-adhesive joints to transfer both loads and moments. All our examples are taken from maritime applications. Experience has shown that bolt-adhesive joints in the maritime industry are not designed for hybrid action where one joining method improves the performance of the other. Rather they are used in a fail-safe-mode where one joining method takes over should the other fail. Three different applications will be discussed: (1) composite superstructures and composite to steel joints on large ocean going vessels, (2) adhesive bonding of windows, also known as "direct glazing" and (3) cellular sandwich concept for large ocean going ships such as bulk carriers. The sandwich is composed of two steel faces and a lightweight concrete core.

1 Introduction

This chapter addresses bolt-adhesive joints to transfer both loads and moments. All our examples are taken from maritime applications. This chapter does not include thread-locking—using adhesives to stop nuts and bolts from coming loose (see Chapters Science of friction-adhesive joints and Technology of friction-adhesive joints for more information about thread-locking).

Experience has shown that bolt-adhesive joints in the maritime industry are not designed for hybrid action where one joining method improves the performance of the other. Rather they are used in a fail-safe-mode where one joining method takes

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over when the other fails. As a consequence, design for adhesive bonding and bolting is usually done independently from each other.

Based on the applications we have seen, we interpret bolt-adhesive connections as *adhesively bonded joints combined with vertical members that limit potential movement in the in-plane direction*. This may include bolts, studs or metal strips that are welded or bolted in place.

This chapter will not address selection of materials, including adhesives. Interested readers are referred to [52, 55]. Having said that, the examples discussed here use common shipbuilding materials, e.g. steel or composite sandwich. This helps to minimise changes needed to the support structures and the yard building processes.

2 Motivation for Using Bolt-Adhesive Joints

Concerns over long-term performance of adhesively bonded joints prevent in many cases the use of adhesive bonding as a joining method for load bearing connects [51]. Hence hybrid joints have received more attention recently. Under which circumstances is it beneficial to use hybrid joints?

- The joint is subject to loading from different directions: Anon [2] the adhesive carries shear stresses while the bolts carry transverse loading. A special case is composite pultrusions or aluminium extrusions which may have interlocking features that are used to connect the profiles.
- As mentioned by Anon [2], bolts may help make a bonded joint survive exposure to fire. Bolts are usually not loaded during service. However, in the event of a fire adhesives soften eventually and the bolts will carry the load.
- A further advantage in using bolt-adhesive hybrid joints is that the issue of predicting long-term performance of the bonded joint is avoided since bonding is being combined with a proven joining method [51].

There are situations where hybrid joints are not effective:

- As Anon [2] point out, structures that are operated at higher temperatures and are required to be stiff may not be suitable for bolt-adhesive joints. The adhesive will soften at elevated temperatures thus reducing the joint's stiffness.
- A further potential disadvantage according to [2] is the fact that electrical continuity is interrupted by the adhesive layer.
- Furthermore, by using two joining methods fabrication and inspection costs are increased. Hentinen and Hildebrand [25] quantified the cost penalty for fabrication of bolt-adhesive joints compared to bonded only solutions.

While "adhesion" is essential for corrosion protection to ensure the corrosion prevention coating adheres to the steel surface, there are few applications where adhesively bonded joints are used in safety critical applications. The most prominent example is the joint between the steel deck and the composite superstructure of the French La Fayette class frigates [34]. Hybrid joining is probably the application that has been developed furthest. It is used for joining of composite superstructures to steel main structures and for the joining of windows.

Recent changes by the International Maritime Organisation [28] open up the possibility for using risk based design to demonstrate equivalent levels of fire safety. This has opened up the possibility for using composites on large ocean going vessels as previously only non-combustible materials were allowed. With it comes the challenge of joining the composite structure to the main steel structure. An early study by Hentinen and Hildebrand [25] demonstrated the feasibility of joining composite to steel and they developed possible joint solutions. McGeorge et al. [37] presented results from research into the use in a frigate-type naval ship of a bonded tuning-fork type of joint offering some degree of mechanical interlocking. They concluded that the bonded joint would offer the required integrity and will not be the weak link in the structural assembly. Bohlmann and Fogarty [7] report results from the prototype development for a US Navy destroyer and the joining methods they had developed. Finally Speth et al. [49] and Ritter et al. [46] report on the superstructure to deck joint for a large yacht.

Adhesive bonding of windows, also known as “direct glazing”, has become standard practice on passenger and cruise ships with more than 10 years of accumulated experience in the shipbuilding industry. Wacker et al. [50] reported the bonding of window panes and their design. Weitzenböck [53] reports on the experience gained so far with bonded windows.

Bergan et al. [6] introduced a cellular sandwich concept for large ships such as bulk carriers. The sandwich is composed of steel faces and a lightweight concrete core. The main motivation was to simplify shipbuilding (fewer parts) and make it cheaper (concrete is cheaper than steel). During material testing it was discovered that the sandwich configuration had to be changed. Initially the load transfer between the concrete core and the steel face relied entirely on the adhesion between concrete and steel. Later on it was discovered that one needs additional mechanical fasteners, such as shear studs to improve adhesion also in the long-term.

All the examples presented in this section will be discussed in more detail later on.

3 How to Gain Confidence

Adhesive bonding has been used for many years in transport applications. However, there are still very few examples where adhesively bonded joints are used in safety critical applications. One of the reasons is that it is difficult to predict the long-term effects of the (marine) environment on such a joint.

Considerable media attention has been given to the Boeing 787 and Airbus A350 aircraft development programmes. Both aircraft make extensive use of composites in the fuselage leading to significant reduction in structural weight and number of components and fasteners. However, what is receiving less attention is the fact that the fuselage sections are still joined using fasteners. In fact they are the main critical item in the assembly process as discussed by Peck [44]. Another interesting detail is that the lack of suitably certified fasteners was one of the main contributing factors for the considerable delays the 787 Dreamliner has experienced to date [36]. Hence, also for the most modern commercial airplanes adhesion in critical load bearing joints is not relied on alone. However, at the same time there is evidence of the long-term performance of bonded (aluminium) aircraft structures. Beevers [5] reports on a study using bonded joints that had been recovered from a scrapped Nimrod/Comet 4C aircraft which was built in 1963. The aim was to establish the condition of the adhesive in a 30-year-old structure. The tests showed that tensile strength and fracture toughness of the adhesive still met or exceeded the manufacturers' original specification. Another aircraft that is making extensive use of adhesives is the Fokker Fellowship F-28. Bond [8] reports that the Fellowship F-28 contains more than 900 bonded assemblies. At the time of writing of Bond's report these aircraft had been in service for up to 25 years without any reported failures or damage of the bonded connections. An example to illustrate the time scale it takes to build confidence in hybrid joining methods is the development of weld bonding (spot welding and adhesive bonding). Studies of the properties of weld bonded joints by Menges and Schmidt [42] and Reinhardt [45] were the basis for the design of a loading ramp for a truck (see also [47]). These East German developments were at least partly based on initial studies carried out earlier in the Soviet Union. Drain and Chandrasekharan [18] report that use of adhesives in hem flanges of, e.g. doors of cars had become common practice. However, structural bonding was still very much a topic of research with impact, fatigue and durability being the key issues. Today weld bonding is a standard joining process known for its superior crash performance. For example Keller et al. [32] report results from a project to use weld bonding for a vehicle subassembly. The crash performance was better than a spot welded assembly. It was noticed that the numerical models to model material behaviour needed further development to be able to make better predictions during the product development process. Another interesting development is that weld bonding had also been developed for aircraft manufacture. Croucher et al. [11] reported on a study to develop weld bonding for fighter planes. More information about weld-bonding can be found in Chapters Science of weld-adhesive joints and Technology of weld-adhesive joints.

Weitzenböck and McGeorge [51] outlined an approach to introduce adhesive bonding into marine applications despite the lack of documented long-term performance. This approach uses sound risk management principles and comprises the following three steps:

1. Hazard identification.
2. Risk assessment.
3. Adoption of suitable risk control measure,

Three risk control measures are proposed:

1. use state of the art in design, material selection and fabrication of bonded connections,
2. make it possible to detect failure early on, before it becomes critical and

3. develop a qualified repair procedure in case the bonded connection fails and requires repair.

This approach implies that not all possible joint configurations on a ship or offshore structure can be bonded as some of the risk control options are difficult or impossible to implement in critical parts. For example, the onset of failure of the bonded assembly may be difficult to detect or there may not be enough time to qualify a repair procedure. However, by introducing a further risk control option, namely bolting, many more application suddenly become feasible.

While adding bolts or similar items to the joint may increase confidence, there is a trade-off to be considered. Fabrication cost will increase as Hentinen and Hildebrand [25] point out. They compared adhesively bonded and bolt-adhesive joints between steel and FRP sandwich material. While there was no difference in cost for the fabrication of the edges, joining to the ship structure was twice as expensive compared to the bonded only solutions. It is interesting to note that for quasi static tensile test both joint concepts obtained almost identical values while for flexural loading the bonded only solutions was clearly superior. However, it is worth pointing out that for certain types of loading, e.g. high temperature, it is advantageous to use hybrid joints, as an adhesive may fail due to high temperature.

There are two main conclusions that can be drawn from these discussions. Adhesives are not usually used alone for major safety critical joints. Use of failsafe design, such as adding bolts or other mechanical fasteners, may help overcome the lack of confidence in the long-term performance of adhesives.

4 Design and Analysis of Bolt-Adhesive Joints

4.1 Introduction

Strictly speaking bolt-adhesive joints are not the preferred option for joining two components. Using two joining methods simultaneously incurs a cost penalty. However, there are situations where it is an advantage to use hybrid joints, e.g. loading from different direction or exposure to high temperatures. Still, the main reason for using bolt-adhesive hybrid joints for marine applications is the uncertainty about the long-term performance of bonded joints and how to document it. By combining adhesive bonding with a well proven and tested joining method, one can accept some un-quantified uncertainty about the durability of the adhesive.

4.2 Science of Bolt-Adhesive Joints

Kelly [33] carried out experimental and numerical studies of the load transfer in hybrid bolt-adhesive composite single-lap joints. He studied how different kinds of adhesives affect the way adhesives and bolts interact. Very stiff adhesives result in joints where the bolts contribute very little to the load transfer. However, adhesives with lower strength and modulus and increased ductility resulted in more flexible joints allowing the bolts to transfer a larger share of the loading. Kelly [33] sums up the results of his study as follows:

- The load transferred by the bolt increases with increasing adherend thickness.
- The load transferred by the bolt increases with increasing adhesive thickness.
- The load transferred by the bolt decreases with increasing overlap length.
- The load transferred by the bolt decreases with increasing pitch distance.
- The load transferred by the bolt decreases with increasing adhesive modulus.

Note: the bolt "pitch distance" is defined as the distance between bolts in a row. Kelly points out that if bolts are to make a significant contribution to the load transfer, the joints need to be flexible, either by selecting a suitable adhesive or joint design. Shenoi and Hawkins [48] provide an introduction and guidance to joint design for composite materials, including bolted connections. Broughton et al. [9] presented a general design procedure for bolt-adhesive joints. They discuss tools and procedure for design and analysis of joints. da Silva et al. [12, 13] review and benchmark all known analytical formulas for bonded lap-shear joints. da Silva et al. [13] selected some approaches from the literature survey and subjected them to a systematic benchmark study. The first conclusion was that no single model works equally well in all cases. The authors recommended candidates for: (1) long overlaps, brittle adhesives and elastic adherends (any linear analysis), (2) ductile adhesives and elastic adherends (Hart-Smith), (3) adherends that yield (Adams, Comyn and Wake) and (4) joints with composites (Adams and Mallick).

Adams [1] proposed a simple bondline strength criterion assuming that the bondline strength is proportional to the overlap length. This criterion is appropriate for short overlaps. But such short overlaps are discouraged because the short overlaps tend to compromise the bonded joint's long term performance (creep, fatigue) and its defect and damage tolerance. For longer overlaps used for structural joints, Adams' simplified approach is unsafe as it ignores that the efficiency of the joint decreases with bondline length. This may mislead the designer to think that increasing bondline length will increase capacity. For structural adhesives, nonlinearity must be taken into account. In some cases this can be done without finite element (FE) analysis. Hart-Smith assumes that the strain to failure is a material property. That works if the real case is similar to the tested case from which the strain to failure was determined (see also [43]). However, generally speaking, Hart-Smith's assumption is incorrect and can lead to problems if the real case differs significantly from the tested case from which the strain to failure was determined, e.g. much stiffer adherends. This phenomenon is documented by Echtermeyer et al. [19], Guthu [23] and McGeorge [41]. FE analysis helps if geometry does not lend itself to use of simple formulas and makes it easy to predict strains at given loads assuming no failure. To be reliable, failure prediction must account for both nonlinear material behaviour and the fracture process that causes failure. This can be achieved by simple formulas for some simple geometry [40] or using FE analysis with plasticity and cohesive elements for more general geometries [23]. For flexible adhesives, time-dependent failure modes govern. However, this is not quite true for very low stresses where linear elastic methods can be used. To explicitly account for creep and time dependent failure is complicated both with regard to modelling and testing to challenge/validate models.

4.3 Practical Design of Bolt-Adhesive Joints

Experience has shown that bolt-adhesive joints in the maritime industry are not designed for hybrid action where one joining method improves the performance of the other (“$1 + 1 \geq 2$”). Rather they are used in a fail-safe-mode where one joining method takes over when the other fails (“$1 + 1 = 1$”). Based on the applications we have seen, we interpret bolt-adhesive connections as adhesively bonded joints combined with vertical members that limit potential movement in the in-plane direction. This may include bolts, studs or metal strips that are welded or bolted in place. Provided a suitable adhesive is used, bolt-adhesive joints can also be part of the corrosion protection strategy by providing an electrical insulation layer against galvanic corrosion.

Broughton et al. [9] provide an overview of the design process for bolted and bonded joints. There are different types of bolted connections. Eurocode 3 [20] divides bolted connections into three categories:

- Category A: bearing type
- Category B: slip-resistance at serviceability limit state
- Category C: slip-resistance at ultimate limit state

Serviceability limits are typically excessive vertical or horizontal deflections. Slip-resistance for bolt-adhesive joints is provided by the adhesives not the compression forces of the bolts. This means that category A would be equivalent to bolt-adhesive joint with a highly flexible adhesive or sealant. The bolts always carry the load. For category B type joints slip should not occur at the serviceability limit state. The design serviceability shear load should not exceed the design slip resistance. This implies that under normal operational loads the adhesive is providing all the strength. And finally for category C type joints slip should not occur at the ultimate limit state. The design ultimate shear load should not exceed the design slip resistance. This implies that the adhesive should carry all the loads—always. Basically, this is an adhesive joint. This is only possible for adhesives with documented long-term performance.

The main long-term concerns for the bolts are probably corrosion and not fatigue as the bolts are not loaded during service [4]. Corrosion of bolts can be minimised by selecting suitable corrosion resistant materials or coatings and ensuring that the design avoids exposure of the joints to water. More information about corrosion can be found in the forthcoming Det Norske Veritas Recommended Practice on “Specification, design and installation of fasteners for the offshore oil and gas industry”.

Bolted connections need to pass a number of criteria. Some of the most basic ones are that the bearing strength of the plate and the shear strength of the bolts are sufficient. The bearing strength of composite plates can be determined for example from DNV [17]

$$\sigma_{\mathrm{bear}} = \frac{R_{\mathrm{bear}}}{3\gamma} \tag{1}$$

with σ_{bear} is the shear load divided by $d \times t$, t the thickness of structural laminate, d the bolt diameter, $\gamma = 1.0$ for holes with a difference between bolt and hole diameter <10 mm, $\gamma = 1.6$ for holes with a difference between bolt and hole diameter of <1.0 mm, R_{bear} is the elect value for different laminates from table in DNV [17].

A formula for determining design shear resistance for the bolt may be found in, e.g. Eurocode 3 [20]:

$$F_{\mathrm{v,Rd}} = \frac{\alpha_{\mathrm{v}} f_{\mathrm{ub}} A}{\gamma_{\mathrm{M2}}} \tag{2}$$

with A = tensile stress area of bolt A_{s}, α_{v} between 0.5 and 0.6 (see Eurocode 3 [20]), γ_{M2} = partial safety factor for resistance of bolt (=1.25), f_{ub} = ultimate tensile strength for bolt, $F_{\mathrm{v,Rd}}$ = design shear resistance per bolt.

Bonded joints are strongest when they are loaded in shear. Hence, hybrid bolt-adhesive joint will also mainly be loaded in shear. Furthermore, as the bondline surface is usually quite large, bonded joints tend to be lightly loaded. This is partly also because adhesives that exhibit good gap filling characteristics have much lower shear strength than aerospace grade adhesives with very thin bondline thickness. Now, depending on other requirements such as ability to compensate for thermal miss match, the joint could be designed such that under normal service conditions, the adhesive carries all loads (non-slip condition) while accidental loading or failure of adhesive due to excessive ageing is carried by the bolts (bearing condition). This means that for service conditions the bolt-adhesive joint behaves like a bonded joint while in accident scenario the joint is a bolted joint.

Bolt and adhesive joints are designed independently. Hence there is no universal design basis and requirements. They are different from case to case. Table 1 sums up the requirements or design basis for the application examples discussed later in this chapter. For adhesives, there are no strict requirements as they are not usually allowed for safety critical connections, mainly because their long-term performance is not known precisely. However, for bolts a number of codes or rules are available. For example DNV [17] provides guidance on how to design bolted connections in composite materials. The steel–concrete–steel (SCS) sandwich material was designed on the basis of Eurocode 4 [21] and DNV [14]. For the

Table 1 Design basis for bolt-adhesive joints for application examples

	Adhesive	Bolt
lightweight composite superstructures for ships	No requirements, but low strains or stresses recommended Use closed form solutions or FE	Established codes, e.g. classification society
Direct glazing of windows	Strain/stress limits Simple formulae or FE analysis for larger windows	engineering judgement—no design code
Steel–concrete–steel sandwich plates	Adhesion is not considered	Shear studs—established design codes, e.g. Eurocode 4

windows, the number and location of the bolts are selected on the basis of engineering judgement.

5 Application Examples

5.1 Introduction

The following sections describe known application examples of hybrid bolt-adhesive joints used in marine structures. The first main group of examples are related to lightweight composite superstructures for ships, both large ships and high speed craft. Next, we will be presenting direct glazing of windows, probably the best established hybrid joining case. Lastly we will be outlining an application of a novel material and structural arrangement—the SCS sandwich material.

The case descriptions follow a common structure:

What is the challenge?

- What is the (joining) problem?
- Why hybrid joints?
- What are the design challenges?
- What are the materials technology and fabrication challenges?
- What are the requirements?

Description of solution addressing:

- Analysis and design
- Fabrication and inspection
- Long-term performance

Status?

- What is the (service) experience if any?

5.2 Composite Superstructures

5.2.1 What is the Challenge?

The use of composites in superstructure modules has been investigated in a number of research projects showing promise of considerable weight-saving in excess of 50% of the weight of a steel design for the module enabling considerable fuel savings and emission reductions. Some details on the structural design can be found in for example [7, 25] while fire safety is discussed in [39]. For large ships combustible materials are not allowed. Recent changes in safety regulation permit the use of combustible materials provided one can show equivalent levels of fire safety (SOLAS Regulation 17, see also [28]). McGeorge et al. [39] demonstrate equivalent fire safety via a rigorous risk assessment. To be able to use composite superstructures, one needs to devise methods for efficient and reliable joining of the composite to steel or sometimes aluminium. However, the ultimate challenge for using this new technology in practice is to convince the relevant approval authority or flag state that the safety of this solution is equivalent to steel.

Hentinen and Hildebrand's [25] research was motivated by trying to increasing the use of fibre reinforced plastic (FRP) sandwich structures in superstructures to save weight. Their aim was to develop joints that can easily be installed in a traditional (steel) shipyard. Hence they developed joints with integrated steel substructure that can be installed by welding without the need for bolting, adhesive bonding or lamination at the shipyard. Hentinen and Hildebrand [25] investigated solutions where the metal structure is bolted and/or bonded to the FRP structure (see also Fig. 1).

Bohlmann and Fogarty [7] report on a project to demonstrate the feasibility of building part of the superstructure of a US Navy destroyer in composite. To be able to fit the composite module, it was necessary to join two different materials. However, since adhesive bonding on its own was not acceptable to the Navy officials, a hybrid bolt-adhesive joint was chosen. Many different joint configuration and concepts were evaluated. The one that was selected for further study is shown in Fig. 1. Its main benefits are that it has a smooth outside, and the lower steel plate can be welded directly to the deck and bolted and bonded to the sandwich laminate.

McGeorge et al. [37] developed a bonded tuning-fork type joint offering some mechanical interlocking (see Fig. 1). By testing prototype joints, they showed that the joints were stronger than the elements they were designed to join. A comprehensive ageing programme was undertaken to improve the confidence in the long term performance of the joints [38]. Nevertheless, there appears to remain a challenge concerning confidence in the long term performance of bonded joints among decision-makers.

Ritter et al. [46] and Speth et al. [49] report on a very recent project to convert two old Dutch frigates to super yachts. One of the many changes is the fitting of new lightweight composite superstructures to these vessels. The two papers focus

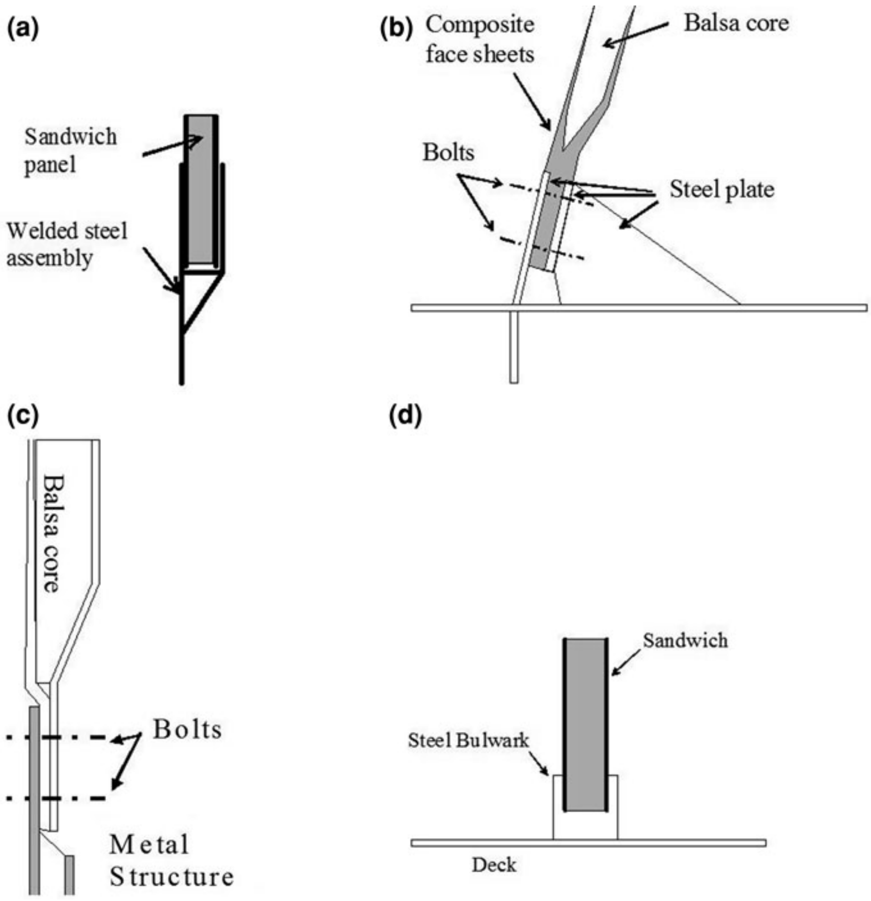


Fig. 1 Hybrid joint concepts for connecting composite superstructures to a steel deck: **a** McGeorge et al. [37]; **b** Bohlmann and Fogarty [7]; **c** Hentinen and Hildebrand [25]; **d** Speth et al. [49]

mainly on the design and verification of the composite-steel joints between superstructure and deck.

5.2.2 Description of Solution

The joint designs by Bohlmann and Fogarty [7] and Hentinen and Hildebrand [25] rely on tapering the sandwich faces into a solid laminate as shown in Fig. 1. Different solutions are chosen for the tapered sandwich core—extruded aluminium or higher density core material. Bohlmann and Fogarty [7] sandwich the laminate between two steel plates. One of the plates is welded to the steel deck and secured by adhesive bonding and bolting. The back plate is bolted to the laminate.

Any gaps are compensated for using liquid shims. This joint design has to meet stringent requirements. The hybrid joint aligns with and connects to the (steel) support structure of the lower deck. This is to minimise impact on the steel design and fabrication of the frigate. Furthermore, this allows the steel part of the joint to be fitted and welded using existing steel ship yard skills. The new superstructure module is made of sandwich material. A requirement from the Navy is that the outside is smooth and follows existing lines—presumably to avoid any changes in radar cross-section. As a consequence, the bolts had to be countersunk into the metal flange resulting in the metal flange becoming quite thick. In fact it is the heaviest item of the whole joint according to [7].

The joint was designed such that the bolts or the adhesives could take all the critical loads without help from the other joining method. Static tests of the prototype joints confirmed failure at more than twice of the design load. Furthermore, there was good agreement between the 2D plane strain FE predictions and experimental results. Bohlmann and Fogarty [7] concluded that the new joint is strong enough to survive all critical loading conditions without performance degradation. In addition the authors proposed further improvements to reduce fabrication costs.

Hentinen and Hildebrand [25] had identified decks and bulkheads in the superstructure of large ships as a possible application for use of FRP sandwich. Being able to join panels to the aluminium or steel main structure is a major challenge. Hentinen and Hildebrand proposed four different joint configurations where the sandwich-metal joint could be prefabricated enabling the installation on board the ship by welding only. This was then compared to an adhesive-bolted joint developed earlier. The most promising joint configuration had an extruded aluminium profile in the tapered section which was further studied using FE analysis and experiments. Two-dimensional plane strain analysis was carried out and tensile and flexural strength experiments were conducted. The correlation between predicted and measured load–displacement was good. However, even though the load at failure was predicted quite well, the deflection was over-predicted almost by a factor of 2. The comparison of bonded only and bolt-adhesive joints revealed that in-plane strength is almost identical. However, in bending, the bonded only solutions were two and a half times stronger than a bolt-adhesive hybrid joint.

Ritter et al. [46] and Speth et al. [49] carried out double lap-shear tests. The test results were used to calibrate their FE model for the double lap shear joint. The model was then extended to a full scale joint model where the composite was modelled with its faces only and finally the whole assembly. Furthermore, the authors used the test results to calculate factors of safety (FOS). Unfortunately no full scale joint tests were performed to validate the predictions.

The load cases investigated in the studies mentioned above were (1) distributed pressure on the outside of the panel [7, 25] and (2) in-plane tensile loading [25, 49]. Failure was predicted by Speth et al. [49] using von Mises stresses. They predicted failure to initiate in the laminate at the base of the joint on the "outside". Hentinen and Hildebrand [25] also calculated von Mises stresses for the adhesive and interlaminar shear stresses in the composite faces. They identified critical stresses both in laminate and adhesive at the wedge shaped core at the lower end of the panel.

Bohlmann and Fogarty [7] did not predict failure; rather they modelled load and deflection of the joint and compared it with experimental results. They achieved very good agreement between the predicted and measured deflections until immediately prior to failure. They observed that the final failure was initiated by shear failure of the balsa core just outside the joint region.

5.2.3 Status and Outlook

Most authors indicate that adhesively bonded joints are more efficient to build than hybrids. However, Bohlmann and Fogarty [7] identify three reasons that could delay or stop the development of bonded only solutions:

1. Need for more extensive adhesive characterisation,
2. Change of design of supporting structure required, best all composite structure! (this may not be the case for other joint designs)
3. Reluctance of customer to adopt “high risk” approach for critical component

Le Lan et al. [34] discussed the joint design process and selection of the final configuration of the composite steel joints for the French La Fayette-class frigates. Even though hybrid bolt-adhesive joints achieved a higher tensile strength during qualification testing, the bonded joints were selected due to ease of manufacture of the bonded connection. Anon [3] came to the same conclusion.

None of the above studies addressed fire protection. However this is essential for getting approval on large passenger and cargo ships. McGeorge et al. [39] outline a risk based approach for a composite superstructure on a RoRo Ferry by using Regulation 17 from the International Convention for the Safety of Life at Sea (SOLAS). Most studies, discussed here are feasibility studies. There is very limited industrial production experience. However, as Bohlmann and Fogarty [7] point out, fabrication is key to reliability of the joints and the possible acceptance of bonded joints later on.

5.3 Direct Glazing

5.3.1 What are the Requirements?

Adhesive bonding is used extensively in outfitting of ships mainly in non-critical joints, for example flooring compounds. However, there are few examples where adhesives are used to transfer loads. Bonding of windows, also known as direct glazing, has become standard practice on passenger and cruise ships (see also Fig. 2). Typical windows are shown in Fig. 3.

There are international regulations that govern the design and fabrication of windows. The IMO Load Line convention regulates where and what size window or side scuttle can be use on board a ship. This is further explained in Unified

Fig. 2 Cruise ship

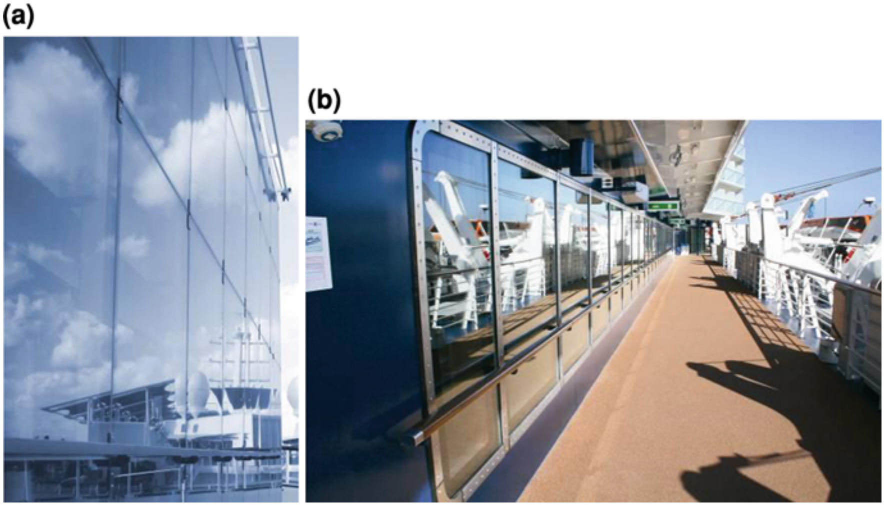


Fig. 3 Bonded windows for cruise ships: **a** glass façade showing (small) retaining frames, **b** fire protective glazing with substantial retaining frames (with permission from Brombach + Gess)

Interpretation (UI) LL62 by the International Association of Classification Societies [26]. The main concern is damage stability and to maintain the watertight integrity of the ship's hull in case of an accident. There are strict requirements on what kind of window can be used for openings below the freeboard deck, the first tier of enclosed superstructures and deckhouses. However, higher up on the superstructure, it is quite feasible to realise (very) large windows or glass facades. LL62 also states that *Side scuttles and windows together with their glasses, deadlights and storm covers, if fitted, shall be of approved design and substantial construction in accordance with, or equivalent to, recognised national or international standards. Non-metallic frames are not acceptable*. Window frames are typically designed such that if the window has to sustain water pressure the glass will be compressing the frame and transferring the load directly to the ship side shell. Only internal pressure or suction loads will act on the bond line directly. Usually, there are concerns about the durability of adhesives and to avoid the need for extensive testing; retaining frames and bolts are installed to secure the window pane against premature failure for the adhesive.

5.3.2 How are Windows Designed?

The design and fabrication of windows and side scuttles is well established. Rectangular windows are designed and built according to ISO 3903 [31], while side scuttles follow ISO 1751 [30]. The glass is tested and marked according to ISO 614 [29]. However, there are no IMO or IACS regulations for large panorama windows. Hence their design approval and fabrication follow-up is based on regulations from classification societies. Most of the windows are made of toughened glass. However, due to safety concerns it is becoming more common to use laminated glass. The polymer interlayer retains the fractured glass thus improving passenger safety in accident scenarios. Large window panes are bonded directly to the ship structure. The function of the glass is not to add stiffness to the ship's superstructure (which is common for cars) but to shield the inside of the superstructure from the elements. While the supporting structure carries the global loads the elastic adhesive layer needs to be able to compensate for the ship structure displacements due to load and thermal mismatch to minimise the loading onto the window panes. The glass panes are to carry wind and water pressure, wind suction and impact loads due to falling objects. The environmental loads are usually specified in class rules, see for example Det Norske Veritas Rules for Ships [15], while displacements due to superstructure deflection have to be calculated using global FE analysis of the ship structure.

The hybrid joint between the glass pane and the steel structure is designed in two stages. First the adhesive joint is specified using some simple formula. For example Burchardt et al. [10] provide a diagram for dimensioning the joint geometry. The minimum bondline thickness is 6 mm while the recommended overlap length is between 12 and 20 mm. According to [16] the minimum joint width can be calculated as follows:

$$d = \frac{bP_{\mathrm{w}}}{2{,}000\sigma_{\mathrm{t}}}\ (\mathrm{mm}) \tag{3}$$

with d is the joint width, not <0.02 b (mm), b the length of shortest window side (mm), P_w the wind suction load = 1.25×10^{-3} $(50 + 0.5\ V)^2$ (kN/m^2), V the speed in knots, σ_t is the allowable tensile stress for the adhesive (MPa). Normally to be taken as the stress at 12.5% elongation.

The thickness of the bondline is to be not less than [16]:

$$t = kl \times 10^{-3} \tag{4}$$

where $t =$ is the minimum 6 mm and not to be less than $d/2$ for $d > 12$ mm, $k = 1.5$ for glass, $l =$ length of longest window side (mm).

Furthermore, it is important to protect the bondline of external windows against UV radiation by using ceramic screens printed onto the glass. Moreover, the use of sealants is important to avoid having cavities in the joint where water may collect which may in turn triggers corrosion. The adhesive used for direct glazing is usually a 1-part polyurethane adhesive while the sealant is silicone based. Alternatively, the adhesive could also be used for filling any remaining cavities.

DNV [15] provides formulae for calculating the minimum thickness of the monolithic glass pane of windows and side scuttles. The following formula is used to determine the minimum thickness of laminated glass. It is based on the thicknesses of the individual glass panes to ensure the combined glass is as strong as monolithic glass panes [15]:

$$t = \sqrt{t_1^2 + t_2^2 + \cdots + t_n^2} \tag{5}$$

where n is the number of laminates, t_1 to t_n the thickness of each glass in the laminate, t is the equivalent thickness of laminated toughened safety glass.

The thickness of the polymeric interlayer is not taken into account. The resulting glass pane is usually noticeably heavier than an equivalent monolithic glass. High performance interlayers may lead to considerable reduction in total thickness for the laminated glass thus reducing the weight of the windows.

The need to use bolts in addition to the bonded joints finds its basis in IMO [27] requiring that "*…, all windows and side scuttles in bulkheads separating accommodation and service spaces and control stations from weather shall be constructed with frames of steel or other suitable material. The glass shall be retained by a metal glazing bead or angle*". Furthermore UI LL62 [26] specifies *substantial construction* and not allowing *non-metallic frames.* Today, all windows are fitted with additional mechanical fasteners. There are no guidelines on the size and spacing of these fasteners.

5.3.3 Practical Experience

Despite the widespread use of direct glazing, assessing the long-term performance of bonded joints has not been possible yet. There is a lack of documented long-term performance of the bonded windows. Fortunately, DNV keeps systematic records of the inspection reports from DNV classed ships. They are stored in a database called Nauticus Production System (NPS) [53].

A preliminary analysis of the records in NPS related to windows of passenger and cruise ships gave some surprising insights. There were no reports of adhesive failures of windows. The only reports of failures or comments related to windows can be summed up as follows:

- Use of non-certified glass—when fire rating was required
- Window wipers defective on lifeboats or the bridge
- Broken glass due to heavy weather damage
- Crack in side shell of hull that started at the corner of a big window

Discussions with DNV surveyors confirmed that failure of the bondline for windows was not known to be an issue. However, glass breakage due to heavy weather damage, such as green seas, means that further improvements are needed concerning the design and proper dimensioning of the windows, in particular the thickness of the glass panes.

5.4 Steel–Concrete–Steel Sandwich Panels

5.4.1 What is the Challenge?

A feasibility study with respect to strength and weight of an innovative bulk carrier design as shown in Fig. 4 was carried out by Bergan et al. [6]. The innovative bulk carrier design utilises a sandwich concept with steel faces and a concrete core with a density of 900 kg/m^3. The sandwich concept eliminates the need for traditional transverse frames, longitudinal or transverse stiffeners and corrugated bulkheads. Therefore, all surfaces are smooth.

The strength calculations performed showed that the concept was feasible with respect to strength and the weight of the cargo hold region. Furthermore, it was competitive with a traditional steel design at that time. The total weight was similar to a conventional design. A later study by Weitzenböck and Grafton [54] identified a need for further validation of the material properties and joining methodologies in order to confirm the concept.

Experiments carried out in the early phases of the project by Bergan et al. [6] indicated that there was a problem with the initial concept of gluing concrete to steel. Panels that had been produced for experimental studies got damaged during transit—in some cases the steel faces delaminated completely. Gerwick and Venututi [22] report of a study were fatigue performance of SCS beams was monitored. The SCS beams had additional shear connectors, so called stirrups, installed on the inside faces of the steel sheets. The study clearly indicated that after a few thousand cycles only the stirrups were carrying the load. The bond strength between the concrete core and the steel plates had been lost. In line with this, DNV's standard for offshore concrete structures requires that the forces are

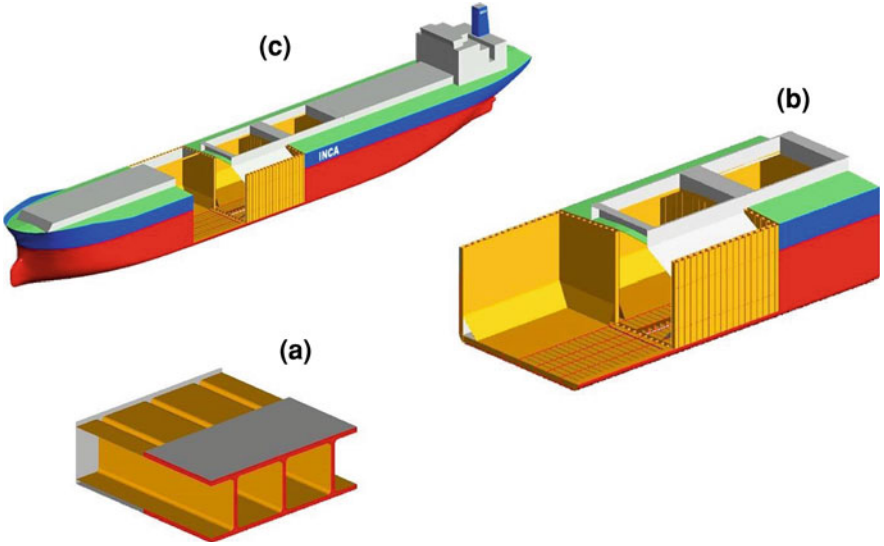


Fig. 4 Steel–concrete–steel (SCS) sandwich concept applied to a bulk carrier: **a** cellular structure assembled from SCS panels, **b** cargo hold made up of SCS structures, **c** bulk carrier assembled from SCS panels

transferred between the members by reinforcements, shear keys or other devices [14].

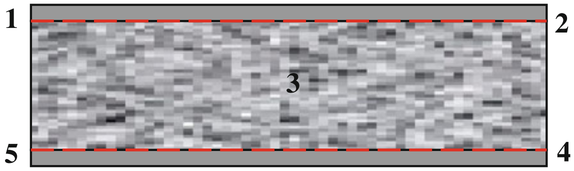
These observations were the basis for a systematic study of the SCS sandwich panels, the results of which will be reported below.

5.4.2 Solution to Improving Bond Strength of SCS Panels

A benchmark study was carried out as reported by Weitzenböck and Grafton [54]. Two different configurations of the SCS sandwich panel were considered. The original concept consisted of two steel plates with a concrete core and is shown in Fig. 5. Load transfer between the steel plates and the concrete core relies entirely on adhesion between the steel interface and the concrete core. Later on this was modified by the introduction of shear studs as adhesion alone was not considered reliable enough. A typical example is shown in Fig. 6.

The results of the parametric study by Hayman [24] show that for most cases there is a clear advantage in using welded studs to improve the shear strength of an SCS panel. Even if a solution without studs appears to give an approximately equal weight to one with studs, the need to ensure an adequate shear connection between the face sheets and the core makes it advisable in practice to use studs in all cases. Steel–concrete composites with studs have been successfully used for many years in the construction of buildings and bridges; the latter are subjected to fatigue loading. Therefore, steel–concrete composite with studs can be considered a proven

Fig. 5 SCS sandwich—“no studs” (*1* face 1: steel plate; *2* bondline 1 between face 1 and core: adhesion of concrete to steel; *3* core: lightweight concrete; *4* bondline 2 between core and face 2: adhesion of concrete to steel; *5* face 2: steel plate)



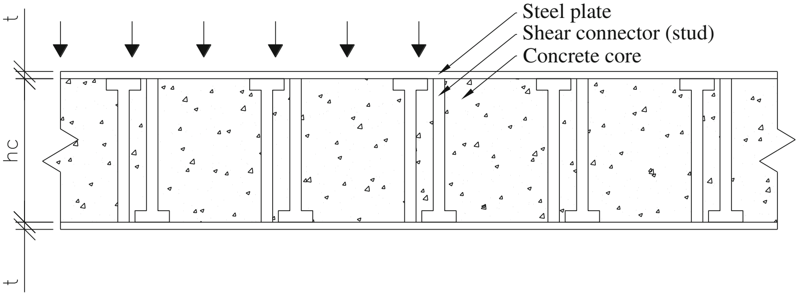


Fig. 6 Typical SCS panel—“with studs”

technology. The novelty of the proposed panels is that, in addition to ensuring the shear connection between sandwich elements, the studs are also used to reinforce the core, avoiding shear tension failure and limiting cracking of the concrete core.

The benchmark study by Lervik and Mayorca [35] focused on assessing SCS-panels with studs from the structural point of view and comparing their performance with typical steel solutions. The study looked into the application of panels to ships and offshore facilities, particularly horizontal elements such as decks. Based on the review of existing design standards and recommendations, the basis for design of SCS was proposed. Ultimate and fatigue limit states are considered. Service limit state was only briefly discussed as there are no specific design requirements for control of deflections in ships and offshore facilities. It is assumed that water tightness is provided by the steel skin. A parametric study was carried out in order to identify SCS-panel (with studs) dimensions and spans for various loads and boundary conditions. The results showed that SCS is capable of covering relatively long spans. Because studs were designed to transfer the horizontal shear force between plates and core and to prevent shear tension failure, design was governed by either shear compression or bending capacity.

The challenge that SCS panels are faced with for most applications in conventional ship applications is its self weight. In the parametric study two different concrete cores were considered, light weight concrete (LWC) and high strength concrete (HSC). The aim was to investigate if the tenfold increase in compressive strength could give any benefit in spite of the almost threefold weight increase. It was concluded that for panels in which the bending capacity limits the maximum feasible length, LWC-cores resulted in lighter panels for a given span. It should be noted that it is possible to increase the shear and bending capacity of the HSC-panels by pre-stressing the panels or increasing the steel plate strength. However, this option makes HSC-panels competitive only for high imposed loads, which are several times larger than the self-weight.

Two case studies were conducted to compare SCS panels with typical steel solutions [35]. The comparison only considered replacing some decks of an existing ship with SCS. The basic conclusion was that it was difficult to match the weight of the existing steel decks with SCS panels. The limitation of the studies is that the main structural system is the result of an optimization process for a traditional steel structure. Steel structures are good at resisting tensile forces but may buckle under compression forces. The SCS-panel is capable to efficiently carrying both axial compression and tension. Taking into consideration that SCS behaves differently than steel, it is foreseen that a better utilization of SCS can be achieved if a main structural arrangement was developed that exploits the SCS advantages.

5.4.3 Status of SCS Sandwich Technology

SCS is still at a prototype stage awaiting commercial exploitation. By adding shear studs to the steel interfaces the SCS can be designed and produced using existing knowledge and practices. However, the main stumbling blocks are not technical but of economical nature. SCS panels are best suited to solutions which are not weight critical and where other benefits of the technology can be utilised to offer additional advantages.

6 Conclusions

The reoccurring message from the discussions of the maritime applications is that hybrid bolt-adhesive joining is used mainly because there is a lack of confidence in the durability of adhesively bonded joints. This is also why existing designs do not usually utilise the composite action of the two joining methods. Rather, the two joining methods are used in parallel where one joining method takes over when the other fails. While there are many good technical solutions, most decision makers in industry and regulators are risk-adverse and tend to prefer traditional design solutions and material choices.

Bolt-adhesive joints are usually used to join dissimilar materials. The application cases discussed here illustrate this. While direct glazing of windows is an accepted way for making large-scale windows, composite superstructures and the necessary hybrid joints have yet to be established as an industrial standard for large ocean going vessels. However, polymer sandwich structures have been used on small and larger vessels for many years. And finally, SCS sandwich requires further development in order to industrialise this material.

References

1. Adams, R.D.: The design of adhesively-bonded lap joints: modelling considerations. In: 46th SAMPE Symposium, pp. 402–414 (2001)
2. Anon: Guide to the Structural Use of Adhesives. The Institution of Structural Engineers, UK (1999)
3. Anon: Committee V.5 naval ship design. In: Proceedings of the 16th International Ship and Offshore Structure Congress, Southampton, UK (2006)
4. Bickford, J.H.: An Introduction to the Design and Behavior of Bolted Joints, 3rd edn, pp. 840–871. Marcel Dekker, NY (1995)
5. Beevers, A.: Forensic studies of adhesive joints, part 2—bonded air-craft structure. The performance of adhesive joints (PAJ)—project 3: environmental durability. http://www.adhesivestoolkit.com/ (1995). Accessed Sept 2010
6. Bergan, P., Bakken, K., Thienel, K.C.: Analysis and design of sandwich structures made of steel and lightweight concrete. In: III European Conference on Computational Mechanics: Solids, Structures and Coupled Problems in Engineering (ECCM-2006), Lisbon, 5–8 June 2006
7. Bohlmann, R.E., Fogarty, J.H.: Demonstration of a composite to steel deck joint on a Navy destroyer. In: 9th International Conference on Marine Applications of Composite Materials: paper L, Melbourne, FL, USA, pp. 19–21 (2002)
8. Bond, A.E.: A review of industrial case histories. MTS programme on the performance of adhesive joints—project 3: environmental durability. http://www.adhesivestoolkit.com/ (1995). Accessed Sept 2010
9. Broughton, W.R., Crocker, L.E., Gower M.R.L.: Design Requirements for Bonded and Bolted Composite Structures. National Physical Laboratory, NPL Report MATC(A)65, January (2002)
10. Burchardt, B., Diggelmann, K., Koch, S., Lanzendörfer, B.: Elastic Bonding. Verlag Moderne Industrie, Germany (1998)
11. Croucher, T., Vanaman, A., Lee, S.: Computer controlled weldbonding of aluminium on the Fairchild A-10. Metal Prog. (1981)
12. da Silva, L.F.M., das Neves, P.J.C., Adams, R.D., Spelt, J.K.: Analytical models of adhesively bonded joints—part I: literature survey. Int. J. Adhesion Adhesives **29**, 319–330 (2009)
13. da Silva, L.F.M., das Neves, P.J.C., Adams, R.D., Wang, A., Spelt, J.K.: Analytical models of adhesively bonded joints—part II: comparative study. Int. J. Adhesion Adhesives **29**, 331–341 (2009)
14. DNV: Offshore concrete structures. Offshore Standard—DNV-OS-C502 (2007)
15. DNV: Rules for Ships. Sect. 6, Part 3, Chap. 3. "L. Side Scuttles, Windows and Skylights" (2010)
16. DNV: Rules for High Speed, Light Craft and Naval Surface Craft. Sect. 1, Part 3, Chap. 6. G. Windows, 8 pp (2010)
17. DNV: Rules for High Speed, Light Craft and Naval Surface Craft. Sect. 9, Part 3, Chap. 4. Bolted Connections, 28 pp (2010)
18. Drain, K., Chandrasekharan, S.: Automotive applications for adhesives. In: ASM Engineered Materials Handbook. Adhesives and Sealants, vol. 3, pp. 551–557 (1990)
19. Echtermeyer, A.T., McGeorge, D., Sund, O.E., Andresen, H.W., Fischer, K.P.: Repair of FPSO with composite patches. Presented at the fourth international conference on composite materials for offshore operations (CMOO-4), Houston, TX, USA, 4–5 October 2005
20. Eurocode 3: Design of steel structures, part 1–8: design of joints, EN 1993-1-8 (2005)
21. Eurocode 4: Design of composite steel and concrete structures—part 2: general rules and rules for bridges (2005)
22. Gerwick, B.C., Venututi, W.J.: Fatigue Behaviour of Prestressed Concrete in a Ship Hull. Technical and Research Bulletin 2-24, The Society of Naval Architects and Marine Engineers (1979)

23. Guthu, G.O.: Modelling of mechanical response and fracture in adhesively bonded joints. Master thesis, Faculty of Mathematics and Natural Sciences, University of Oslo (2010)
24. Hayman, B.: Benchmark study of INCA panels without studs. In: Weitzenböck, J.R., Grafton, T. (eds.) Assessment of the INCA Steel-Concrete-Steel Sandwich Technology—Public Report. DNV Technical Report No. 2010-1284 (2010)
25. Hentinen, M., Hildebrand, M.: How to efficiently join FRP structures to metal ships? In: 3rd International Conference on Fast Sea Transportation, FAST'95, Lübeck-Travemünde, Germany, 25–27 September 1995
26. IACS: Side Scuttles, Windows and Skylights (Regulation 23). Unified Interpretation LL62, 2 pp (2010)
27. IMO: SOLAS Chapter II-2 Part B, Regulation 33: Windows and Side-Scuttles (1992)
28. IMO: SOLAS Chapter II-2 Part F, Regulation 17: Alternative Design and Arrangements (2002)
29. ISO 614: Shipbuilding and marine structures—toughened safety glass panes for rectangular windows and side scuttles—punch method of non-destructive strength testing (1989)
30. ISO 1751: Shipbuilding and marine structures—ships' side scuttles (1993)
31. ISO 3903: Shipbuilding and Marine Structures—Ships' Ordinary Rectangular Windows, 2nd edn (1993)
32. Keller, H., Howard, M., Hoyer, J.: Weldbonding an Improvement, Theoretically and Practically. Swissbonding, Rapperswil (2006)
33. Kelly, G.: Load transfer in hybrid (bonded/bolted) composite single-lap joints. Compos. Struct. **69**, 35–43 (2005)
34. Le Lan, J.Y., Livory, P., Parnelix, P.: Steel/composite bonding principle used in the connection of composite superstructure to a metal hull. In: Proceedings of SANDWICH2, Gainesville, USA (1992)
35. Lervik, A., Mayorca, P.: Benchmark study of INCA panels with studs. In: Weitzenböck, J.R., Grafton, T. (eds.) Assessment of the INCA Steel-Concrete-Steel Sandwich Technology—Public Report. DNV Technical Report No. 2010-1284 (2010)
36. Marsh, G.: Boeing's 787: trials, tribulations, and restoring the dream. http://www.reinforcedplastics.com/view/4282/boeings-787-trials-tribulations-and-restoring-the-dream/ (2009). Accessed 31 Aug 2010
37. McGeorge, D., Lilleborge, J., Høyning, B., Eliassen, G.: Survivable composite sandwich superstructures for naval applications. In: Proceedings of the SANDWICH'6, Fort Lauderdale, USA (2003)
38. McGeorge, D.: On the long term properties of steel-composite interfaces for marine applications. Presented at the fourth international conference on composite materials for offshore operations, Houston TX, USA, 2005
39. McGeorge, D., Høyning, B., Nordhammar, H.: Lightweight composite sandwich RoPax superstructure. In: Papanikolau, A. (ed.) Risk-Based Ship Design. Springer, Berlin (2009)
40. McGeorge, D.: Inelastic fracture of adhesively bonded overlap joints. Eng. Fract. Mech. **77**, 1–21 (2010). doi:10.1016/j.engfracmech.2009.07.002
41. McGeorge, D.: Predicting failure of bonded structural joints. In: Weitzenböck, J.R. (ed.) Using Adhesives in Marine Engineering (2011) (to be published)
42. Menges, G., Schmidt, P.: Untersuchungen zum Langzeitverhalten kombinierter Kleb-Punktschweisßerbindungen (Investigations into the Long-Time Behaviour of Combined Bonded and Spot Welded). Schweissen und Schneiden, 19 pp (1967)
43. Osnes, H., McGeorge, D.: Experimental and analytical strength analysis of double-lap joints for marine applications. Compos. Part B Eng. **40**(1), 29–40 (2009)
44. Peck, S.J.: Streamlining automated processes for composite airframe manufacturing. JEC Compos. Mag. June–July(58), 34–36 (2010)
45. Reinhardt, K.G.: Festigkeitseigenschaften und Gesichtspunkte für die Bemessung von Punktschweiß-Klebverbindung. ZIS Mitteilungen **10**, 1609–1628 (1968)
46. Ritter, G.W., Speth, D.R., Yang, Y.P.: Qualification of adhesives for marine composite-to-steel bonded applications. J. Ship Prod. **25**, 198–205 (2009)

47. Ruttge, H.: Vorteile durch Einsatz des Punktschweißklebeberfahrens beim Herstellen von Ladebordwänden. Schweißtechnik **19**, 167–169 (1969)
48. Shenoi, R.A., Hawkins, G.L.: Practical design of joints and attachments. Compos. Mater. Marit. Struct. **2**, 28 (1993)
49. Speth, D., Yang, Y.P., Ritter, G.: Qualification of adhesives for marine composite-to-steel applications. Int. J. Adhesion Adhesives **30**, 55–62 (2010)
50. Wacker, G., Brügge, D., Fach, K., Franzelius, W.: Theory and practice: requirements for adhesive bonding in marine structures. Proc. Inst. Mech. Eng. Part M J. Eng. Marit. Environ. **218**(M4), 217–226 (2004)
51. Weitzenböck, J.R., McGeorge, D.: The designer's dilemma: how to deal with the uncertainty about the long-term performance of adhesively bonded joints. Proc. Inst. Mech. Eng. Part M J. Eng. Marit. Environ. **218**(4), 273–276 (2004)
52. Weitzenböck, J.R., McGeorge, D.: BONDSHIP Project Guidelines, 254 pp (2005)
53. Weitzenböck, J.R.: Adhesive Bonding in the Maritime and Offshore Industry. Swissbonding, Rapperswil (2009)
54. Weitzenböck, J.R., Grafton, T.: Assessment of the INCA steel-concrete-steel sandwich technology—public report. DNV Technical Report No. 2010-1284 (2010)
55. Weitzenböck, J.R. (ed.) (2011) Using adhesives in marine engineering (to be published)