Traditionally, the shipbuilding industry is focused on steel. However, there is also a trend towards lightweight and material substitution in order to increase cargo load and decrease fuel consumption. However, special requirements exist in regard to joining technology. The Center of Maritime Technologies and the SLV Mecklenburg-Vorpommern have developed a novel connection for shipbuilding.

Aeronautics Lead the Way

Lightweight design of moving structures combines numerous advantages: The lower the structural mass that has to be accelerated and transported, the lower the fuel consumption, the lower the transportation costs and the better the carbon footprint. In some application cases, the goal of lightweight design is a performance improvement, such as an increased payload or a greater range. In addition, the knock-on effects of weight reduction are not negligible. A lower structural weight can lead to smaller motors, which in turn can lead to further weight reductions. Two different approaches exist for the reduction of structural weight. First, the application of lightweight design principles, such as the usage of skin-stiffened structures, and second, the material substitution, for example exchanging steel with composites.

The aeronautic industry is leading the way forward with material substitution. When Airbus developed the A320 in the eighties, aluminum alloys accounted for approximately 65% of the structural weight, whereas the new A350 is composed of only 20% aluminum alloys. In contrast, the share of composites in overall weight has increased from 13% to 53% [1]. A similar trend of combining different materials and an increased usage of fiber-reinforced polymers (FRP) is also observed within the rail and automobile industry.
Shipbuilding

One sector which seems to have slept through the trend toward lightweight design and material substitution seems to be the civil shipbuilding industry. On the other hand, the worldwide ship traffic is responsible for approximately 4.5% of the global greenhouse gases [2]. Essentially, container ships, tankers and cruise ships are made of steel and welded together out of smaller steel structures.

This fact is quite surprising as the boat and yacht building industry has been a pioneer in the application of composite parts within the industrialised manufacturing sector. For example, the Scrimp process (Swedish corvettes of the Visby class, showing Airbus A380.

An example that shows the potential of FRP in the shipbuilding industry is the car carrier Siem Cicero, produced by the Croatian shipyard Uljanik. In this ship, the three upper decks were exchanged with a FRP structure, leading to a weight reduction of 25% in this area [3].

Joining Technology

Combining steel and other materials, such as FRP, is therefore the future of shipbuilding, as it does not make sense to exchange the entire steel structure with FRP. This is due to technical and economic reasons. Therefore, the joining technology is a key enabler in using FRP structures in shipyards. The conventional joining methods for metal-FRP is bonding or bolting. However, these cannot be applied directly to the shipbuilding industry, where the preferred way of joining is welding. Typical shipbuilding tolerances make it complicated to prefabricate holes. In addition, the rule based minimum thickness of 5 mm makes it complicated to produce the holes simultaneously within the steel and the FRP. One argument against bonding is that ships are generally manufactured in a non-controlled environment, meaning that the structure is exposed to changing temperature and humidity conditions. In addition, bonding is a time-consuming and cost-intensive approval process within the shipbuilding industry.

Standard Connector for Composite and Steel

The goal of the German-founded project Fausst (Faser und Stahl Standard Verbindung. English: Fibre and Steel Standard joint) is to develop a connector according to the needs of the shipbuilding industry, using both FRP and steel, which complies with shipbuilding rules and which does not require additional specialized production steps in the shipyard. Figure 1 shows the joining technology.

Reworks and changes are standard procedures in shipyards: metallic parts are cut to the final dimensions or tolerances directly in the shipyard. Welding is the normal joining process. In contrast, in the case of thermoset...
FRP parts, only minor changes, for example through shimming, are possible.

However, to ensure cost efficiency and processability, the joining element has to be able to cope with these standard processes in the shipyard.

The developed semi-finished product meets the requirements of both worlds, shipbuilding and FRP. Fausst is composed of a metallic connection element, for example a flat bar, onto which one or several hybrid textiles are welded. These hybrid textiles are integrated into an FRP production through lamination and infusion. After curing, a FRP part with a steel edge is obtained. This steel edge can then be adapted to the ship’s structure and welded to it using common shipbuilding techniques.

Manufacturing of the Semi-finished Product

Figure 2 shows the different productions steps involved in the manufacturing of the semi-finished product. The first step is the design of the textile part of the semi-finished product. In cooperation with Fritz Moll Textilwerke, a hybrid warp knitted textile was developed, which on one side is made out of 100 % steel fibers and on the other side of 100 % glass fibers.

Each layer is composed of five different yarn systems, which are held together through the in-lay yarn. These yarn systems are three warp and two weft in-lay yarns. The in-lay and warp yarns are in the width direction of the textile. Each in-lay and warp yarn is one single yarn, whereas the weft in-lays are continuous. Therefore, for an approximately 150 mm long fabric, 60 in-lay and 180 warp yarns are needed, and only six different weft yarns, as these are not covering the entire length of the textile and are made out of steel and glass yarns. This effect leads to the steel and glass fibers meandering and overlapping, which in turn leads to a load transfer due to friction, as well as due to interlocking at the crossing points. The manufacturing process is performed with an electronically controlled knitting machine, which permits manufacturing speeds of up to 100 m/h. In the presented case, Comez’s standard machine Decortronic 1000EL was used, which is generally used in the textile industry for the production of ribbons or bordures. Currently, a flat textile with only one metallic side is being produced. However, the design is flexible and could also be manufactured with a circular knitting machine.

The next step is the design of the metallic connection element. Four principles have to be considered, being (1) the distance between the FRP part and the joining place has to be sufficiently large, in order to pre-
vent the temperature in the FRP part from rising above 50 °C when welding it to a steel structure. A minimal length is needed [4].

(2) This connection element permits processing in a subsequent step, for example when adapting it to the surface. (3) Any stress on the fibers has to be put along the line of the fibers, minimizing waviness. (4) The loading and the neutral axis should be aligned. In this way a variety of connection geometries can be designed. Figure 3, in order to join monolithic or sandwich parts with a metallic structure.

In a last step, one or several layers of the hybrid knitted fabric are joined to the connection element via resistance seam welding. This process permits the efficient production of Faust connectors with several layers of fabric using a robust and well-known process.

The idea behind this design was the attempt to integrate parts produced by specialized manufacturers, such as wall systems and cabins, into the ship using lightweight design, and welding directly in the shipyards. In other potential application cases, for example in the automotive industry, the metallic parts could be initially joined by welding to the hybrid textile and then jointly be infused in a subsequent step. In this way, the semi-finished product is manufactured using two different standard processes, which can be automated and are suitable for mass production.

**Application of the Semi-finished Product**

The Faust semi-finished product is designed for resin infusion manufacturing processes like hand lay-up, resin transfer moulding (RTM) or Vacuum Assisted Resin Transfer Moulding (VARTM), where each layer of Faust is overlapped with other layers of FRP non-crimp or woven fabrics in order to construct the FRP part. Then, the entire stack is impregnated with a resin. Theoretically, it should be possible to use a pre-preg as fiber material, as long as resin films are also used to reduce the risks of porosity.

Then an FRP part with a Faust edge can be joined to a steel part via welding in a steel production company, for example a shipyard.

**Example of Use**

Similar to the aerospace industry, the approval of FRP structures for military ships is subjected to different rules than the civilian one. This makes it easier for the adoption of FRP structures. For example, the Saab Kockums shipyard developed a concept in which the superstructure of frigates was substituted with an FRP-sandwich construction. In addition to the aforementioned advantages, this has the benefit of a reduced radar signature. The connection between the steel hull and the FRP is performed using a U-profile, the resulting FRP-sandwich superstructure is bonded and then welded to the ship hull at the U-profile [5]. In this application case this joining approach is compared to the newly developed Faust connection system.

**FIGURE 3** Examples of joint geometries: flat connector of different thickness, materials and number of Faust layers (a and b), box profile (c) and round profile with welded Faust layers (d) (© CMT)

**FIGURE 4** Comparison between U profile and Faust sandwich structure: U-profile schematic (left), Faust-FRP schematic (middle) and foto of the Faust connection (right) (© CMT)
The selected Fausst connector features a symmetrical two-step design, using a total of four Fausst layers. In cooperation with Saertex, a sandwich set-up was manufactured via infusion. Figure 4.

For the mechanical tests the goal was to measure the strength of the joining element, therefore the center was filled with the hybrid textile to act as spacer.

Figure 5 shows a load displacement diagram of the tensile specimen as well as the specimen geometry. Due to the specimen geometry it is not possible to calculate the strength as the cross section changes at the welding seam. Therefore, a linear joint strength is defined which is 217 kN/m having a real overlap of 20 mm. It has to be mentioned that the width of the weld seam is approximately 3 mm. In a further test series using a biaxial non-crimp fabric between the hybrid Fausst layers, tensile strengths of 260 kN/m and compressive strengths of 800 kN/m were achieved.

Comparing these values with an adhesive joint, similar tensile strengths are obtained with this overlap for an adhesive system with a shear strength of 5 MPa. This value corresponds to a realistic value of a steel-FRP adhesive joint, if knock down factors such as ageing are considered. The advantage of the Fausst connection, in contrast to the bonding to a profile, is that less steel is used, which leads to less weight, the elimination of a manufacturing step (the bonding of the FRP in the profile) and the assurance that a permanent joint is achieved through the welding.

Outlook
The Fausst semi-finished product establishes a novel joining technology between steel and FRP structures. This technology is based on a hybrid textile. Tensile loads over 200 kN/m are transferred with 4 layers of welded Fausst textile. The advantages over adhesive or mechanical joints are the shorter overlap, the fiber-optimized load transfer and the process speed.

A future goal of the development team is the standardization of the semi-finished product and the approval in the maritime industry, so that designers can work with certified material values. An additional advantage of Fausst is that the quality of the semi-finished product is controlled during production, meaning that during implementation only the quality of standard processes, such as lamination and welding, has to be checked.

The first focus of the joining technology was the ship building industry, however, this joining technology is also suitable for other sectors such as the automotive, rail or construction industry, where high loads need to be transferred, short assembly times are needed or the use of pre-outfitted semi-finished products is advantageous.

This joining technology is also suitable for the automotive or rail industry.

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