FAUSST – bridging the gap between steel and fibre reinforced materials

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Synopsis

For a variety of applications, such as shipbuilding or automotive, a variety of materials is used in order to meet certain design constraints or certification limitations. Within ship building for international waters, different design codes are distinguished for civil and naval use. While the SOLAS (safety of life at seas) ship code and the HSC (high speed craft) code have strict regulation in the use of composite materials, some naval rules enable such materials already leading to ship designs e.g. the Visby or Zumwalt class. However, the joining of multi-material structures remains challenging from a technical and regulative point of view.
Composite materials aboard of ships has a variety of benefits, such as weight reduction, fuel reduction, increased corrosion resistance and the ability to use different innovative design solutions. Nevertheless, these benefits have to be pondered against the higher material and process costs. Moreover, strict design rules according to naval requirements, e.g. shock resistance, impact, etc. need to be met for the materials as well as their joints.
The presented developments focus on one of the process challenges needed, being the joining of a steel structure and a composite material. Within the shipbuilding industry the preferred joining mechanism is welding, whereas other procedures such as bonding or riveting are complex in several manners, e.g. approval. To overcome this challenge FAUSST, a joint based on a hybrid knitted fabric, has been developed. This fabric is composed of steel and glass fibres in a way that a transition element is created, thereby effectively bridging both materials. It can be welded on one side to a metallic structure and integrated on the other side into a FRP. Depending on the design of the transition element loads of up to 240 kN per meter joint can be transferred in the presented design with an overlap length of only 10 mm. This transition element, therefore, may lead to more sophisticated designs using composite materials.

Keywords: fibre reinforced material, steel, joining, hybrid material, multi-material structures

1. Introduction: the well unknown material

Composite materials, such as fibre-reinforced plastics (FRP) are well-known e.g. in the boats and yachts industry or the private aviation industry for decades. Partly, the technologies in these sectors have been adapted and further developed in the aeronautic, automotive and construction sector. In contrast, the civil shipbuilding industry has been much more reluctant to the implementation of FRP or other novel materials. This is mainly due to the regulatory framework – e.g. SOLAS design code (Stevens and Quinn, 2017) -, which implies that mainly steel is used as structural material as the risk of fire is one of the main design considerations. In the last decades, the regulatory framework has been changing allowing the usage of other materials such as FRP, depending on operational or risk mitigating design considerations (Hoppe 2005). Therefore, currently the question is rather "When" than "If" FRP will be implemented within a wider use e.g. aboard of cruise or other commercial ships. With respect to naval shipbuilding, rule and regulative framework is mainly under the sole responsibility of the state. Therefore, examples of successful FRP implementations are already more than 30 years existent, such as MCM vessels. However, a breakthrough of FRP as structural material has not been reached; using FRP in modern navy vessels, such as the Visby-class corvettes or parts of the Zumwalt-class destroyers, turns out to be challenging, cost intense or facing challenges toward the use of multi-material structures. The latter issue turns out to be one of the major drawbacks in shipbuilding using multi material construction with FRP and for instance steel. Moreover, vessels exceeding a certain size or of a certain class are predominantly built by larger and more traditional, more precisely steel focused, shipyards. Those shipyards have not built up the knowledge of the smaller shipyards already familiar with the use of FRP; it is the well unknown material that comes with a variety of options in terms of fibres, matrix systems and layer configuration.

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However, FRP structures contain a huge potential for naval vessels. Due to the lightweight aspect, the integration of even heavier equipment in a later stage of production or as retrofit remains an option. The integrated functionality of walls does not only contain material for the structural strength but also thermal insulation, electromagnetic shielding and ballistic protection. Also, the effect of shrapnel, blast and ignition due to friction is lower compared to conventional steel structures. Today, some new naval ships contain some FRP structures, especially in the superstructure, using these advantages. These FRP components are commonly outsourced by the shipyard and a component supplier delivers parts to be mounted to the hull or other structures. This leads again to the challenge of joining.

Within the project FAUSST, a novel joining solution between steel and FRP structures is developed with the focus for the application within the shipbuilding industry. The aim is to overcome major obstacles in terms of rules, testing and design as well as manufacturing processes.

2. Multi-material joining techniques in shipbuilding

Today, there are already technologies to join dissimilar materials. While two very basic system and the combination of them dominate in the applications, there are more methods currently under development. However, they are not state-of-the-art will not be further discussed here. The three major ways to join dissimilar materials are:

- Mechanical fixing
- Bonding
- Mechanical fixing and bonding

Fixing by bolts, rivets and screws. This technique is well-known and commonly used, e.g. in the aeronautic sector. This process, especially riveting, is highly automated today and ensures a cost-effective and safe joining of materials. However, automated riveting, as well as bolting or using screws implies the interference of the structural integrity by drilling holes. It can be seen, that such areas are often the starting point of cracks with respect to fatigue of the structure. In thicker layers, such as plates and stiffeners used in shipbuilding with scantlings above 4.0 mm, these methods become less productive. Attention has also been paid towards the phenomenon of unequal load transfer in such joints due to the predominant linear behaviour of FRP materials under loading (Wilmes 1999). Finally, such joints are not a 100% tight connection.
Bonding is well-known as well. Using specialised adhesives, the possibility of connecting different materials is tremendous. Especially in the automotive and the railway sector the development of standards, e.g. DIN6701 “Adhesive bonding of railway vehicles and parts”, lead the way to make adhesive bonding a safe, productive and reliable joining technique. However, the biggest challenge due to the absence of a non-destructive testing method, is the very accurate process to achieve a high-quality connection. This includes not only the surface preparation of the parts itself, the environmental conditions during the process, but also the correct storage of the components of the adhesive. Moreover, the behaviour over time for most of the adhesives is not known yet neither a suitable and standardised testing method for aging can be applied.
The usage of both, bolts and bonding for instance, is nowadays the typical way to connect dissimilar materials. Here, the mechanical fixing is used as fall-back option if the adhesive bond fails. However, by adding bolts to the adhesive bond an artificial hot-spot is created and downgrades the properties of the joint. Moreover, the creation of an artificial hot-spot within another load-carrying joint material, the adhesive, without an adequate NDT method does imply a certain risk in operation.

All three options to join dissimilar materials do not fully satisfy the requirements of modern engineering and production processes: easy handling, easy design, no extra testing and approval. All these requirements and obstacles of the solutions are currently the technical knockouts for many application using fibre-reinforced plastics. Approval for new joining technologies is one of the key challenges in design and production. The goal of creating light-weight structural-systems demands for a wide use of lightweight materials. This leads to different types of joints for dissimilar materials. As a function of contribution to structural or safety relevant systems, the requirements for such joints increases. Moreover, in dependence from the probability of loss of life or loss of functionality by failure of the joint, the safety margins increase as well as the scope of testing. In terms of naval use, scenarios may ask for a withstand of a two-hits-threat, including fire, blast, etc. In this matter, not only the structures itself, but also the joints need to be tested to show their validation. Therefore, the national regulative bodies are in charge to determine the accepted level of risk and the associated scope of testing to prove.

The introduction of the problem above leads to the following key messages:
• Multi-Material structures are the future for all transport-systems, special vehicles and vessels
• Today, there is no conclusive concept to join dissimilar materials
• State of the art concepts make use of an additional material/rivet/bolt/screw
• To unlock the potential of lightweight, a standard joining concept is mandatory

3. The solution is to omit the problem: the hybrid solution

The summary given above of the challenges in the state of the art technologies were the motivation for a complete new idea of joining dissimilar materials for maritime applications. Two main key-challenges had to be met: a mechanical fixture of the two materials and to avoid unknown or additional materials. The solution came from a well-known maritime technique for joining ropes: splicing. Subsequently, the joint developed, FAUSST, is combining two dissimilar materials on fibre level. Using metal and non-metal fibres (e.g. glass) a hybrid fabric was made using warp-knitting technique. Catching up the idea of splicing, warp-knitting enables a two- or even three-dimensional mechanically fixed combination resulting in a hybrid fabric. By varying the amount of material in the fabric, one side becomes 100% metal the other one 100% non-metal. This opens the opportunity to weld the metal-side of the fabric to a solid (e.g. steel) metal structure. The opposite side can be integrated to the FRP structure in the lamination process. Within the hybrid zone a mechanically lock occurs once tensile force is put on the metal as well as on the pure non-metal side.

To create this joint for the dissimilar materials metal and glass fibre reinforced plastics, no adhesive is needed. Both welding and laminating, together with their materials used, are approved technologies. In other words, the materials used for the joint are already approved by the structure to be built. The key issue of an unknown material and its behaviour (e.g. adhesive) is omitted. This leads to a standardised solution and general approval.

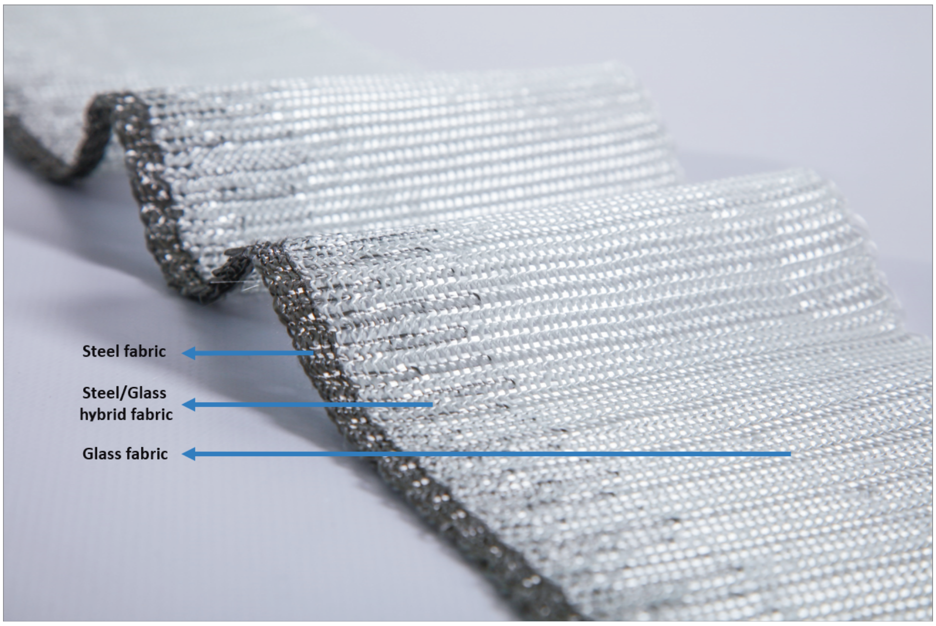

Figure 1: warp knitted hybrid fabric from steel and glass fibres

3.1. The FAUSST concept

Figure 2 summarises the process chain of manufacturing the semi-finished product FAUSST, as well as the implementation within a FRP and steel structure. The following subchapters will give a brief summary of the process steps.

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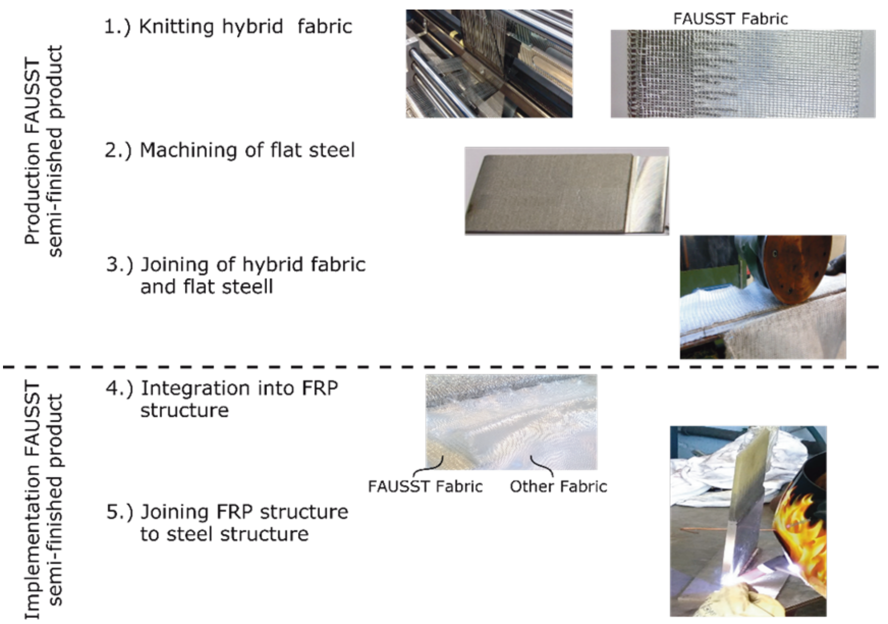

Figure 2: Fabrication and installation process of FAUSST

3.1.1 Production of the FAUSST semi-finished product

The FAUSST semi-finished product is composed of a hybrid fabric, which is welded to a flat steel. The warp knitted hybrid fabric is designed in cooperation with Moll Textilwerke GmbH & Co KG (Germany) and manufactured using a Decortronic 1000/EL electronic crochet knitting machine (Comez International s.r.l). The fabric is composed of 3 layers of weft in-lays, 2 layers of warp in-lays, which are connected via open lap pillar stitches. The pattern of the ca. 150 mm wide fabric is designed in a way that about 10 mm of the fabric are composed of 100% steel and about 90 mm 100% glass fibres. The transition part has a changing length of the weft in-lay of the two yarn systems, both in lengthwise and thickness direction, to reduce the stiffness mismatch between the steel and glass fibres and to assure an interlocking of the fibre systems. For the steel fibres Bekinox VN8.1.1.40Z from Bekaert and for the glass fibres EC-16-200-350-U from PD-Glasseiden were used.
The function of the flat steel is to transfer the loads between the steel and the FRP structure. In order to prevent secondary loadings, such as out of plane bending of the FRP, which could lead to premature failure, the flat steel may be machined in order to reduce the load eccentricity. The flat steel has to be of a certain length to (1) allow for final machining for adaptation to the steel structure and (2) prevent heating up of the FRP component due to heat transfer during welding to the steel structure.
In a last step, one or several layers of FAUSST fabric are first spot welded to the (machined) flat steel and then resistance seam welded (welding class 22 EN ISO 4063) to create a permanent connection between the fabric and flat steel. Currently, this process is performed manually, however, it can be easily automated. While first designs and tests were done using flat steel bars, other geometries have also been successfully applied and tested. From 0.8mm thick flat steel bars (i), as they are used in the automotive industry, to box-section (iii) and tubes (iv) were realised as demonstrated in figure 3. It is possible to apply multiple layer of the hybrid fabric in one weld (ii). Successful tests were also done using aluminum flat bars.

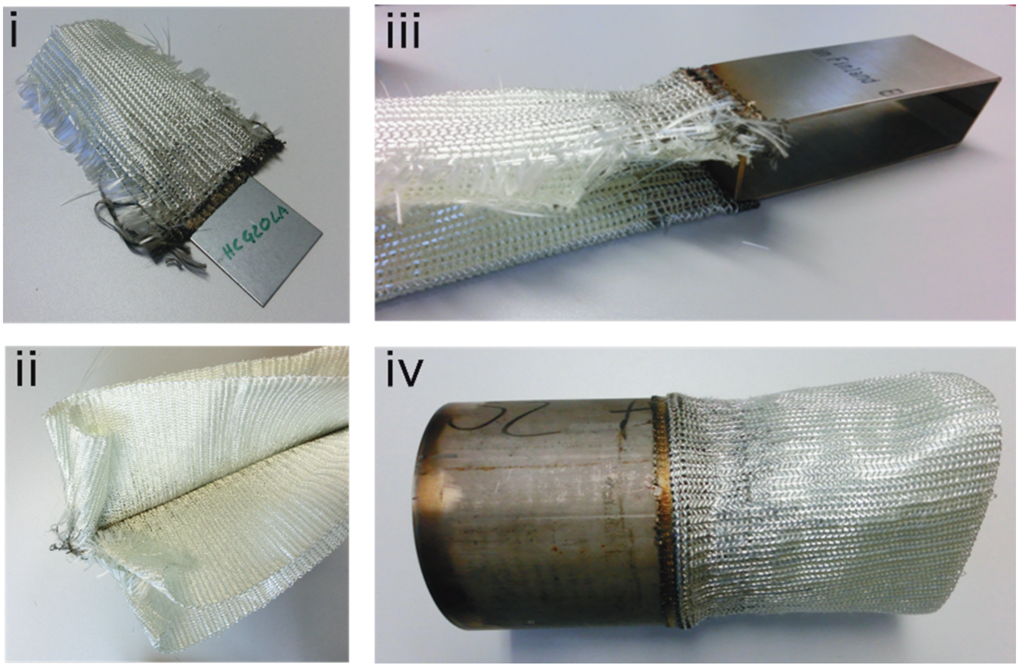

Figure 3: different geometries of FAUSST

3.1.2 Implementation of the FAUSST semi-finished product to the FRP component

During the lamination process of a FRP component, the FAUSST connector is integrated into the component by overlaminating the individual FAUSST layers with the component plies – similar to the process of ply splicing. It has to be noted, that the process has been developed for liquid resin processes such as Resin Transfer Moulding (RTM) or Vacuum Assisted Resin Transfer Molding (VARTM). However, using resin films, similar results should be obtained for prepreg materials corresponding processes (Black, 2017). The load transfer between the FAUSST layers and the component plies, therefore relies mainly on the mechanical properties of the resin and the overlap length. In case that higher loads are to be transferred, through thickness reinforcement like tufting (Dell'Anno and Treiber, 2016) are feasible. Figure 4 demonstrates the layout from single skin to sandwich FRP and the integration of FAUSST using a flat steel bar. The FRP part holds an A-60 fire class according to FTP code (2010 FTP Code).

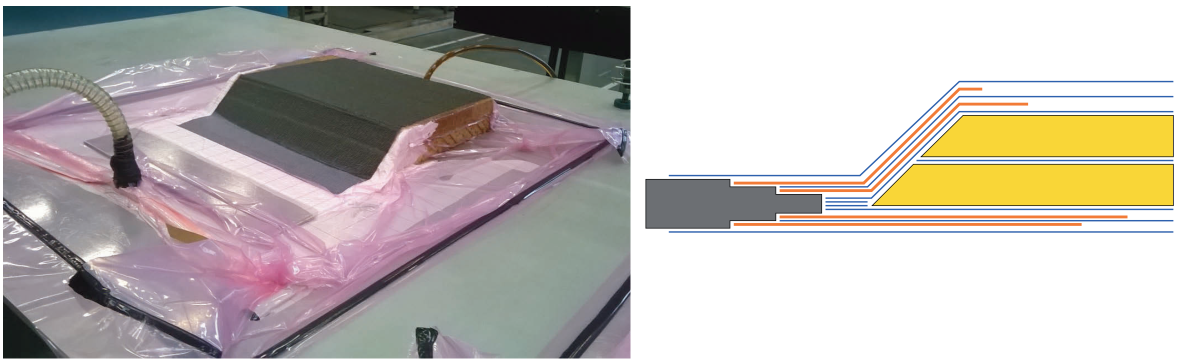

Figure 4: Left side: vacuum infusion of demonstrator. Right side: Layout of FAUSST integration - Grey=steel bar; red=hybrid fabric of FAUSST; yellow=core material; blue=glass fibre plies

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3.1.3 Welding of the FRP/FAUSST component to the steel structure

In a last step, the cured FRP component is welded to a steel structure via the FAUSST integrated steel section. Dependent on the plate scantlings of the steels part as well as the weld details, a minimum distance from the weld seam to the start of the FRP part has to be foreseen. Typically, for a 5.00 mm flat bar, 100 mm distance is sufficient. Welding tests as well as the measurement of the heat distribution ensures that also a length of 50mm or less is non-critical. The welding process was chosen to be WIG welding (welding class 141 EN ISO 4063).

3.2 Experimental Methods

3.2.1 Materials

The specimens considered here are made with four layers of FAUSST fabric. Figure 5 shows the specimen geometry. The flat steel was machined in order to align the centre lines of the steel and the FRP parts. The used FAUSST fabric was knitted as described above with a gauge of 10 needles per inch and a stitch density of 2.75 stitches per cm. The overlapping length of the fabrics was 10.0 mm
The gap between the layers was filled using the FAUSST fabric. Using a standard VARTM process, the panels were infused with Ampreg 22 with standard hardener (Gurit) and then cured according to the manufacturer recommendation at 80°C for 5h.

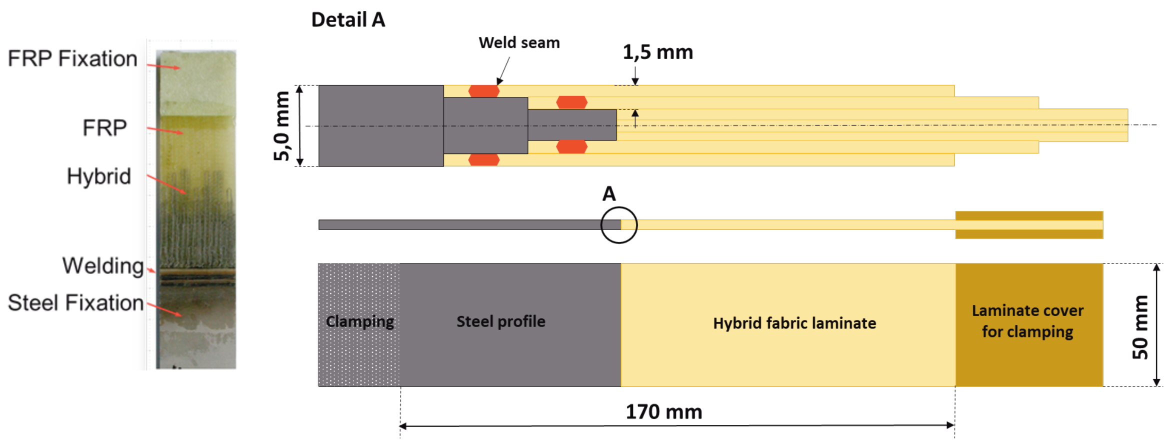

Figure 5. Specimen geometry and welding details. Left side: photo of specimen. Right side: schematic of layout. Note: specimen not scale

3.2.2 Test protocol

From the manufactured panels, end tabs were secondary bonded on the FRP side. Then, 50 mm wide specimen were cut using a saw. Tensile tests were performed on a universal testing machine (Zwick Z600) in accordance with ASTM D3039 under displacement control.

4 Results

Figure 6 shows representative Force-Strain curves for the tested configurations. All specimens behaved linear to failure and had a similar apparent stiffness. Prior to total failure, at around 75% of this load, first damage in terms of loss of linearity was observed. The lowest strength at first failure was obtained at 9.6 kN,

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whereas higher failure loads occur at 12 kN and above. All specimen failed at the transition from the 100% steel part to the hybrid fabric, where the load is only transferred through the steel fibres.

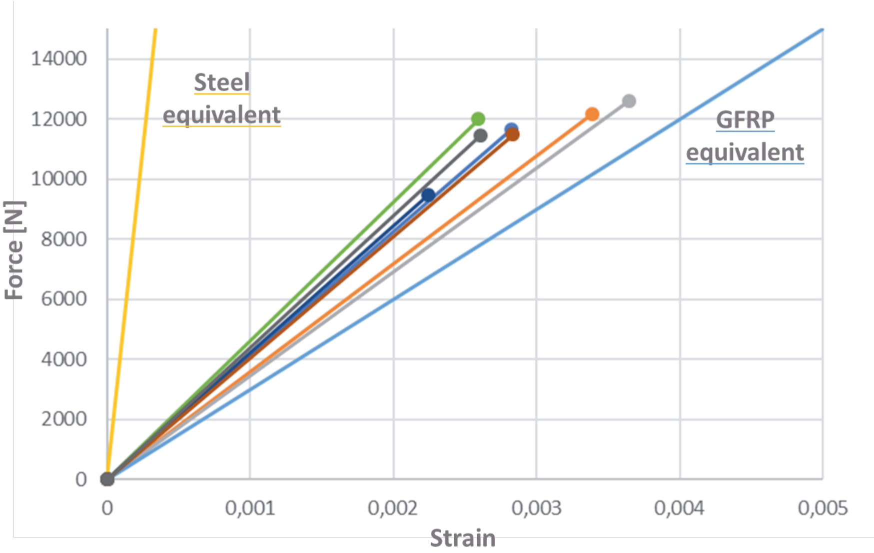

Figure 6. Representative Force-Strain curves. Note: Curves with dot mark the FAUSST specimens at first failure load. Steel and GRFP (43Vol.% of Bi-directional E-Glass fibres) are displayed for comparison.

5 Discussion

The specimens above had a cross section area of 250mm^2 (50mm width and 5mm plate thickness). The strength obtained can be referred to this section. With respect to the results of the described tests above, the FAUSST configuration with four layers of fabric reaches between 38MPa and 48 MPa tensile strength. The internal load distribution looks differently and refers more to a lap-shear loading.

Although not further discussed here, static comprehensive, dynamic tensile as well as blast tests are currently performed. First results indicate a high static comprehensive strength at 80% of the tensile strength. Dynamic tensile testing indicates a fatigue strength 10 MPa at $1*10^7$ cycles with respect of the cross section of 250mm^2.

As all specimen failed at the same location, an update of the fabric is under development. At the failure location, only the in-lay steel fibres and the matrix material are present. Therefore, either, the amount of steel fibres can be increased by having a higher stitch density, another fibre system with a higher strength or by changing the knitting pattern to improve the fabric design.

4. Conclusion

The results of the developments of FAUSST demonstrate a solution for a standardised approach of a metal to FRP joint. By avoiding the use of additional materials beside the materials used in the FRP structure, testing and approval are no drawback anymore. This textile based transition joint shows that loads in average of 200kN/m can be successfully transferred from a steel to a FRP structure. Alternatively, this technology can also be used for load transfer in FRP materials, which have a low bearing strength.

The manufacturing processes of the half-finished product FAUSST is based on standard processes found in the textile and welding industry, making the product suitable for industrialisation and mass production. The implementation phase of the FAUSST connector to join a FRP and steel structure is also based on standard processes such as lamination and welding reducing the need for specialised processes and equipment.

Currently, the research focus lies within the shipbuilding industry and on the connection between glass FRP and steel. However, it is feasible to combine other materials within the knitted fabric, such as aluminium and carbon fibres.

FAUSST is developed as a key-enabling technology for the wider use of FRP structures. Joining remains number one of the challenges when using FRP material in shipbuilding. With respect to the expected effectiveness in terms of cost and fulfilling the requirements, todays naval ship designs are challenging. While currently the structure is designed and built to last 20 years and longer, the availability of new actors, sensors or the occurrence of new threat scenarios, make retrofits necessary. Multi-material concepts, e.g. using FRP materials and structures may path the way for easier retrofits, e.g. through weight reserves, integrated functionalities, etc. Moreover, FRP offer great potential for fulfilling the requirements of modern naval ships. FAUSST in this matter, will be further developed to support the use of FRP and fulfil the high requirements at reasonable costs.

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