Bolted Joint Connections of FRP-Components in Submarines Subjected to Underwater Shock

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1 Introduction

The application of fiber reinforced plastic (FRP) and sandwich components is an established practice at various locations in state-of-the-art submarines. Due to acoustic reasons, easy formability and low mass density at comparatively high strength values, these components bear a huge potential for buoyancy-related constructions. The shock-design and -calculation of these components as well as their connecting parts are crucially supported by Finite Element simulations using LS-DYNA.

The present work shows an investigation of FRP-based bolted joint connections in today's submarines and their connection to the pressure hull in terms of modelling and simulation. The transfer from detailed models to simulation of a full-scale shock submarine, as shown in Fig. 1, is presented and discussed.

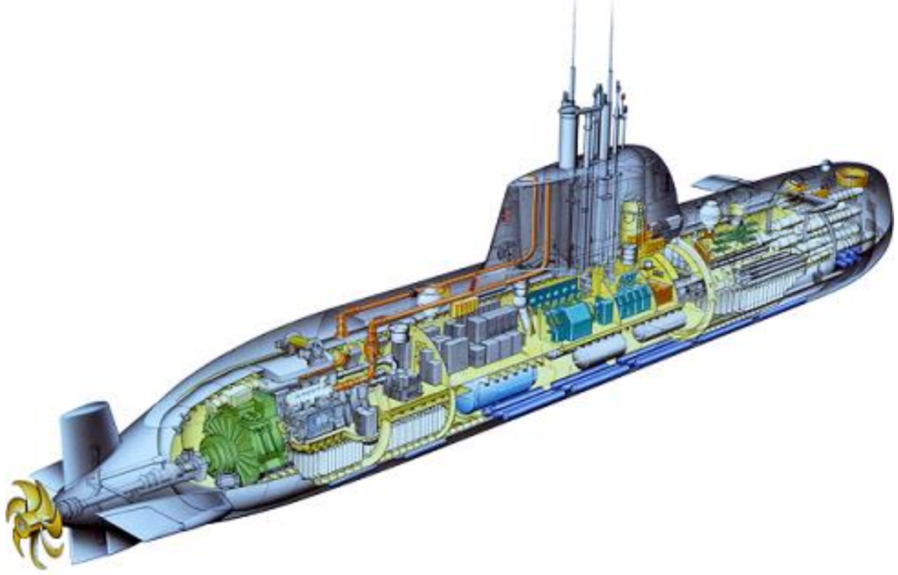


Fig.1: State-of-the-art non-nuclear submarine.

2 Load Case UNDEX

An important load case for the design of modern submarines are underwater explosions. An underwater explosion (UNDEX) is caused by the detonation of an explosive charge with a defined mass and distance to the investigated object. Typical UNDEX threats are remnant World War II or modern naval mines. After a submerged detonation, a shock wave forms a shock front that travels radially from the charge's center and eventually impinges a submarine's structure. The principle shock wave formation due to different particle velocities is shown in Fig. 2.

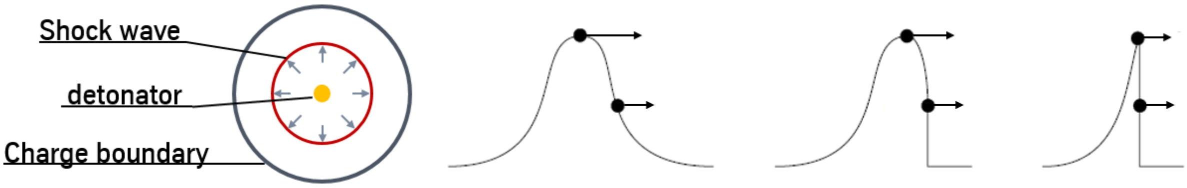


Fig.2: Visualization of a detonation (left) and the resulting shock front formation (right) [1].

In a sufficient distance from the charge, the shock front travels approximately at the speed of sound, which is a function of various parameters like the temperature or the salinity of the water. The resulting pressure-time correlation $p(t)$ of the shock wave in sufficient distance from the detonation point can be approximated by

$$p(t) = p_{\max} e^{-\frac{t}{\theta}}, \tag{1}$$

where the peak pressure $p_{\max}$ and the time constant θ are parameters that depend on the applied explosive. The corresponding pressure-time correlation is depicted qualitatively in Fig. 3 (left), where p_0 is the ambient pressure. Following [2], these parameters are defined for Trinitrotoluene (TNT) as

$$p_{\max} = 52{,}4 \cdot \left(\frac{\sqrt[3]{W}}{R}\right)^{1{,}13} \text{ in MPa} \tag{2}$$

and

$$\theta = 0{,}084\sqrt[3]{W} \cdot \left(\frac{\sqrt[3]{W}}{R}\right)^{-0{,}23} \text{ in ms.} \tag{3}$$

Here, W and R are the charge weight and the distance from the charge, respectively. Additionally, cavitation effects occur in the water that lead to oscillating gas bubbles, as illustrated in Fig. 3 (right) that buoys towards the surface. These gas bubble pulsations may have a critical influence on a ship's survival, in particular when the bubble attaches to the hull. However, numerical simulations of these bubble effects are costly and complex, and therefore not treated in the current investigation. A load representation by a pressure-time correlation can, therefore, be seen as a good approximation within the framework of the current presentation.

In order to describe and understand underwater effects und structural responses, different experiments ranging from the component level to full-scale submarine UNDEX tests [3] were conducted in the course of the present project. Corresponding photographs of the experiments are shown in Fig. 4. Here, the component was attached to a steel raft and then positioned in a defined depth in sea water. The charge was positioned likewise in a defined distance and angle to the component and then detonated, eventually.

In order to ensure shock safety for a large amount of components and a full-scale submarine, respectively, the shock event and its related characteristics have to be adequately represented in numerical simulations.

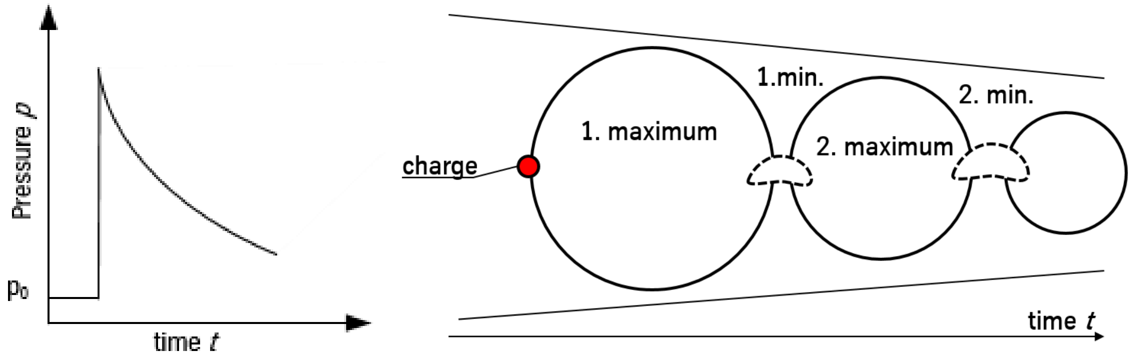


Fig.3: Pressure-time approximation for a shock wave (left) and bubble oscillation [1] (right).

Fig.4: UNDEX experiments: steel raft for specimen carriage (left) and wave puncture at the surface (right). The experiment was conducted by the Swedish Defence Materiel Administration (FMV) in Muskö, Sweden.

3 Material Modelling

3.1 FRP Modeling: Orthotropy and TShell Stacking

The strong anisotropy of FRP materials due to fiber directions is considered by using orthotropic material models, like for example **`*MAT_ORTHOTROPIC_ELASTIC`** or **`*MAT_ENHANCED_COMPOSITE_DAMAGE`**. Due to comparably high thicknesses of the used laminates in the area of bolted joint connections (up to t=50mm) a representation of every layer in an extra element row is very costly. Therefore, a number of layers are combined within a stacked TShell element (**`*PART_COMPOSITE_TSHELL`**).

3.2 Bolt Modelling: Strain Rate Dependency

The strain-rate dependent response of the bolt material is of particular importance because of the increased strength values at higher loading rates. In order to exploit that potential, different strain-rate dependent tensile experiments were conducted with the basic material of the bolt, which is shown in Fig. 5 in form of a true stress-strain diagram.
In the shown example, a significant raise of approximately 25% of the yield strength can be observed when comparing the quasi-static strain rate to a strain rate of 100 1/s. Furthermore, the influence of manufacturing and finishing on the material behavior has to be respected by investigating specimens taken from the final bolt.

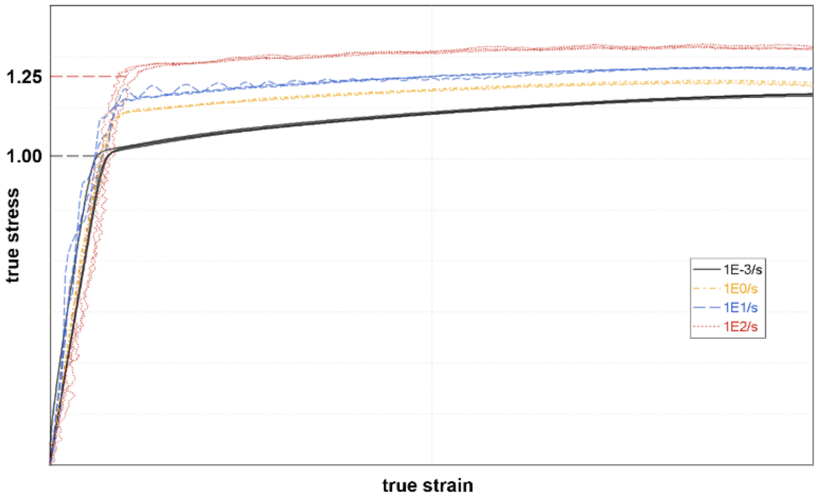


Fig.5: True stress-strain diagram from a uniaxial tensile test at different strain rates. For every strain rate, three experiments were conducted.

4 Simulation Models for Bolted Joints

A bolted joint connection consists of various parts that interact with each other and give an overall compound answer. For an adequate representation of this behavior, the consideration of pre-stress, friction, strain-rate dependency, and further parameters cannot be modelled in detail in a full-scale UNDEX submarine simulation. For this, intermediate steps have to be undertaken that simplifies the complexity of bolted joints to a reasonable level of complexity for the sake of computational cost and evaluation effort. These steps are:

1) Detailed level: Starting with certain material modelling characteristics, a detailed basic model is used for a sophisticated analysis of each connection type. Here, all components are modelled with solid elements, as exemplary shown in Fig. 6 (left).
2) Component level: After that, the bolt connection behavior is transferred to a component-level simulation to check for the transferability of the detailed model results. In this stage, the bolt is modelled with beam-spring elements that refer to the behavior from 1), as exemplary shown in Fig. 6 (right).
3) Full-scale submarine level: In the final stage, the results from 1) and 2) are applied to a full-scale submarine simulation for a final shock-safety assessment.

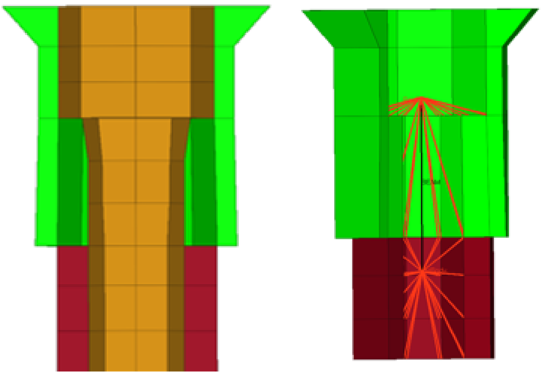


Fig.6: Example for bolted joint connections. Solid model (left) and beam model (right).

4.1 Detailed Level

In a first numerical investigation, detailed models, as shown in Fig. 7, are set up that represent the joints in a high level of complexity. That includes, amongst others, the modelling of every layer in the FRP, solid-modelling of the bushes and nuts, and the representation of the contact situation of the relevant components for different load scenarios. Furthermore, the parameters pre-stress and friction can be studied and evaluated. This way, it is possible to evaluate and understand crucial mechanisms that characterize the overall behavior. The model is then evaluated in terms of plasticity for the metallic components under consideration of a certain safety factor S_f.

The shown example represents a typical bolted joint connection. The components that hold the bush are different layers of carbon fiber reinforced plastics (CFRP) and glass fiber reinforced plastics (GFRP). FRP materials are modelled with TShell elements in order to combine several layers into one hexahedral element. All other elements are modelled with hexahedral solid elements. Additionally, a fitting piece is positioned between the fundament and the FRP.

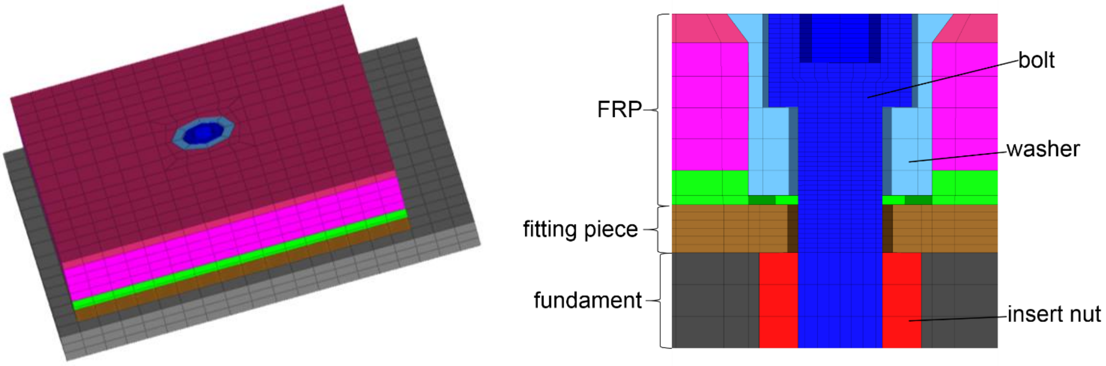
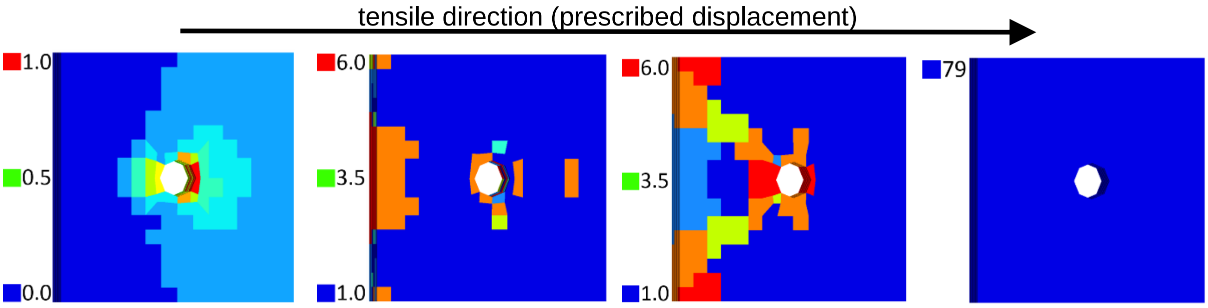


Fig.7: Example for a bolted joint connection. Full model (left) and section-cut view (right).

In the presented load case, the fundament is constrained in all translational directions, while the FRP is given a prescribed displacement in order to create a shear load in the bolt. The FRP area in the direct vicinity of the bolt is one of the most critical parts for the whole compound's structural integrity. Therefore, FRP materials have to be additionally investigated in detail. Different failure criteria, for example, based on the maximum stress, the Chang-Chang or the Puck criterion, can be used within an external routine for a sophisticated analysis of each ply of the material. An example for such a detailed investigation for the FRP is shown in Fig. 8 with a maximum stress criterion, which distinguishes between six failure modes based on the six stress tensor components.



(a) (b) (c) (d)

Fig.8: Detailed laminate evaluation in terms of the laminate stress factor (a), the location of the most critical layer (b), the mode, in which the highest laminate stress factor is reached (c), and the critical timestep (d).

Fig. 8 (a) displays the laminate stress factor, which is used to identify the most critical spots of the laminate. In the shown example, the elements of the laminate, which are directly adjacent to the bush, have the highest laminate stress factor. In Fig. 8 (b) the most critical layer within every FRP-TShell element is displayed in order to exactly locate the highest stress factor. In Fig. 8 (c) the most critical mode is displayed, which depends on the chosen failure criterion. In this case, the six different modes from the maximum stress criterion are displayed. Fig. 8 (d) shows the timestep, at which each element has the most critical timestep. In the shown example this is the same value for very element because of the continuously rising displacement and load, respectively.

For a further investigation of the FRP materials, other criteria can be applied that can be assigned to certain failure mechanisms. One example are Chang-Chang [4] based models, which are formulated in LS-DYNA [5] in the two-dimensional space as

$$\frac{\sigma_{11}^2}{X_T^2} + \beta\left(\frac{\tau_{12}^2}{S_C^2}\right) \geq 1 \tag{4}$$

for a longitudinal tensile failure,

$$\frac{\sigma_{11}^2}{X_C^2} \geq 1 \tag{5}$$

for a longitudinal compressive failure,

$$\frac{\sigma_{22}^2}{Y_T^2} + \frac{\tau_{12}^2}{S_C^2} \geq 1 \tag{6}$$

for a tensile matrix mode, and

$$\left(\frac{\sigma_{22}}{2S_C}\right)^2 + \left[\left(\frac{Y_C}{2S_C}\right)^2 - 1\right]\frac{\sigma_{22}}{Y_C} + \frac{\tau_{12}^2}{S_C^2} \geq 1 \tag{7}$$

for a compressive matrix mode. Here, σ_{ij} and τ_{ij} are the components of the stress tensor, X_i, Y_i, and S_c are the corresponding strength values. The β parameter can be used to interpolate between the Hashin criterion (β =1) and the maximum stress criterion (β=0) for the longitudinal failure. Furthermore, the most critical failure modes are investigated in order to counter possible weak points. The failure mode visualization from Fig. 8 (c) can then be used to identify mode-dominant areas, which can furthermore be used for effective improvements of the FRP structures.

The overall answer, for example in terms of a force-displacement correlation, can be transferred to the component and full-scale submarine model for a simplified representation of the bolt in a beam model. Furthermore, a clear point of failure for every tested load situation can be defined, until which all components and their connection to each other are still intact. Henceforth, this failure point can be used in the component simulation and the full-scale submarine simulation without having to model the full detail of the connection.

4.2 Component Level

After a bolted joint is evaluated in the detailed view, a model on the component level is set up with a less detailed bolted joint modelling. Furthermore, the component level is used to validate the simulations with experiments. In these simulations, the surrounding water has to be considered. This can be performed via various methods, for example modelling the water with either Eulerian or Lagrangian elements or using additional tools like the Underwater Shock Analysis (USA) add-on for LS-DYNA [3]. A detailed investigation considering different methods of Fluid-Structure-Interaction (FSI) has been undertaken in [6].

Fig. 9 shows an example of a component in the experiment (left) and simulation (right). The much more simplified representation of the bolted joint is then compared to the detailed model and checked for plausibility. Furthermore, the interaction of a number of bolts is taken into account on this level and the applicability of the bolted joint for the full-scale submarine simulation is approved.


[redacted]

Fig.9: Component-level experiment conducted by the Bundeswehr Technical Center for Ships and Naval Weapons, Maritime Technology and Research (WTD 71) in Elpersbüttel (left) and simulation (right).

One of the most crucial simplifications is the replacement of the 3D-bolt solid modeling with a simplified bolt, for example a beam-spring, as shown in Fig. 10. Further simplifications are the combination of multiple FRP layers into the one element or the omission of parts like the insert nut. In the shown example, the bolt is represented by a number of beam elements in axial direction to account for a detailed movement analysis.

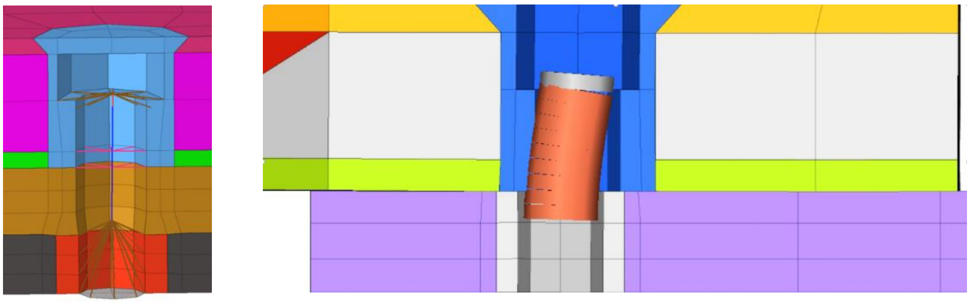


Fig.10: Left: Simplified modelling of a bolted joint connection with beam and spring elements in a components-level simulation. The orthogonal spring elements in red color represent the bearing stress. Right: Deformed bolted joint connection under shear load. The beam thickness is visualized in brown color and grey color for the bolt head, respectively.

Furthermore, the bolt head is given another behavior due to its changed geometry and to account for rotational degrees of freedom. The bolt head and the screwed part are connected with **`*CONSTRAINED_NODAL_RIGID_BODY`** elements to their adjacent contact partner. The bearing stress is represented by spring elements (red color) that additionally account for a certain amount of play. In the shown example, these spring elements are only attached to the bush (blue color), but they may as well be added to the fitting piece (orange color).

4.3 Full-Scale Submarine Level

The bolted joint compound behavior, which was obtained from the detailed bolted joint simulations, can be used to for a significantly simplified bolted joint connection in the submarine simulation. When applying a force-displacement description, for example, in beam elements, the bolts can be evaluated in terms of their forces and moments. An example of a bolt evaluation in terms of normal and shear forces is given in Fig.11. In the shown configuration, the bolt is predominantly loaded in one of the tangential direction, which leads to high shear forces.

The resulting force-based equivalent stress shows a number of peaks due to different reasons. The first peak is caused by the initial shock wave transition. This excites the structure leading to structural responses and, therefore, to the consecutive peaks. A sufficient time of simulation is needed to capture all of the critical peaks because the global maximum can occur significantly after the shock wave passed through. This is caused by the interaction of different structural parts with varying stiffness or eigenfrequency, respectively.

Additionally to the structure's mass, the water, which is adjacent to the structure, has to be accelerated and decelerated by the bolted joints. Thus, the bolted joint reactions are moreover significantly influenced by the flow and inertia of the water. This way, every bolted joint is evaluated under consideration of a safety factor S_f and, if the shock safety is not fulfilled, adjusted in diameter, length, or form of the connection compound.

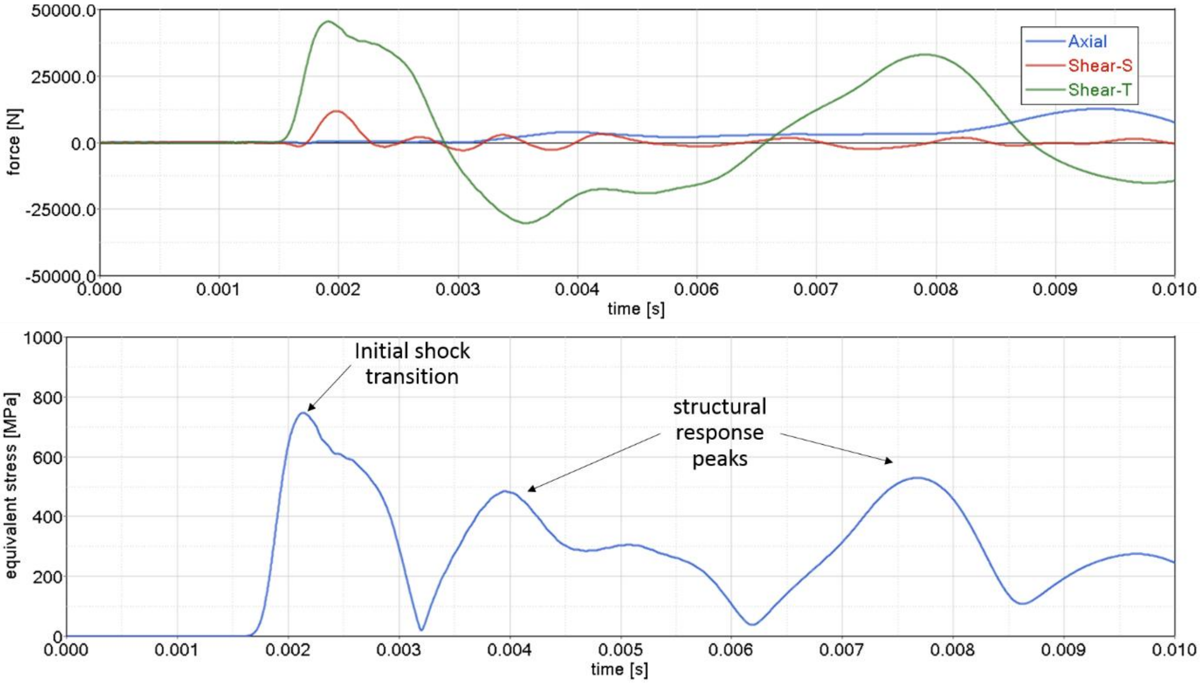


Fig.11: Exemplary force-time correlation for a bolt under shock loading (top). Resulting equivalent stress with multiple peaks (bottom).

5 Summary

An overview on experimental and numerical results and model for the evaluation of bolted joints in a submarine were presented. Different models with varying grade of complexity are used to evaluate the bolted joint connection on a detailed level, components level and conclusively on a full-scale submarine level. The downgrading of complexity is required because of current limitations of the calculation capacity but can be well justified by the deduction to additional detailed models. With the present modelling technique a comprehensive review of underwater-shock loaded bolted joint components can be performed.

6 Literature

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