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Proceedings of the ASME 2026 45th International Conference on Ocean, Offshore and Arctic Engineering
OMAE2026
June 7-12, 2026, Tokyo, Japan

OMAE2026-180656

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DEVELOPMENT AND VALIDATION OF A LOCAL FATIGUE DESIGN CONCEPT FOR WELDED JOINTS IN OFFSHORE STRUCTURES SUBJECTED TO MULTI-AXIAL AND VARIABLE LOADING

Moritz Braun[1,2], Sascha Maurice Isay[1], Shi Song[1], Jan-Hendrik Grimm[1], Niklas Michael Bauer[3], Jörg Baumgartner[3], Leon Wilms[4], Dennis Birkner[4], Karsten Schürmann[4], Marc Voßbeck[4]

[1] Hamburg University of Technology, Institute for Ship Structural Design and Analysis, Hamburg, Germany
[2] German Aerospace Center (DLR), Institute of Maritime Technologies and Propulsion Systems, Geesthacht, Germany
[3] Fraunhofer Institute for Structural Durability and System Reliability LBF, Darmstadt, Germany
[4] Ramboll Deutschland GmbH, Hamburg, Germany

ABSTRACT

Fatigue assessment of welded maritime structures is vital for safe, cost-effective offshore design. Conventional methods struggle with complex loading, variable amplitudes, and thick sections, often leading to overly conservative designs. In the joint industry research project SMATRA, a novel local approach combining notch stress analysis and fracture mechanics was developed, accounting for weld geometry, post-weld treatments, and multi-axial loading. By integrating 3D surface scans, automated FEM modeling, and a two-phase life prediction model (initiation and growth), prediction accuracy improved by 24–77% over IIW, Eurocode 3, and FKM standards. Validation on small-scale specimens and a full-scale double-Y-joint confirmed accurate crack initiation prediction. A practical design tool reduced assessment time by 80% and enabled seamless workflow integration. Material savings exceeded 25% in weld volume and plate thickness while maintaining safety. The project outcomes enable more efficient, safe, and sustainable offshore structures and establishes a foundation for industrial standardization of local fatigue assessment methods in the offshore industry.

Keywords: Fatigue of welded maritime structures, notch stress concept, multi-axial loading, crack initiation, crack growth, 3D scanning, finite element modeling, offshore wind energy plants

NOMENCLATURE

c	Exponent of the super-ellipse criterion
k	Inverse slope exponent of S-N curves
N	Number of cycles to failure
R	Stress ratio
SCF	Stress concentration factor
$\Delta\sigma_{\perp}$	Stress range normal to the weld
$\Delta\sigma_{\perp}^{R}(N)$	Endurable stress range at a given N
$\Delta\tau$	Shear stress range
$\Delta\tau^{R}(N)$	Endurable shear stress range at a given N

1. INTRODUCTION

The assessment of the fatigue strength of welded maritime structures is a key challenge in the design of modern offshore structures such as foundations for offshore wind turbines (OWT), platforms or navigation aids. These structures are exposed to extreme, complex and cyclical loads from wind, waves, operational vibrations and combined environmental influences over long periods of time. Due to their safety-relevant function, reliable fatigue verification is essential. At the same time, there is a growing need for economic optimization of design.

The fatigue strength concepts used to date, in particular the nominal stress concept and the structural stress concept, are characterized by their ease of application and good empirical validation, but they reach their limits when it comes to modern design details, thick sheets and non-proportional load situations. They often do not allow sufficient consideration of local effects due to the seam geometry, post-treatments or variable

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amplitudes. The result is conservative designs with partially oversized welded joints, which are economically disadvantageous.

In contrast, local verification concepts, such as the notch stress concept, offer significantly greater potential for realistically representing actual stress conditions. These concepts are already established in industries such as automotive engineering; however, the maritime industry has so far lacked systematic investigation, validated applications and adapted methodology for large-scale structures typical of offshore applications. At the same time, technological advances in manufacturing, simulation and measurement methods (e.g. high-resolution surface scanners, digital image correlation) are increasing the feasibility and attractiveness of such approaches.

The joint industry research project SMATRA project (funded by the German Federal Ministry for Economic Affairs and Energy) has therefore developed a new, scientifically sound and practical design concept for the fatigue strength of welded maritime load-bearing structures. The aim is to realistically consider local effects such as seam geometry, post-treatments, multi-axial and variable stresses, and the dependence on sheet thickness and crack propagation. Based on experimental and numerical investigations on small and large samples, a computer-aided, efficient verification method is to be developed that enables safer, more economical and more efficient design and allows new manufacturing and post-treatment technologies to be put into practice more quickly.

2. DEVELOPMENT AND VALIDATION OF A NEW LOCAL DESIGN CONCEPT FOR WELDED MARITIME LOAD-BEARING STRUCTURES

2.1 Advances in the prediction of multi-axial and non-proportional stresses

The key objective of the project was to improve the accuracy of predictions for non-proportional, multi-axial stresses—one of the greatest challenges in the fatigue assessment of offshore structures. In the substructures of OWT, wind, waves and nacelle vibrations occur at different times and from different directions, resulting in complex, non-proportional stress states. Previous methods, as implemented in standards such as IIW [1], Eurocode 3 [2] or the FKM guideline [3], are unable to adequately capture these effects correctly.

As part of project, a novel super-ellipse criterion was developed [4] that more accurately maps the stress and strain states in multi-axial, non-proportional load cases. This criterion is based on an extended form of the classical fatigue hypothesis according to Gough and Pollard and considers the effect of non-proportionality and directional change of the loads. This is enabled by a change of the exponents of the original Gough-Pollard equation (1)

$$\left(\frac{\Delta\sigma_{\perp}}{\Delta\sigma_{\perp}^{R}(N)}\right)^{c}+\left(\frac{\Delta\tau}{\Delta\tau^{R}(N)}\right)^{c}\leq 1 \qquad (1)$$

where $c = 2.15$ is applied for proportional and $c = 1.26$ for non-proportional loading.

The performance of the new approach was validated using a comprehensive database that integrates all publicly available fatigue strength tests on welded joints under multi-axial loading, see Figure 1.

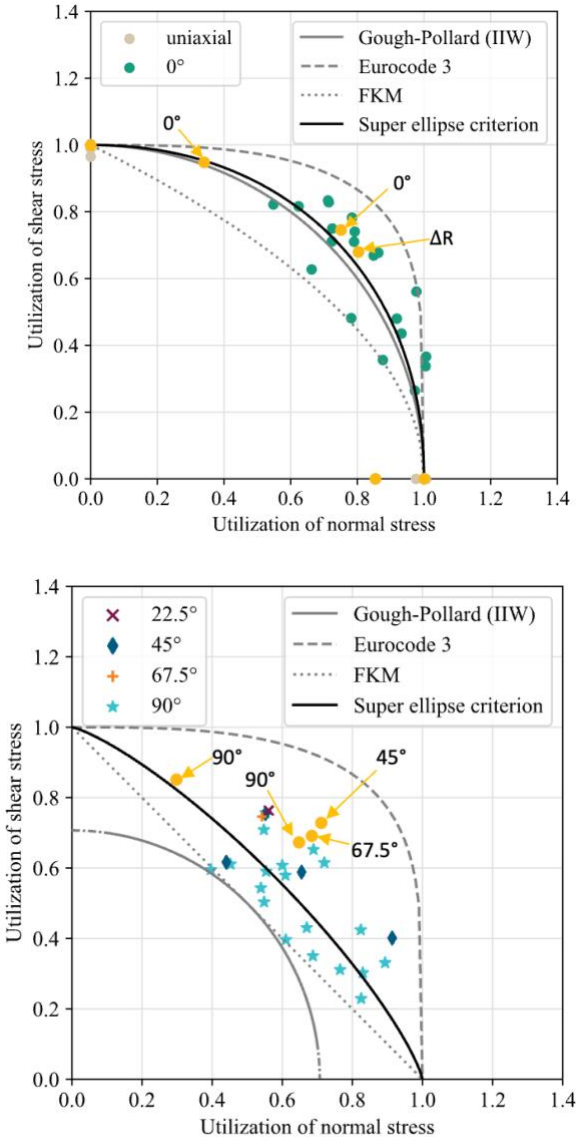


FIGURE 1: Comparison of the newly developed super-ellipse criterion with existing concepts from international standards and recommendations for uniaxial and multiaxial proportional loads (top) and non-proportional multiaxial loads (bottom) based on a database compiled in the project. The comparison clearly shows a significantly better description of the test results by the newly developed criterion. The utilization is described by the two terms of Eq. (1).

The results show a significant improvement in prediction accuracy. Compared to established methods, the super-ellipse criterion achieved an increase in prediction accuracy of 24 to 77%, especially for non-proportional loads. This improvement is crucial as it reduces the risk of overly conservative designs

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without compromising safety. In addition, the approach is easily applicable.

2.2 Consideration of variable amplitudes and mean stresses

The transfer of the new method to variable amplitudes and mean stresses was another key step. Classic fatigue strength assessment is often based on constant loads, whereas real operating conditions are characterized by highly fluctuating loads. The project demonstrated that the method for estimating service life under multi-axial, non-proportional loading can also be applied to variable amplitudes. To achieve this, the variable amplitudes (Gaussian spectrum) were simply transformed into equivalent constant stress ranges using the IIW transformation formulae with a damage sum of $D = 0.5$. The resulting predictions showed a comparable accuracy to tests with constant amplitude.

Another gap in the literature was the lack of systematic investigation of the influence of mean stress under multi-axial loading. To close this gap, special fatigue strength tests were carried out in which specimens with different stress ratios R (ratio of minimum to maximum stress) were subjected to uniaxial and multiaxial loading, see Figure 2. All specimens were stress-relieved beforehand to minimize the influence of residual stresses. The results showed that the influence of the mean stress under non-proportional loading did not differ significantly from that under proportional loading. This is an important finding for practical application. In many cases, the classic mean stress correction methods can also be used for multi-axial loads without the need for additional, more complex models.

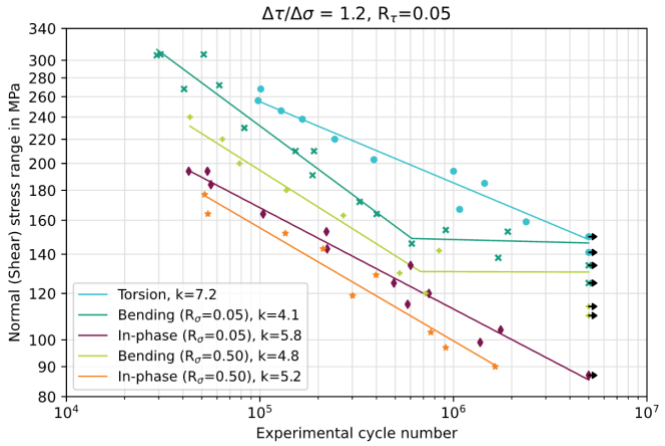


FIGURE 2: Results of tests with different stress ratios R.

2.3 Realistic representation of seam geometry and sheet thickness

A decisive advance was made in considering the local seam geometry and sheet thickness. Traditional methods often use simplified, idealized geometries that do not reliably reflect actual stress peaks. The project demonstrated that accurate mapping of the weld seam shape (especially the transitions between the weld seam and the base material) is crucial for predicting crack initiation, see [5].

By combining 3D surface scans with finite element simulations, crack initiation could be predicted precisely. In a fatigue test on a manually welded steel T-joint, the first cracks occurred exactly where they were predicted in the model with real geometry. This confirms the high added value of detailed geometry data. The use of reverse engineering and digital image correlation (DIC) made it possible to identify critical areas in offshore structures at an early stage and optimize them in a targeted manner.

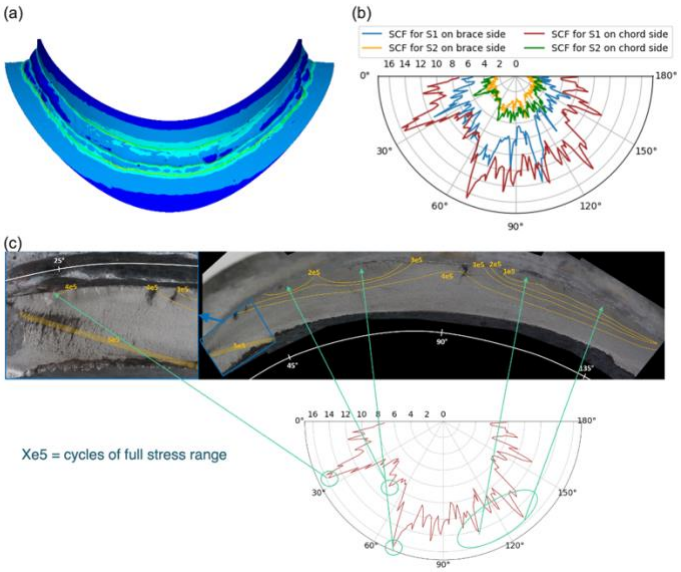


FIGURE 3: Comparison of the first principal stress for the FE model of a T-tubular joint with the actual weld scan (a) and evaluated stress concentrations for first and second principal stress at the weld edges of the chord and brace (b) of the model from (a), as well as comparison of the first principal stress at the failing weld transition with the crack initiation points and crack growth along the weld transition (c). The yellow lines highlight the beach marks observed after the test. The numbers on these lines represent the number of cycles to reach the crack depth corresponding to the beach marks. [6]

In addition, a method was developed that quantitatively captures the dependence of fatigue strength on sheet thickness and seam geometry. This method has been validated for various jacket node and T-joint details and enables a more accurate service life estimate that can be directly incorporated into the design. The results show that even minor geometric improvements (such as a smooth transition shape or optimized seam profiling) can lead to significant improvements in fatigue strength.

2.4 Advances in modelling crack initiation and crack propagation

A significant advance was the development of a two-phase life cycle model that differentiates between the crack initiation and crack propagation phases. In the first phase, a local, stress-based approach is used that considers effects such as seam geometry, post-treatment and multi-axial stress. In the second

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phase, a fracture mechanics model is used to simulate crack propagation.

A novel method, h-adaptive element splitting (h-AES) [7], was further developed for crack propagation simulation, see Figure 4. This method enables targeted mesh refinement near the crack front without having to delete elements, which can lead to strong mesh dependency and numerical instability. The h-AES method was successfully tested in two examples, with the results agreeing well with analytical solutions. The method enables realistic mapping of crack propagation in large-scale structures such as ship hulls or offshore platforms, while at the same time reducing the computational effort by more than an order of magnitude.

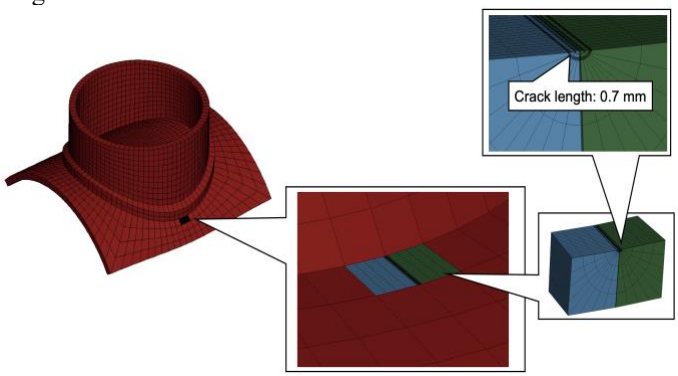


FIGURE 4: Simulation of the crack propagation phase on a T-tubular joint in the as-welded condition using h-AES method.

Since the h-AES method was still too computationally intensive for complex, curved geometries such as jacket nodes, an integrated fracture mechanics concept based on linear elastic fracture mechanics (LEFM) according to Bowness and Lee [8] was also applied. This concept enables a precise estimation of the crack propagation time with a deviation of less than 20% from test results, with significantly lower computational effort. This makes it suitable for industrial application.

2.5 Experimental validation on small and large specimens

Extensive test series were carried out to validate the methods developed. These included small specimens (T-joints, pipe-flange connections) and a large-scale test on a double Y-node in the laboratory of the Institute of Structural Design and Strength at the TUHH. The specimens were made of S355J2 steel, as typically used in offshore foundations. Manufacturing was carried out by experienced industrial partners to ensure high quality.

The test rigs were specially developed for multi-axial stresses (bending and torsion) and equipped with digital image correlation and strain gauges to precisely record crack initiation and crack growth. Prior to the fatigue tests, all welds were scanned using laser scanners to accurately map the geometry in the FE models, see [9, 10]. The results confirm the high validity of the developed methodology. The predictions of crack initiation and propagation correspond very well with the experimental findings.

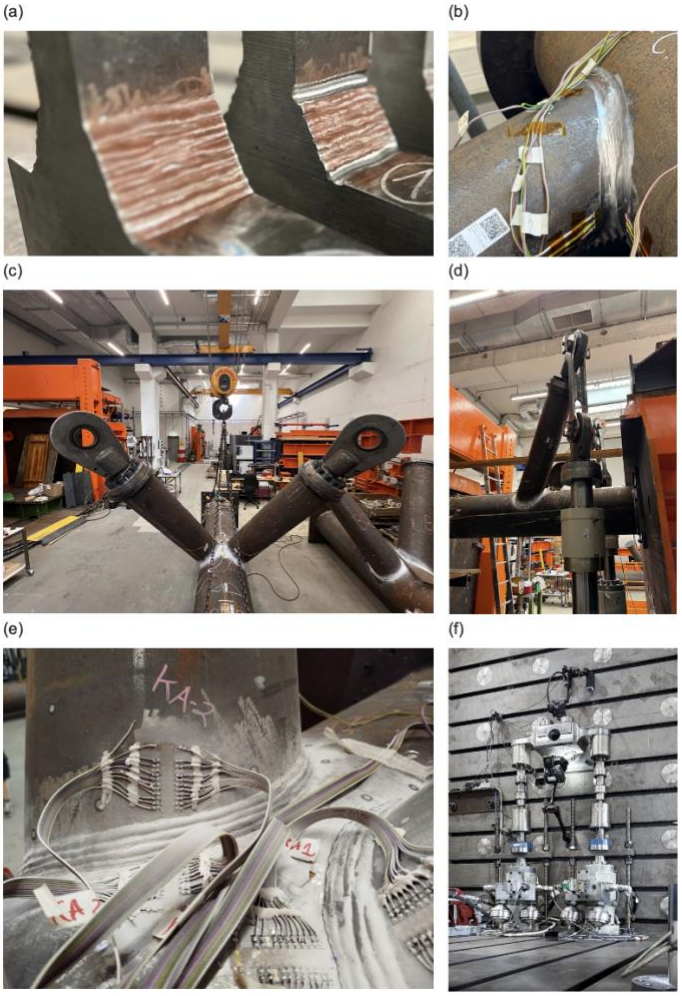


FIGURE 5: T-joint specimens in as-welded and burr ground state (a), weld profiled Y-tubular joint, large DY-tubular joint specimens (c) and large-scale test rig (d) of the selected double Y-node in the TUHH laboratory. The clearly visible white areas on the weld seams originate from the geometry scans and the preparation of the DIC measurements. (e) Close-up of the weld seams of the large-scale test pipe node with clearly visible instrumentation using strain gauges and cracks along the weld seams. (f) Test rig for multi-axis loading of pipe-flange connections under bending and torsion, including camera-based weld seam monitoring for crack detection using DIC at Fraunhofer LBF.

2.6 Development of a practical design tool

A central aspect of the project was the development of a practical design tool that provides a basis for the application of the new verification concept in design practice. The use of high-resolution FE models has been severely limited to date by long computing times and complex modelling.

To solve this problem, three semi-automated tools were developed:

1. Shell model generator for jacket nodes with load and support scenarios,
2. Volume model generator with realistic weld geometry,
3. Submodel generator for local stress analyses.

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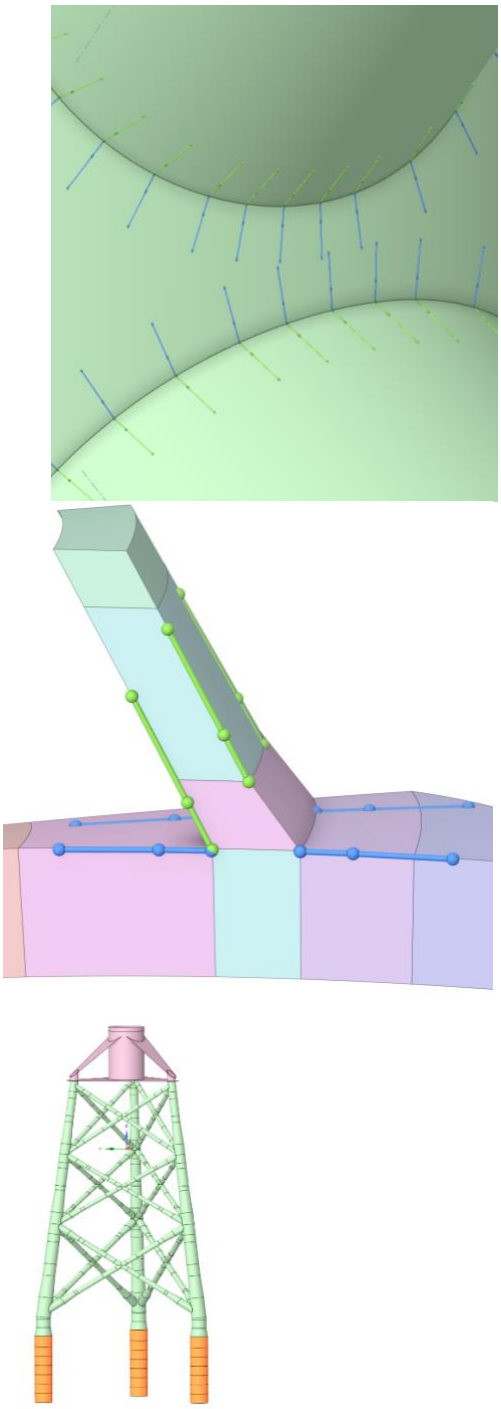


FIGURE 6: Visualization of automatically arranged hotspots and the associated readout paths: jacket, detail of a jacket node, section through a weld seam of a jacket node.

The key technology is the semi-automatic creation of hexahedral macro meshes, which enables efficient mesh refinement in critical areas. This has reduced the calculation time by more than an order of magnitude compared to conventional approaches. Submodels with even finer resolution can also be created automatically, while calculation times remain manageable.

In addition, an interactive analysis tool has been developed that breaks down damage contributions according to stress constellations, vibration magnitudes and internal forces. This enables targeted optimization of the structure both at a global level (support structure) and at a local level (weld seam geometry).

3. CONCLUSION

The SMATRA joint industry research project aimed to develop and experimentally validate a local numerical design concept for the vibration resistance of welded maritime load-bearing structures. The focus was on overcoming the limitations of conventional verification methods, which often lead to conservative and therefore cost-intensive designs for offshore structures.

A key result was the significant improvement in prediction accuracy for multi-axial stresses. With the newly developed super-ellipse criterion, an increase in prediction quality of 24% to 77% was achieved compared to established regulations such as IIW, Eurocode 3 or the FKM guideline. Particularly in the case of non-proportional loads, a clear superiority over previous approaches was demonstrated.

Furthermore, it was demonstrated that the exact representation of the weld geometry has a decisive influence on the accuracy of the prediction. Simplified models could not reliably capture real crack initiation points. Only by combining 3D surface scans with finite element simulations was it possible to accurately predict the actual crack initiation points. Experimental validation on T-joint and jacket node samples confirmed the robustness of this approach.

The development of a two-phase life cycle model with separate consideration of crack initiation and crack growth also makes it possible to predict the remaining service life of jacket nodes in OWT more accurately than before. While local stress-based concepts with geometry and post-treatment influences were used for the initiation phase, an advanced h-adaptive element splitting method (h-AES) and a linear elastic fracture mechanics concept according to Bowness and Lee [8] were used in the growth phase. This made it possible to predict crack propagation with deviations of less than 20% from test results. At the same time, optimized modelling and meshing strategies reduced computing times by more than an order of magnitude, making it feasible to use such methods in practical studies; however, further improvements are still necessary for typical optimization work.

The economic relevance of the project was substantiated by comparative studies. The application of the new local verification concept demonstrated material savings of over 25% in weld volume and a noticeable reduction in the required sheet thicknesses while maintaining the same level of safety. This opens considerable potential for cost reduction in the construction of future offshore structures.

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ACKNOWLEDGEMENTS

The work was performed within the research project SMATRA – Improved assessment of the fatigue resistance of welded maritime support structures using local assessment concepts (in German: Verbesserte Bewertung der Schwingfestigkeit geschweißter maritimer Tragstrukturen unter Anwendung lokaler Nachweiskonzepte) funded by the German Federal Ministry for Economic Affairs and Energy (project numbers 03SX559A, 03SX559B, and 03SX559C).



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