Bridging S-N Method and Fracture Mechanics in Fatigue Evaluation of Fillet Welded T joints of an Oil Tanker

Povezivanje S-N metode i mehanike loma u procjeni zamora zavarenih T-spojeva naftnog tankera

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Abstract

Fatigue failure in fillet welded T joints is a critical concern for marine vessels, particularly for oil tankers which are constantly exposed to fluctuating loads in harsh sea environments. This paper explores the fatigue performance of those joints through a combined approach involving the hotspot stress method and fracture mechanics. The study followed the design provisions of Eurocode 3 for application of loads. Finite element analysis was used to calculate the hotspot stresses which were then applied in the S-N fatigue assessment. In addition, crack propagation of the joints was modeled using FRANC 2D with application of Paris Law. The objective is to predict fatigue life at critical locations susceptible to cyclic loading and verify whether the joints meet the code-specified design resistance. Under ship's actual design load, the joints are expected to sustain more than 2.5 million cycles which is significantly exceeding Eurocode based estimation (as low as 0.5 million cycles) reflecting the conservative nature of Eurocode. The fatigue life under the simulation of crack closely aligns with the S-N prediction and previously published experimental findings, lending confidence to robustness and validating the accuracy of the adopted methods. Ultimately, the study identifies the fatigue critical zones with clarity and offers a practical framework for assessing the durability and safety of the welded joints in marine structures, contributing to the development of more reliable fatigue resistant designs.

KEY WORDS
Fatigue
hotspot stress
FRANC2D
fillet weld
Eurocode 3
fracture

Sažetak

Lomovi zbog zamora u kutno zavarenim T-spojevima ozbiljan su problem za brodove, posebno za tankere za naftu koji su stalno izloženi promjenjivim opterećenjima u teškim morskim uvjetima. Ovaj rad istražuje performanse zamora tih spojeva kombiniranim pristupom koji uključuje metodu žarišnih naprezanja i mehaniku loma. Istraživanje je pratilo odredbe Eurokoda 3 za primjenu opterećenja. Analiza konačnih elemenata korištena je za izračunavanje žarišnih naprezanja koja su zatim primijenjena u S-N analizi zamora. U ovom istraživanju korištena je FRANC 2D simulacija za modeliranje propagacije pukotina u spojevima, uz primjenu Pariškog sporazuma. Cilj je bio predvidjeti životni vijek spojeva na kritičnim mjestima izloženim cikličkom opterećenju i provjeriti zadovoljavaju li spojevi zahtjeve otpornosti definirane propisima. Pod stvarnim opterećenjem broda, očekuje se da će spojevi izdržati više od 2,5 milijuna ciklusa, što značajno premašuje procjene temeljene na Eurokodu (niskih 0,5 milijuna ciklusa). Životni vijek spojeva u simulaciji propagacije pukotine usko se podudara s predviđanjem S-N krivulje i prethodno objavljenim eksperimentalnim nalazima, dajući povjerenje u robusnost i potvrđujući točnost usvojenih metoda. U konačnici, istraživanje jasno identificira kritične zone zamora i nudi praktičan okvir za procjenu trajnosti i sigurnosti zavarenih spojeva u brodskim konstrukcijama doprinoseći razvoju pouzdanijih konstrukcija otpornih na zamor.

KLJUČNE RIJEČI
zamor
žarišno naprezanje
FRANC2D
kutni zavar
Eurokod 3
lom

1. INTRODUCTION / *Uvod*

Fillet-welded joints are widely used in marine structures due to their simplicity, cost-effectiveness, and load-bearing capacity. However, their vulnerability to fatigue, particularly in oil tankers exposed to dynamic wave loads which raises significant concerns. The longevity and performance of marine vessels rely on the establishment of reliable procedures for assessing the fatigue behavior of these crucial components. In contemporary engineering, the fatigue resistance and service life of welded joints play a vital role in ensuring the structural integrity and safety of large structures such as oil tankers. Accurate fatigue life prediction is essential not only for structural integrity but also for ensuring compliance with international safety standards and preventing catastrophic failures.

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To tackle this, researchers have turned to various approaches. Amongst those, the hot-spot stress method, which relies on empirical data, and the fracture mechanics approach, which offers deeper insight into crack initiation and propagation using principles like Paris's law. Together, they provide a more complete picture of fatigue behavior under complex marine loading.

Despite the advances, the lack of any unified framework especially one tailored to marine conditions limits the accuracy of fatigue assessments. This research addresses that gap by integrating fracture mechanics with hot-spot stress analysis along with exploring the application of Eurocode 3, a well-established design standard in structural engineering. Its guidelines incorporate factors such as stress concentration, welding geometry, and material properties, enabling a systematic approach to fatigue analysis. The welds can perform safely within this load under specific loading conditions and limit states without failure. Despite its extensive application in general engineering, Eurocode 3 has not been widely adopted for fatigue analysis in marine structures. Ultimately, the study aims to establish a reliable and standardized methodology for evaluating the fatigue strength in oil tankers, with an emphasis on stress analysis and fatigue life estimation while following Eurocode 3 for validation purposes.

The study first presents the adopted methodology including the fatigue assessment framework, finite element modeling and fracture mechanics based crack propagation. These are followed by a presentation of the simulation results and a discussion comparing the outcomes with existing experimental findings to validate the adopted approach. The paper concludes by summarizing the key findings and insights for improving fatigue resistant design in marine structures.

1.1. Background of study / *Pozadina istraživanja*

Ships, offshore platforms, and other marine constructions are subjected to complex loading histories due to the repeated nature of the ocean environment that leads to fatigue damage, which may fail marine structure if not treated properly [1,2]. For example, the occurrence of excessive stresses due to welding dramatically affects fatigue life through changes in effective stress ratio at the crack-tip during fatigue crack growth which can alter both crack-propagation path and rate [3,4]. It is also shown that local fatigue approaches that account for actual geometry and residual stresses can minimize variability in stress-life (S–N) curves, resulting in a much more dependable assessment of the fatigue [5,6].

The DNV guideline for fatigue analysis in ship structures aims to preserve structural integrity by assessing hotspot stress [7]. A major concern is the accurate evaluation of fatigue damage, which helps forecast the initiation of fatigue cracks in undercut areas of ship structures where stresses concentrate, such as weld toes [8,9]. However, it advocates for a structural hot-spot stress approach, which is preferable to the nominal stress approach when considering the complex geometries and high-stressed regions typical of welded connections [10]. The geometrical stress amplitude at the hot spot is calculated using finite element analysis (FEA) and then integrated with a unified S- N curve to estimate fatigue strength [8,11]. The incorporation of the International Institute of Welding (IIW) hotspot stress approach allows for a more precise method of calculating stress values, significantly improving the fatigue life prediction for fillet welded joints common in ship structures. Although the IIW hotspot stress method is highly efficient and provides a solid foundation for fatigue assessment, design codes such as Eurocode 3 offer a well standardized approach, particularly in fatigue classification and the implementation of the S- N curve [12]. The hotspot stress method exists in Eurocode 3, and it can be used to determine the most dangerous locations for fatigue failure, thus representing a better assessment than nominal stress methods [13]. While the IIW emphasizes that only the geometrical stress amplitude at a hotspot needs to be accurately determined, Eurocode 3 retains this concept, acknowledging the importance of capturing the correct stress distribution in welded joints [14]. The combination of guidelines provided by Eurocode 3 and the IIW method takes weld size and load-carrying capacity into a more accurate evaluation of fatigue life [8,15]. Fracture mechanics provides a general methodology for the interaction between mechanical and geometric parameters in welded joints that may enhance reliability and safety prediction of ship structures [16]. This approach in conjunction with Paris's law results in a more stringent analysis of the endurance of joints concerning fatigue crack propagation [17]. The localized area of damage, which plays a crucial role in the growth of cracks, is effectively incorporated into this method [18]. Fatigue life predictions and maximum load carrying capacities will be estimated based on the integration of the Eurocode 3 guidelines with the IIW hotspot stress method and fracture mechanics principles. FRANC2D software will be used to perform and validate the crack propagation analyses against published experimental data, accomplishing the most needed connection of theoretical models to actual situations in marine structures. To overcome these shortcomings, the current study seeks to perform a full fatigue examination of a 2000 DWT oil tanker class approved fillet welded T-joints. The study will identify stress concentrations, which are recognized as hotspot regions by constructing a finite element (FE) model of cargo hold and static analysis for various loading circumstances according to GL rules.

2. METHODOLOGY / *Metodologija*

This research methodologies followed in this study are shown in Figure 1. The first part evaluates the hotspot stress method to assess fatigue resistance of fillet-welded T-joints. The mid-cargo hold of a DNV class-approved 2000 DWT oil tanker are modeled using ANSYS for finite element. Static analysis, as specified in the DNV rulebook, is applied on model for different kinds of global and local loads.

Local models of these hotspot areas are then constructed with a finer mesh to increase analysis accuracy. The submodeling technique is applied to transfer boundary conditions from the global cargo hold model to these local models. Hotspot stresses are estimated using the surface stress extrapolation method proposed by the International Institute of Welding (IIW). Subsequently, fatigue life at these places is predicted using the S-N technique. The maximum load-carrying capacity that the fillet welds can safely support under certain loading conditions without encountering failure or unacceptable deformation is determined by Eurocode 3, incorporating both tensile and bending stresses. The fatigue life at these hotspot locations is determined under the maximum achievable load, treating the fillet joints as load-bearing elements.

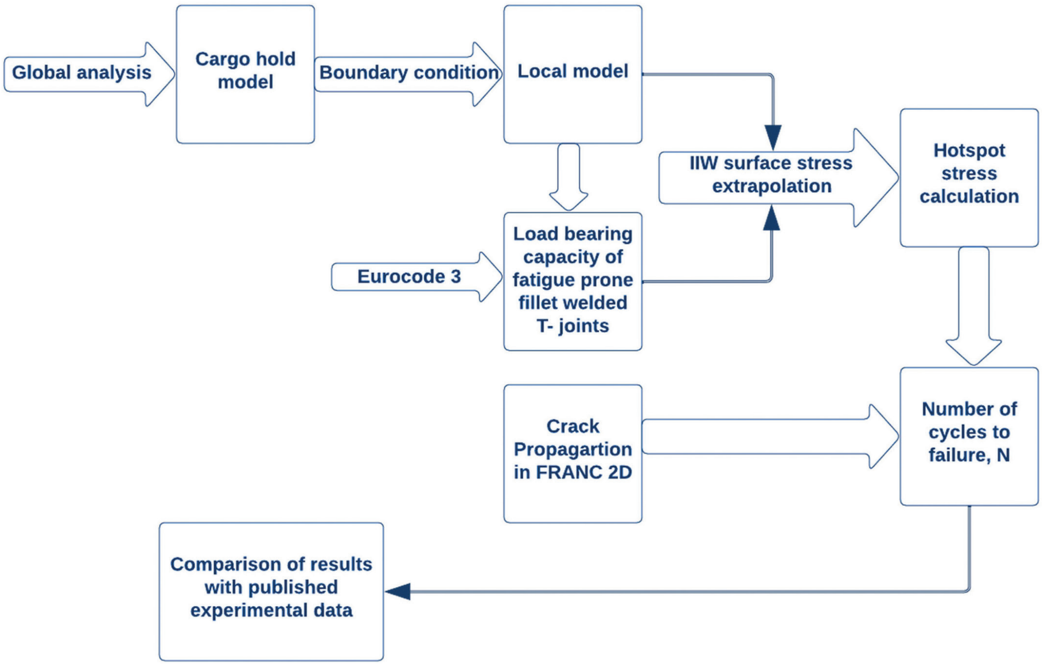


Figure 1 Research methodology
Slika 1. Metode istraživanja

The second portion of this work includes the relevant joints and crack propagation behavior. This is performed using FRANC 2D software that models fracture propagation owing to cyclic loading conditions. Using Paris's Law, a fundamental component of the fracture mechanics field, crack growth rates are utilized to determine the number of cycles to failure for the structure.

2.1. Fatigue Assessment Framework: Eurocode 3 Compliance / *Okvir za procjenu zamora: sukladnost s Eurokodom 3*

Eurocode 3 (EN 1993), the European standard for the design of steel structures, establishes comprehensive protocols for ensuring structural integrity under cyclic loading. Its fatigue specific provisions (EN 1993-1-9) provide the foundational methodology for this study. The standard's approach centers on stress range (Δσ) as the governing fatigue parameter.

Eurocode 3 (EN 1993) is the European standard that governs the structural design of steel components, ensuring safety, reliability, and serviceability throughout the intended service life of structures. Fatigue design is addressed specifically in Part 1-9 of the standard, which provides a detailed methodology for assessing the fatigue strength of steel structures subjected to cyclic loading. This is particularly relevant for welded joints in marine applications, where load variations from waves, cargo, and vessel motion are frequent and severe.

The fatigue provisions in Eurocode 3 are based on a nominal stress or hotspot stress approach, with structural details classified into predefined categories, each associated with a characteristic S–N curve derived from experimental data. These S–N curves relate the applied stress range to the number of cycles to failure and incorporate safety factors to account for uncertainties in material properties, geometry, and loading conditions. Additionally, the code employs cumulative damage assessment using Miner's rule to evaluate the overall fatigue life under variable amplitude loading.

In the context of this study, Eurocode 3 serves as both a benchmark and a reference framework for fatigue life prediction. The fatigue resistance of fillet-welded T-joints is assessed using the hotspot stress method in accordance with the standard, enabling direct comparison of predicted fatigue life against code-specified endurance limits. The conservative nature of the standard is critically examined through fracture mechanics analysis, providing deeper insight into crack growth behavior and verifying whether the code's assumptions hold under realistic marine loading scenarios.

This incorporation of Eurocode 3 not only ensures that the analysis adheres to recognized engineering practices but also allows for the evaluation of its conservatism in predicting fatigue performance. The outcomes reinforce the relevance of the code in structural design while also supporting potential refinements or calibrations for specific applications in the marine industry.

2.2. Finite Element Analysis / *Analiza konačnih elemenata*

The 2000 dwt oil tanker analyzed in this investigation is a classification society, DNV-approved, and specifically designed coastal vessel subject to intensive safety and structural standards regulations. The tanker's principal dimensions are given below in Table 1.

Table 1 Principal particulars of the oil tanker
Tablica 1. Glavni podaci naftnog tankera

Particulars	Value
Length overall	70.8 m
Length between waterline	67.8
Length between perpendicular	67.6 m
Breadth moulded	12.5 m
Depth moulded	5.5 m
Draft	4.0 m
Frame spacing	0.600 m
Service speed	10 knots
C_B	0.792

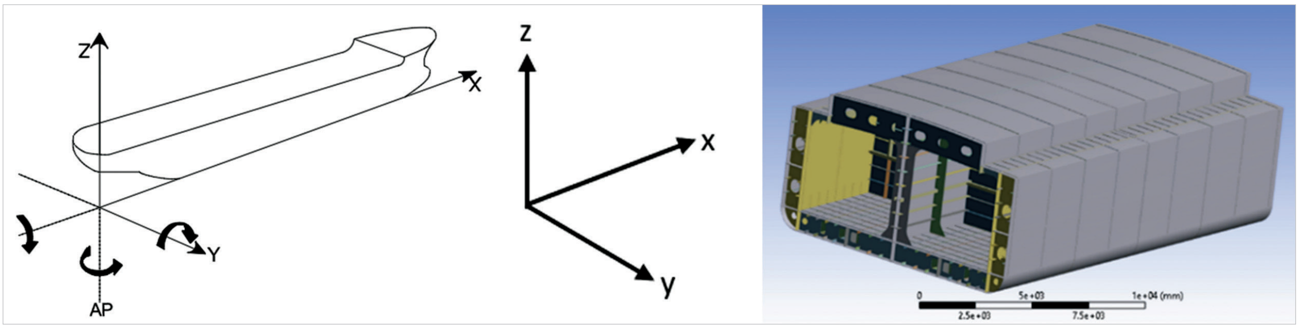


Figure 2 Coordinate system and cargo hold model
Slika 2. Koordinatni sustav i model teretnog prostora

Error Check	Quality Criterion	Warning (Target) Limit	Error (Failure) Limit	Worst
☑	**Min Element Quality**	**Default (0.05)**	Default (0.01)	0.076
☑	Max Aspect Ratio	Default (5)	Default (1000)	15.512
☑	Min Element Edge Length	Default (6 mm)	Default (0.6 mm)	3 mm
☑	Max Element Edge Length	Default (600 mm)	Default (1200 mm)	96.088 mm
☑	Min Quad Angle	Default (30 °)	Default (10 °)	24.228 °
☑	Max Quad Angle	Default (150 °)	Default (170 °)	155.772 °

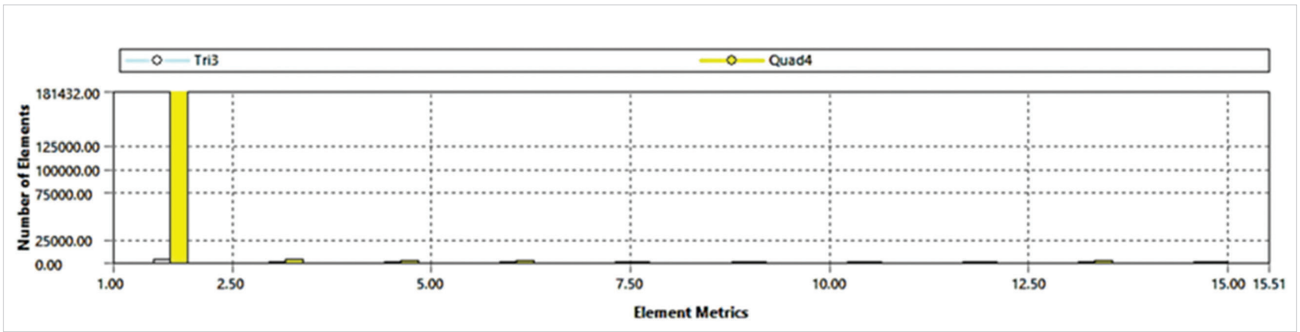


Figure 3 Mesh metric of the cargo hold model
Slika 3. Mrežna metrika modela teretnog prostora

Typically, the finite element model includes the designated hold along with an additional half hold at each end, resulting in a model that spans ½ + 1 + ½ tanks or holds. This approach provides a more comprehensive understanding of structural behavior. In situations where the ship's structure and loads are symmetric, it is permissible to model only half the breadth of the vessel [7]. The hull structure is made of Grade A mild steel, with yield strength 235 MPa and ultimate tensile strength 400 MPa, providing resistance against mechanical and environmental stresses. The coordinate system and the global model are shown in Figure 2.

In ANSYS, the finite element model is built employing four-node shell elements. The mesh metrics have been checked to ensure all the parameters are within the range, as shown in Figure 3. The results from the mesh sensitivity study are provided in Figure. 4, which displays that an element size of 30 mm is ideal for achieving accurate outcomes, striking an effective balance between detail and computational demands.

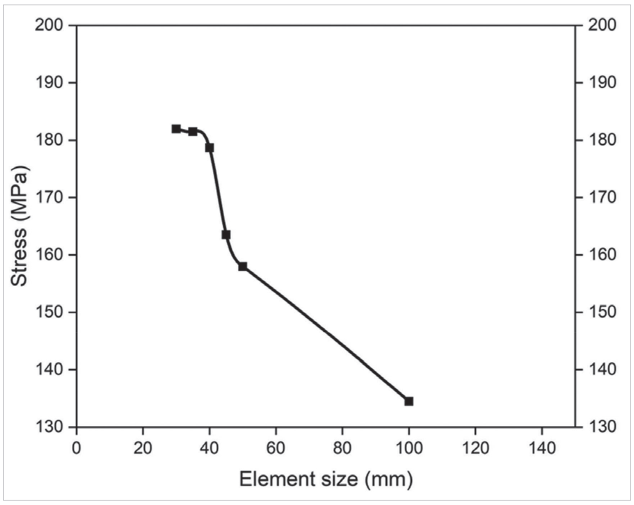


Figure 4 Mesh convergence
Slika 4. Konvergencija mreže

2.3. Application of Load and Boundary Condition / *Primjena opterećenja i granični uvjet*

For simplified fatigue calculations, internal and exterior pressure loads are determined to be employed when global hull girder loads may be given as end moment. For this cargo hold analysis, the following loads are considered [19].

- Hull girder loads
- External pressure
- Internal pressure

Global bending moments and shear forces are applied by creating a rigid element at the neutral axis. Shear pressures and bending moments are applied at both ends to maintain balance. At the free end section, tight constraints are applied on all nodes positioned on the longitudinal members, ensuring that the transverse section remains flat after deformation. The loads and specific boundary conditions applied are shown in Figure 5 and summarized in Table 2 below [20].

Table 2 Boundary condition
Tablica 2. Granični uvjet

Direction	Displacement	Rotation
X	Fixed	Free
Y	Free	Fixed
Z	Free	Fixed

After the static analysis few fillet welds had shown great susceptibility to crack formation as shown in Figure 6 which are;

- HS1: Joint between the margin plate and inner shell bracket.
- HS2: Joint between the inner shell longitudinal and inner shell plate.
- HS3: Joint between the inner shell plate and main deck bracket.

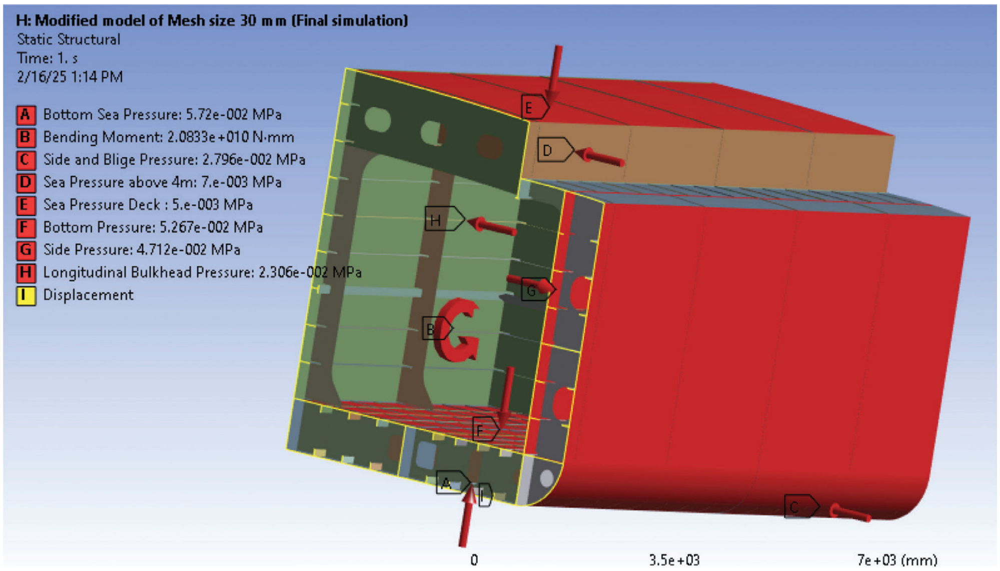


Figure 5 Application of loads and bending moment
Slika 5. Primjena opterećenja i trenutka savijanja

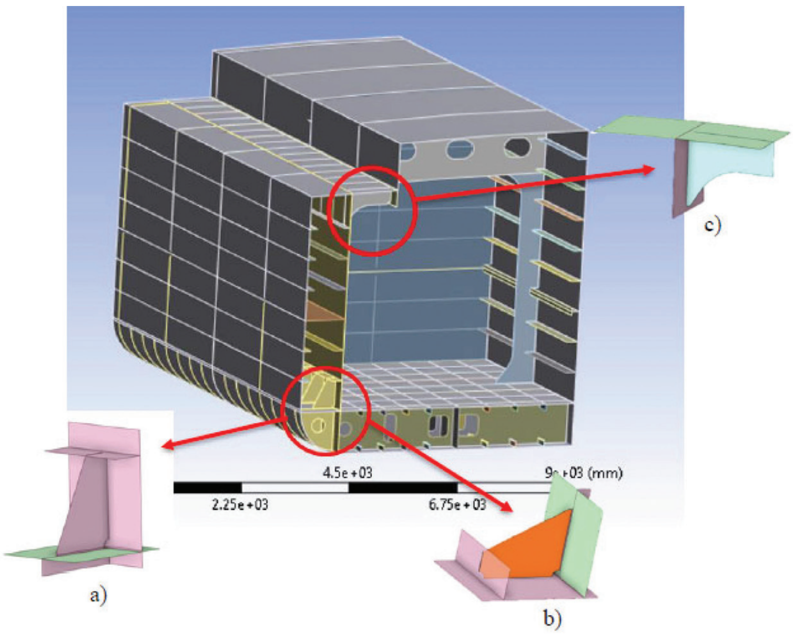
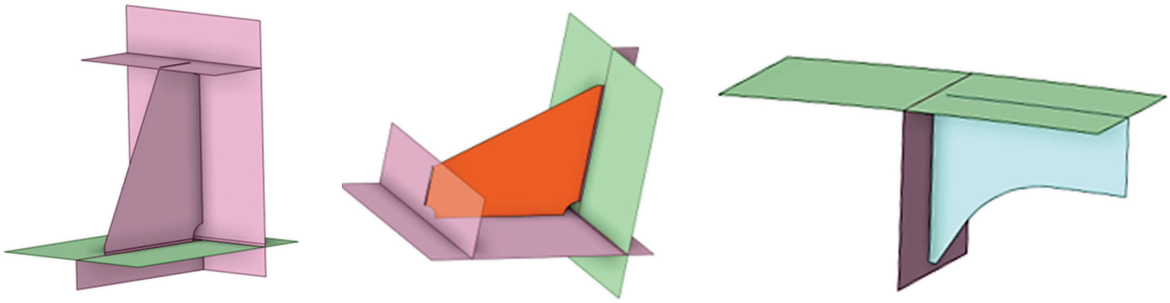


Figure 6 Location of hotspots of global model; a) HS1: Joint between the margin plate and inner shell bracket; b) HS2: Joint between the inner shell longitudinal and inner shell plate and c) HS3: Joint between the inner shell plate and main deck bracket
Slika 6. Lokacija žarišnih točaka globalnog modela; a) HS1: spoj između rubne oplate i nosača unutarnje oplate, b) HS2: spoj između uzdužne i unutarnje oplate, c) HS3: spoj između unutarnje oplate i nosača glavne palube

2.4. Submodeling for Local Analysis / *Podmodeliranje za analizu lokacije*

The sub-modeling technique was used to construct local models of the identified hotspots to conduct a detailed analysis. Local models of the detected hotspots were developed using the sub-modeling technique to conduct a detailed examination of hotspots, as illustrated in Figure 7 and 8.

Boundary conditions allow to transfer external loads, like e.g., the global hull girder loads, to the local model. The proposed size of the local model has been selected based on a compromise in order to minimize the impact of boundaries on the structural detail being analyzed and to define boundary conditions in which a particular solution can be clearly defined [7]. According to the IIW recommendation, local models are developed with a finer mesh size as mentioned [21].



(a) (b) (c)

Figure 7 Local model of a) HS1, b) HS2, c) HS3

Slika 7. Model (prikaz) lokacije a) HS1, b) HS2, c) HS3

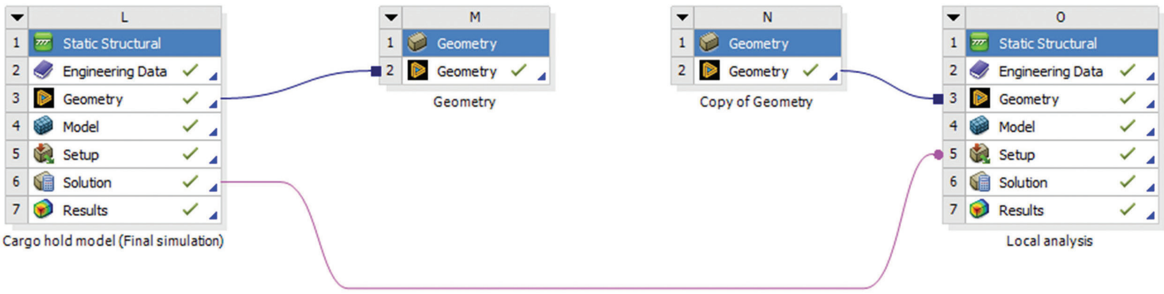
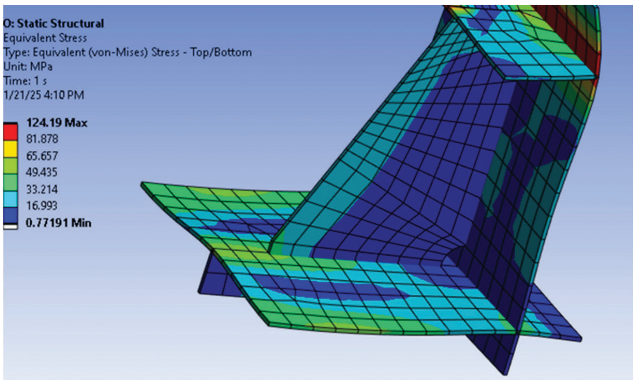
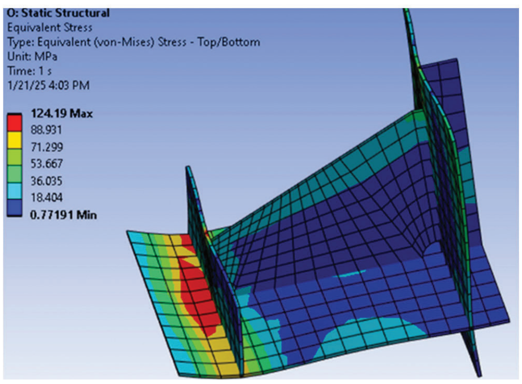


Figure 8 Submodeling

Slika 8. Podmodeliranje



(a)



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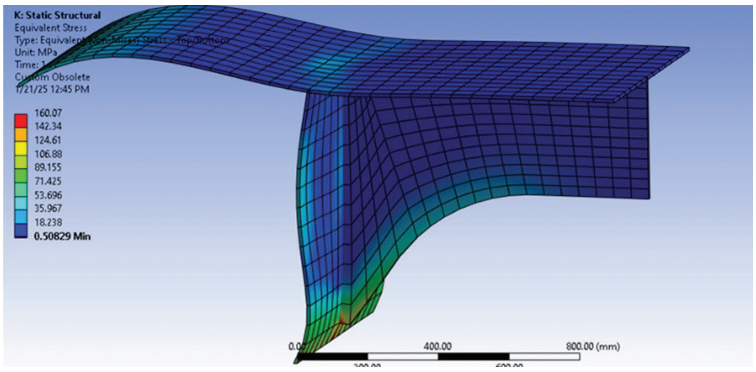


(c)

Figure 9 Stress contour of local models, a) HS1, b) HS2, c) HS3

Slika 9. Kontura naprezanja modela lokacije, a) HS1, b) HS2, c) HS3

2.5. Calculation of Hotspot Stress Using IIW Recommendations / *Izračun žarišnog naprezanja korištenjem IIW preporukama*

In simplified models, the welds are not simulated, except for circumstances when the results are affected by local bending due to an offset between plates or due to a limited distance between adjacent welds. Figure 10 illustrates the specific regions where stress extrapolation is performed in finite element models with a fine mesh. For fatigue-critical spots on the plate's surface, two reference points are placed at defined distances from the weld toe [21].

The structural hotspot stress is calculated using the following equation [21].

$$\sigma_{hs} = 1.67\sigma_{0.4t} - 0.67\sigma_{1.0t} \quad (1)$$

To establish a relationship between hotspot stresses and fatigue life, a fatigue category identified by a FAT number is used. The FAT curves shown in Figure 11, represents the maximum allowable stress range, measured in N/mm² or MPa, corresponding to fatigue life of up to 2 million cycles (2 × 10^6 cycles). Based on the IIW standards, for the load-carrying two-sided fillet welded joints, it is recommended to use FAT 90.

Number of cycles to failure is estimated using following calculation as per the guideline [22]:

$$\Delta\sigma_{hs}^{m}.N = C \quad (2)$$

Where:

Δσ = structural hotspot range

N = number of cycles

C = design value of "fatigue capacity" (= 2×10^6 FAT^m)

m = 3 =slope of the upper part of the S-N curve

FAT = fatigue strength at 2×10^6 cycles

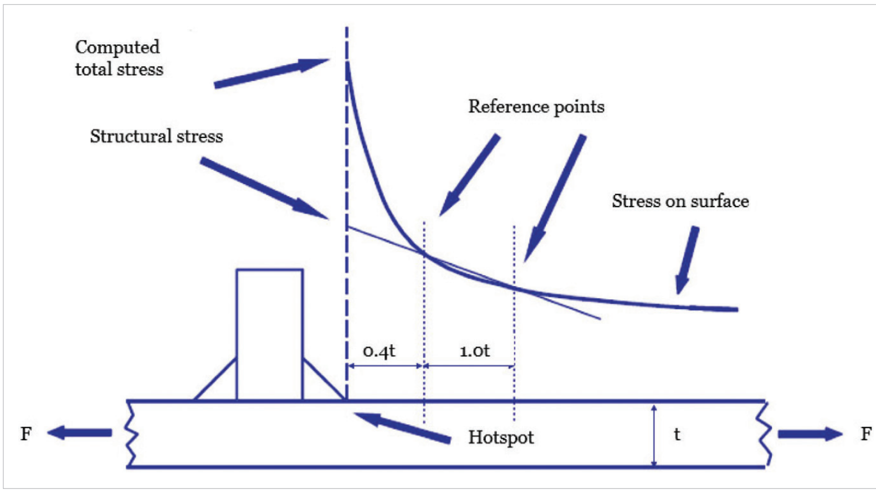


Figure 10 Reference points for linear extrapolation of hotspot stress
Slika 10. Referentne točke za linearnu ekstrapolaciju žarišnog naprezanja

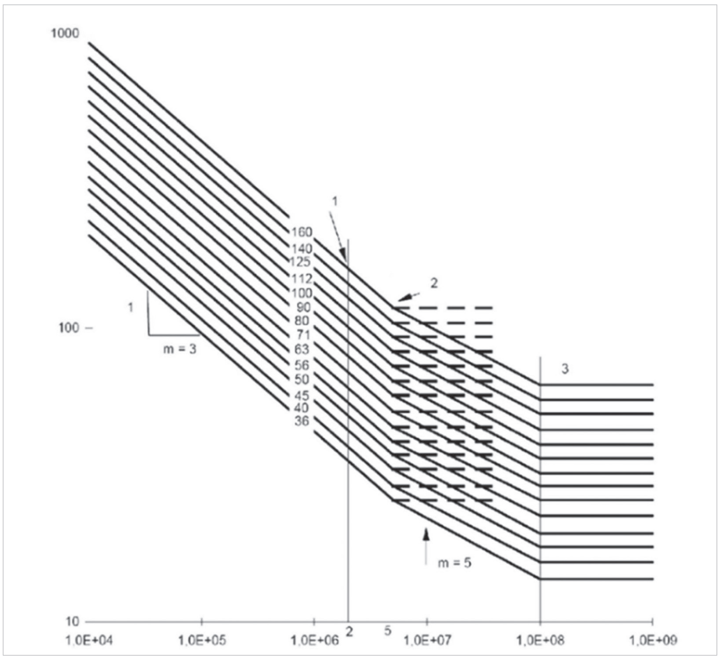


Figure 11 S-N curve with different FAT class [22]
Slika 11. S-N krivulja s različitim klasama snage zamora (FAT klasama)

2.6. Assessment of Fillet Welded Joints in Steel Structures According to Eurocode 3 / *Procjena kutno zavarenih spojeva u čeličnim konstrukcijama prema Eurokodu 3*

In the context of oil tankers, adherence to Eurocode 3 ensures that the welded joints can withstand the operational loads they encounter during service. The assessment begins by applying tensile loads to the hotspot locations identified earlier – HS1, HS2, and HS3. These loads are determined based on the design resistance of the fillet welds, following the guidelines stipulated in Eurocode 3 [12].

According to Eurocode 3, the design resistance of a fillet weld is regarded sufficient if, at every point along its length, the cumulative impact of all forces per unit length transmitted by the weld satisfies the following requirement:

$$F_{w,Rd} \geq F_{w,Ed} \tag{3}$$

Where:

$F_{w,Rd}$ = design weld resistance

$F_{w,Ed}$ = design value of weld force

The design shear strength of the weld $f_{v,wd}$ is calculated using:

$$f_{v,wd} = \frac{\frac{f_u}{\sqrt{3}}}{\beta_w \gamma_{M2}} \tag{4}$$

Where, β_w = correlation factor = 0.8

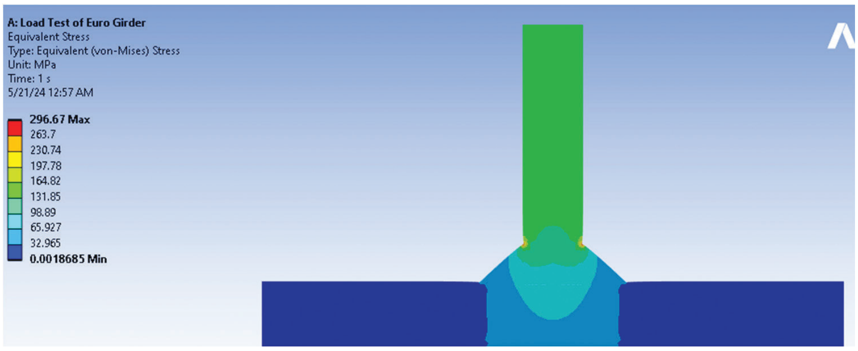
γ_{M2} = Safety factor = 1.25

a = leg length of the weld

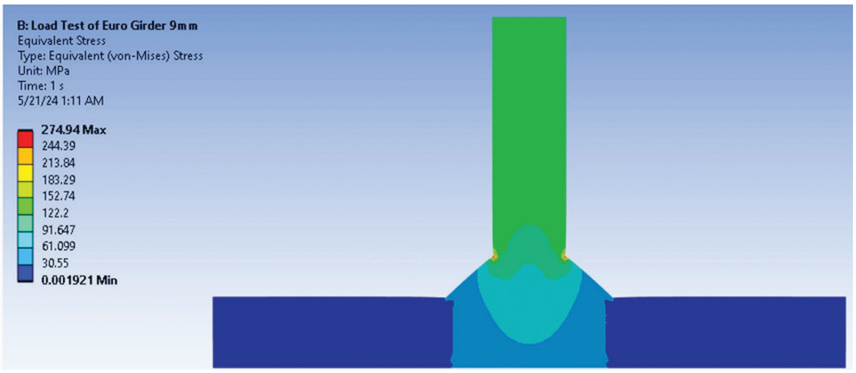
The design resistance per unit length of the weld is then:

$$F_{w,Rd} = f_{v,wd} \cdot a \tag{5}$$

With the maximum tensile loads applied to the hotspot regions, the fatigue life of the welded joints is reviewed. The HS1, HS2, and HS3 finite element models are modified to accommodate the maximum tensile loads obtained by eqn 5. The hotspot stresses are recalculated using the refined models and the surface stress extrapolation method as given in equation (1) recommended by the International Institute of Welding (IIW). The stress contour after analysis is shown in Figure 12.



(a)



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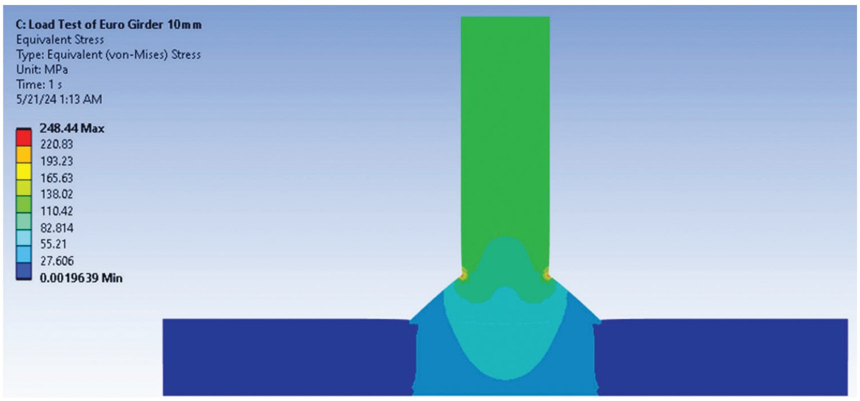


(c)

Figure 12 Analysis of the joints on the application of weld resistance as per Eurocode 3; a) HS1, b) HS2, c) HS3

Slika 12. Analiza spojeva primjenom otpornosti zavara prema Eurokodu 3; a) HS1, b) HS2, c) HS3

2.7. Crack Propagation Analysis Using Fracture Mechanics / *Analiza propagacije pukotine korištenjem mehanikom loma*

To estimate the fatigue life of a component accurately, it is necessary to simulate cracked growth once fracture initiation has occurred, as this has a large impact on the remaining life of the structure of interest. In this sense, the foundations of fracture mechanics give a good platform to examine crack progression behavior during the loading cycle.

In this investigation, cracks are introduced at the previously reported hotspot locations – HS1, HS2, and HS3 – within the fillet-welded T-joints of the oil tanker. Creating cracks makes it feasible to mimic the propagation of the precisely produced crack under cyclic tensile stress. Consequently, it gives a more thorough perspective of the fatigue process after the onset of failure.

Paris's Law provides a fundamental empirical relationship in fracture mechanics that describes the crack growth rate under cyclic loading conditions. It is particularly useful for predicting the progression of fatigue cracks in materials subjected to repetitive stress cycles. The law is expressed mathematically as:

$$\frac{da}{dN} = C(\Delta K)^m \tag{6}$$

where $\frac{da}{dN}$ represents the crack growth rate per cycle, C and m are material-specific constants obtained experimentally, and ΔK is the stress intensity factor range experienced during a loading cycle.

For this study C is considered as 2.60×10^{-11} and m as 2.75. By integrating Paris's Law over the crack length from the initial size a_i to the critical size a_c the total number of cycles to failure N_f can be estimated:

$$N_f = \int_{a_i}^{a_c} \frac{da}{C(\Delta K)^m} \tag{7}$$

The FRANC 2D (Fracture Analysis Code in Two Dimensions) software is used to simulate the crack propagation behavior and apply Paris's Law appropriately as shown in Figure 13, Figure 14 and Figure 15.

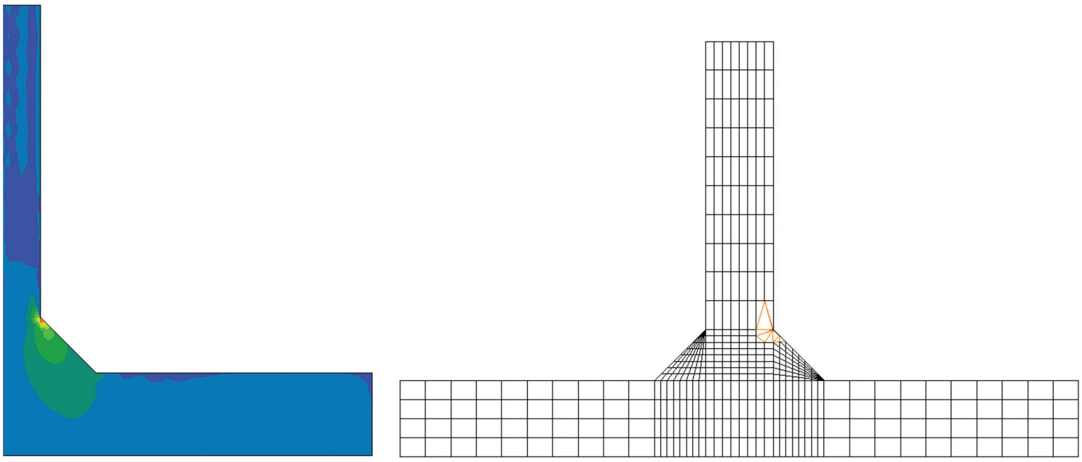


Figure 13 Stress concentration at the weld toe and crack initiation at the location of stress concentration
Slika 13. Koncentracija naprezanja na vrhu zavara i početak pukotine na mjestu naprezanja

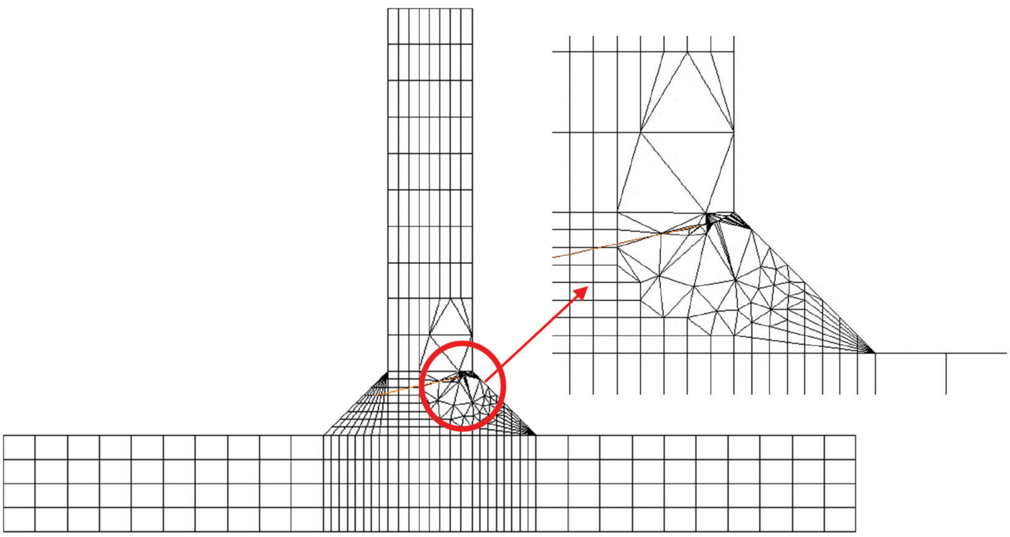


Figure 14. Crack propagation
Slika 14. Propagacija pukotine

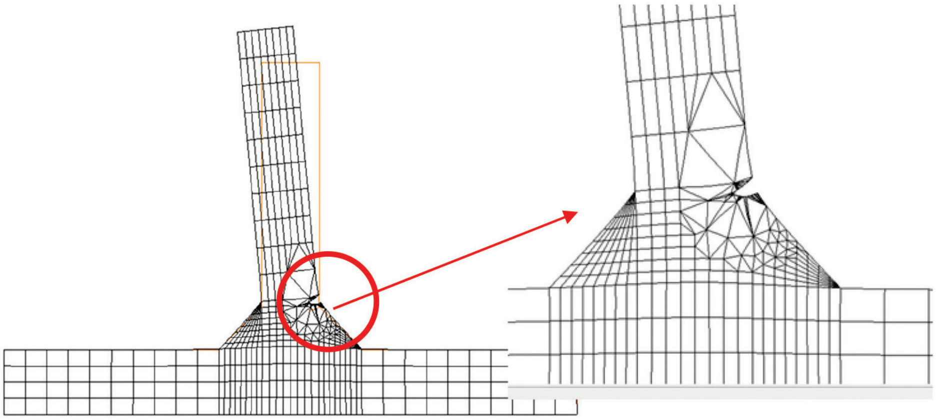


Figure 15 Deformed structure after crack propagation
Slika 15. Deformirana struktura nakon propagacije pukotine

3. RESULT / *Rezultat*

Table 3 summarizes the hotspot stress estimated and the corresponding number of cycles from all the approaches adopted in this study. The comparison amongst the findings from different approaches are shown from Figure 16 to Figure 18.

Eurocode 3 results showed fatigue lives of 0.5 × 10^6, 0.75 × 10^6, and 1.0 × 10^6 cycles for HS1, HS2, and HS3, respectively. The lower fatigue life predictions provided by Eurocode 3 can primarily be attributed to its conservative design philosophy, which emphasizes safety and reliability in engineering structures. As a benchmark, Eurocode incorporates a more comprehensive safety margin than other codes, considering potential variations in load conditions, material properties, and weld geometry.

Table 3 Hotspot stress and the corresponding number of cycles
Tablica 3. Naprezanje žarišne točke i odgovarajući broj ciklusa

Hotspot location	Analysis using ship's design load		Fracture Mechanics Approach	FAT 90 Curve	Analysis using weld's design resistance according to Eurocode	
	Hotspot stress (MPa)	Number of cycles			Hotspot stress (MPa)	Number of cycles
HS1	89.4	2.84×10^6	2.60×10^6	2.03×10^6	140.16	0.5×10^6
HS2	100.66	1.43×10^6	1.20×10^6	1.41×10^6	124.74	0.75×10^6
HS3	115.67	1.0×10^6	1.0×10^6	0.94×10^6	111.48	1.0×10^6

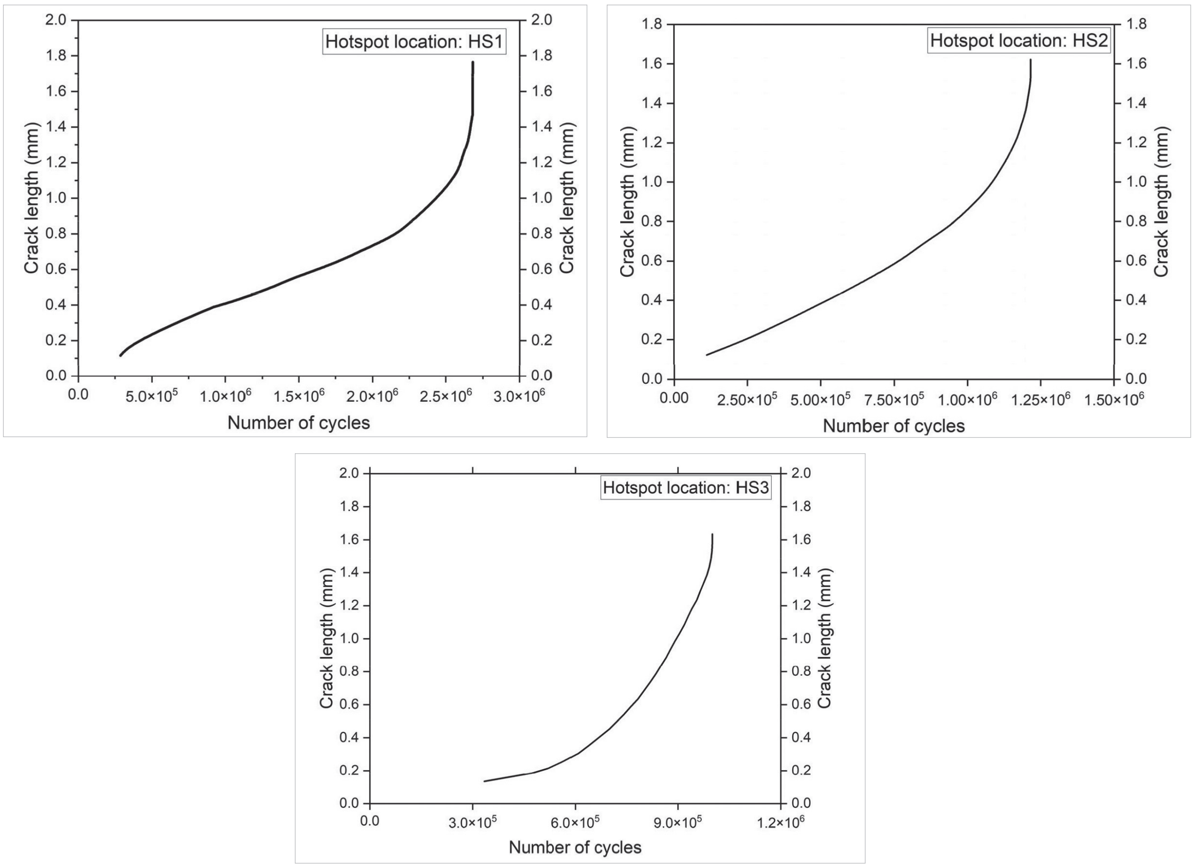


Figure 16 Crack length vs number of cycles curve using Paris law
Slika 16. Krivulja duljine pukotine u odnosu na broj ciklusa korištenjem Pariškim sporazumom

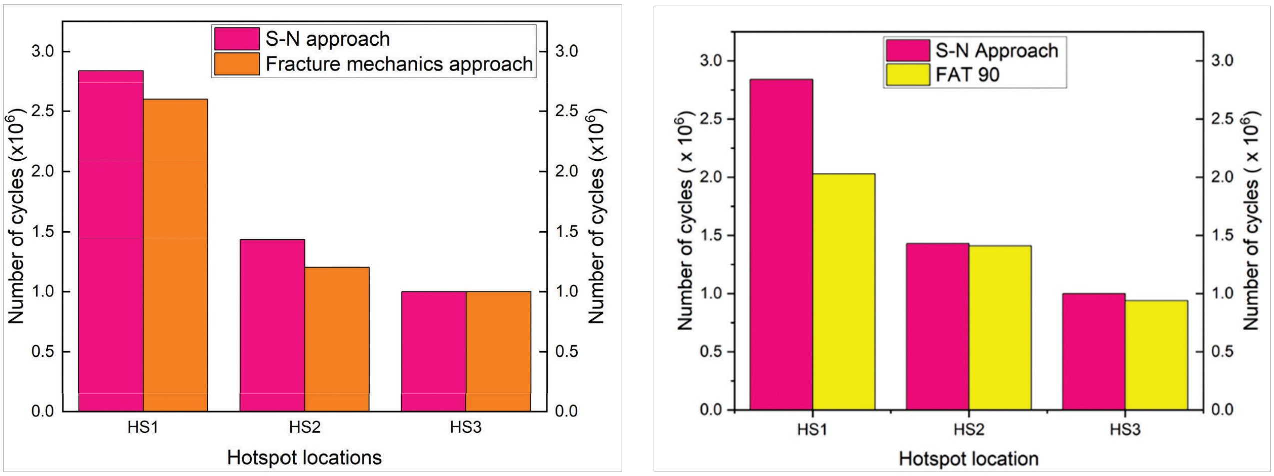


Figure 17 Comparison of the number of cycles predicted using S-N approach with fracture mechanics and FAT 90

Slika 17. Usporedba broja ciklusa predviđenih korištenjem S-N pristupom s mehanikom loma i FAT 90

Predicted fatigue lives using fracture mechanics approach are 2.6 × 10^6, 1.2 × 10^6, and 1.0 × 10^6 cycles for HS1, HS2, and HS3, respectively as shown in Figure 16. The comparison with the fracture mechanics approach and FAT 90 design curve is shown in Figure 17.

4. DISCUSSION / *Rasprava*

The trends identified in both the S-N method and fracture mechanics strongly support the methodologies employed in this study. Each approach offers valuable insights into material behavior under stress, yet there is a notable discrepancy in the results obtained from the two methods as illustrated in Figure 17.

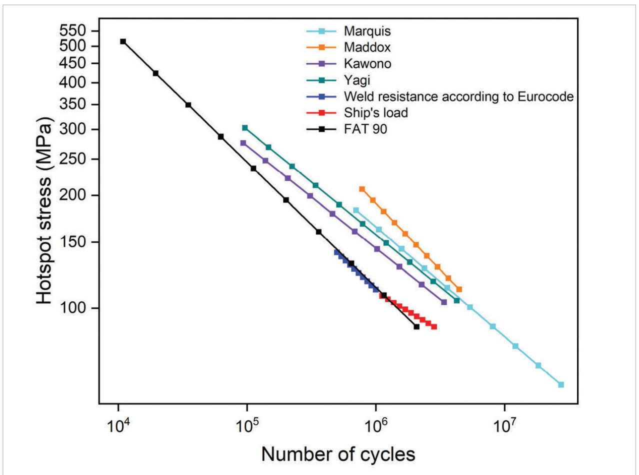
This variation can likely be traced back to the inherent simplifications present in the S-N approach. The S-N technique, which stands for stress-number of cycles, relies on empirical connections obtained from experimental data. While successful for certain applications, this approach does not adequately reflect the complexity of crack propagation under cyclic stress.

The fracture mechanics approach offers a comprehensive view, focusing on predicting material failure and fracture propagation dynamics. It analyzes factors like stress intensity and crack tip behavior, leading to a deeper understanding of material responses to varying loads over time. While both methods provide valuable insights, their differing foundational concepts account for the discrepancies observed in their results.

The comparison of the welding joints' fatigue life assessment, the number of cycles to failure predicted from the ship's design load analysis slightly varied while comparing with the FAT 90 curve at the hotspot locations which is visible from Figure 17. Results for HS1 showed a rise in fatigue life of 2.84×10^6 cycles, which was slightly about 2.46% bigger than the FAT 90 value estimated at 2.03×10^6 cycles. For HS2, the estimated fatigue life is 1.43×10^6 cycles, only 1.4% higher than the FAT 90 value, which is 1.41×10^6 cycles. At HS3, the count is 1.00×10^6 cycles, while that at FAT 90 is 0.94×10^6 cycles, corresponding to a difference of 6.4%.

The comparison illustrated in Figure 18 shows that the predicted fatigue lives from the current study fall within the general range of existing experimental results of other researchers [23]. The FAT 90 curve and Eurocode based weld resistance serves as conservative baseline. The results from the ship's design load shows noticeably higher fatigue life, i.e., approximately 5 million cycles at hotspot stresses below 100 MPa, closely aligning with the experimental results.

While the simulation follows a similar trend to the experimental data, some variation is evident. Marquis dataset, for example indicates lower fatigue lives at higher stress level of around 300 MPa compared to the current model. These discrepancies are likely due to differences in experimental setups, material microstructures, weld quality and residual stress effects which are difficult to fully replicate in numerical simulations. In addition, the environmental and surface condition effects can impact fatigue behavior which are not explicitly modeled in this study. Despite these differences, the overall agreement between the simulation and experimental curves supports that the developed methodologies are effectively designed to address the diverse goals of this research.



Slika 18 Comparison of hotspot stress and number of cycles with experimental data

Slika 18. Usporedba žarišnog naprezanja i broja ciklusa s eksperimentalnim podacima

5. CONCLUSION / *Zaključak*

This research evaluates the fatigue strength and lifespan of welded joints in marine structures by integrating hotspot stress analysis with fracture mechanics per Eurocode 3. It confirms the hotspot stress method's reliability for assessing fatigue failure and identifying stress concentration points while accurately predicting fatigue life based on experimental data. The study also explores crack propagation mechanisms in marine environments, supporting Eurocode 3's conservative predictions. The proposed framework calls for specific fatigue design rules to improve maintenance efficiency and operational performance, ensuring the safety and integrity of critical welded joints in maritime applications.

The key points that have been revealed through this study are summarized as below:

1. Identified the hotspot locations by conducting global and local analysis
2. Predicted fatigue life of the hotspots using both the S-N approach and fracture mechanics principles with minor deviation
3. The predicted lifespans exhibit consistency with experimental data and Eurocode 3 standards
4. Demonstrated the novel application of Eurocode 3 for marine structures, providing a unified framework for fatigue evaluation with global and local stress
5. Design load generates lower stress in S-N approach compared to Eurocode's conservative limit which eventually validates structural safety and highlights the optimization margin.
6. The importance of considering crack propagation in fatigue analysis is revealed through the shorter fatigue life predicted in fracture mechanics approach.

In spite of the contribution of this study to significantly enhance the understanding of the fatigue strength and life of fillet welded connections, it surfaces some limitations. As it is currently focusing on certain joint type and loading conditions, it may limit the wide applicability of the findings. Moreover, the experimental data could restrict the general applicability across different operating conditions. This research can be extended further by considering different weld joints, environmental factors loading scenario and implication of Eurocode 3 for reliability and effectiveness. Overall, the study proposes a holistic approach to assess the marine structure on the way to ensure safety in maritime applications.

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