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SAFETY EVALUATION OF MOORING CHAINS UNDER TENSION AND BENDING MOMENT CONSIDERING RATCHETTING BEHAVIOUR

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ABSTRACT

This study aims to investigate the plastic behaviour of a mooring chain under extreme tensile loading conditions using nonlinear finite element analysis. The plastic response of mooring chains is crucial for maintaining structural integrity under repeated environmental loads. The analyses were performed under cyclic tension and cyclic bending to evaluate the evolution and stability of the plastic behaviour of an R3-grade mooring chain with a nominal diameter of 100 mm. The plastic material properties adopted in the analysis were defined using the Ramberg–Osgood relationship. For cyclic tension, the load amplitude was gradually reduced based on the break load, and the results indicated that stable plastic behaviour was achieved at approximately 80% of the break load, while a conservative limit of 70% or lower is recommended for safe operation. Under cyclic in-plane bending (IPB) and out-of-plane bending (OPB), the accumulated plastic strain increased with the tension angle, and the OPB produced slightly higher deformation than the IPB. At a tension angle of 3°, ratchetting behaviour was observed, indicating that small angular displacements under high tensile forces can still induce progressive plastic deformation. The findings highlight the importance of considering ratchetting and shakedown phenomena in the structural design and safety assessment of mooring chains subjected to extreme cyclic loads.

Keywords: Mooring chain, Extreme cyclic load, Shakedown behaviour, Ratchetting behaviour

1. INTRODUCTION

Floating offshore structures have garnered increasing attention in recent years due to their applicability in deepwater environments and renewable energy development. These structures are continuously subjected to environmental loads, such as waves and wind, making the integrity of their mooring systems a critical factor in overall structural safety. Among the various components of a mooring system, mooring chains serve as fundamental elements that support floating structures by resisting external forces and maintaining position.

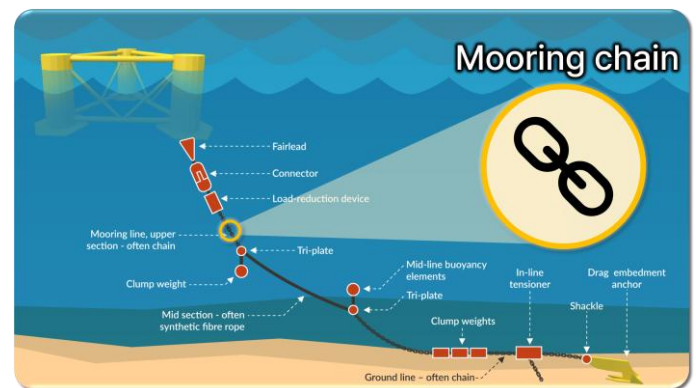


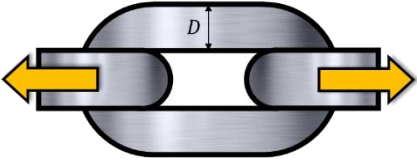
FIGURE 1: ILLUSTRATION OF A MOORING SYSTEM SUPPORTING A FLOATING OFFSHORE STRUCTURE [1]

Mooring chains function as primary structural members designed to withstand tensile loads. The IACS provides empirical formulas [2] for estimating the break load and proof load of mooring chains subjected to tensile loads. The break load refers to the load at which structural failure occurs, resulting in a

loss of capacity. The proof load, on the other hand, is applied prior to deployment to verify the structural integrity of the chain, typically corresponding to approximately 66% to 70% of the break load.

Table 1 presents the material properties associated with the five material grades (R3, R3S, R4, R4S, R5) adopted in the IACS standard [2], along with the empirical formulas for evaluating the break load and proof load of studless mooring chains for each grade. The empirical formulas are expressed in terms of the nominal diameter D and a multiplier α where the values of the multipliers for break load and proof load vary depending on the material grade.

TABLE 1: IACS EMPIRICAL FORMULAS FOR BREAK LOAD AND PROOF LOAD OF STUDLESS MOORING CHAINS FOR DIFFERENT MATERIAL GRADES [2]

Schematic of a studless chain under tensile loading					
					
Material grade	R3	R3S	R4	R4S	R5
Yield stress [MPa]	410	490	580	700	760
Tensile strength [MPa]	690	770	860	960	1000
Elongation [%]	17	15	12	12	12
Formula	$\alpha \times D^2 \times (44 - 0.08D)$				
Break load [kN]	$\alpha = 0.0223$	$\alpha = 0.0249$	$\alpha = 0.0274$	$\alpha = 0.0304$	$\alpha = 0.0320$
Proof load [kN]	$\alpha = 0.0148$	$\alpha = 0.0174$	$\alpha = 0.0192$	$\alpha = 0.0213$	$\alpha = 0.0223$

Meanwhile, mooring chains under tension may also experience bending moments due to the inclination of the tensile force. Choung and Han [3] proposed a calculation methodology for evaluating the in-plane bending (IPB) and out-of-plane bending (OPB) of mooring chains under various tension angles. Using this method, Choung and Lee [4] measured the hotspot stress and stress concentration factor (SCF) induced by bending moments and evaluated the corresponding fatigue performance. In addition, Kim [5] analysed the ultimate strength state (ULS) of mooring chains under bending loads to evaluate their structural performance under extreme conditions.

While established criteria exist for ultimate limit states under monotonic loading, there is a relative absence of design guidance for extreme cyclic loads that may induce plastic deformation and progressive collapse. Figure 2 shows the various plastic behaviours that can occur in a mooring chain under cyclic loading after the proof load has been applied.

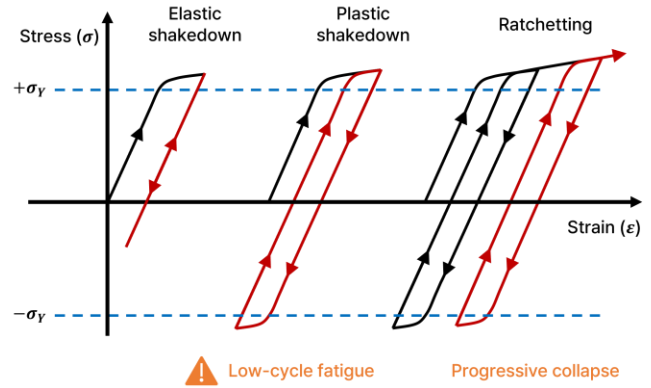


FIGURE 2: PLASTIC BEHAVIOUR TYPES UNDER CYCLIC LOADS [6]

When a proof load is applied, the stress typically exceeds the yield stress, resulting in the occurrence of plastic strain. Under service loading conditions, the structure returns to elastic behaviour after initial yielding [7], a response is referred to as elastic shakedown behaviour. The present study evaluated the plastic behaviour of mooring chains subjected to extreme tensile loads exceeding the proof load. A structure is considered to exhibit stable behaviour when it maintains the elastic shakedown state, even if additional plastic strain occurs during the initial few load cycles.

However, when the load amplitude exceeds a certain level, unstable behaviours such as plastic shakedown or ratchetting may occur [8]. Plastic shakedown refers to a condition in which the total plastic strain does not accumulate, but localised plastic deformation repeatedly develops, leading to low-cycle fatigue failure [6]. Ratchetting represents the accumulation of plastic strain under cyclic loading that leads to progressive collapse, making it highly undesirable and should be strictly avoided in design [6].

In recent years, the characteristics of plastic behaviour have increasingly been considered in structural integrity assessments of offshore structures [9, 10]. Relatively few studies, however, have focused on the reliability of chains under high cyclic load amplitudes capable of causing plastic deformation. Therefore, the present study focused on analysing the plastic behaviour of mooring chains subjected to extreme cyclic loading conditions. First, the plastic behaviour of the chain was analysed under cyclic tensile loads exceeding the proof load. In addition, the plastic responses induced by cyclic IPB and OPB were examined while the chain was subjected to a tensile load equivalent to the proof load. Nonlinear finite element analyses were performed to obtain the numerical solutions under various loading conditions, and the progression of plastic strain was evaluated using the plastic strain magnitude (PEMAG). The evolution of plastic strain magnitude was analysed to distinguish among elastic shakedown, plastic shakedown, and ratchetting behaviours. In cases where elastic shakedown was observed, the number of cycles required for the plastic strain to stabilise was also examined. It is expected that this study will provide practical

insights into evaluating the plastic stability of mooring chains under extreme environmental conditions, such as hurricanes and tsunamis.

2. RESEARCH METHODOLOGY

The present study focused on analysing the plastic behaviour of studless mooring chains subjected to extreme cyclic tensile loads as well as cyclic in-plane bending (IPB) and out-of-plane bending (OPB) conditions. The overall procedure adopted in this study is illustrated in the flow chart shown in Fig. 3.

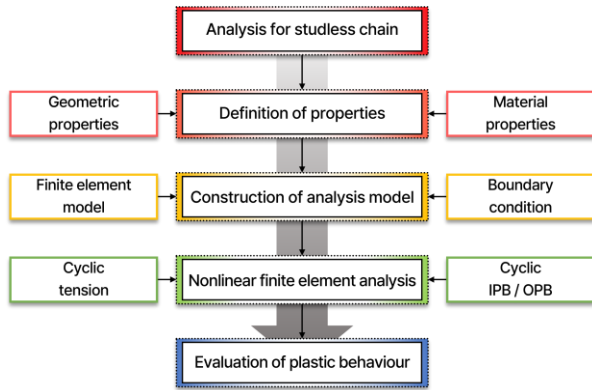


FIGURE 3: OVERALL FLOW CHART OF THE PRESENT STUDY

First, the geometric properties of the studless chain were determined based on the nominal diameter and standard geometry of the chain. The material grade was then selected, and material properties, including strain hardening, were defined. Based on this information, a finite element model was constructed, and appropriate boundary conditions were applied. Nonlinear finite element analyses (NLFEA) were subsequently performed under three loading conditions: cyclic tensile loads exceeding the proof load, cyclic IPB and cyclic OPB loads applied under a tensile load equivalent to the proof load.

2.1. Definition of Geometric and Material Properties

Figure 4 shows the geometry of the studless chain used in this study. The cross-section of each chain link is circular, and its overall geometry follows a horizontal-to-vertical ratio of $6D$ to $3.35D$, where D is the nominal diameter [11]. In this study, a nominal diameter of 100 mm was applied.

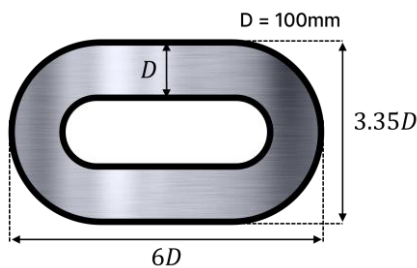


FIGURE 4: GEOMETRIC PROPERTIES OF THE STUDLESS CHAIN IN THE PRESENT STUDY [11]

Figure 5 presents the fitted stress–strain curve for the R3 grade material adopted in the present study, obtained using the Ramberg–Osgood equation [12]. The Ramberg–Osgood constants α and n were calibrated to match the yield stress, tensile strength, and elongation of the R3 grade, summarised in Table 1.

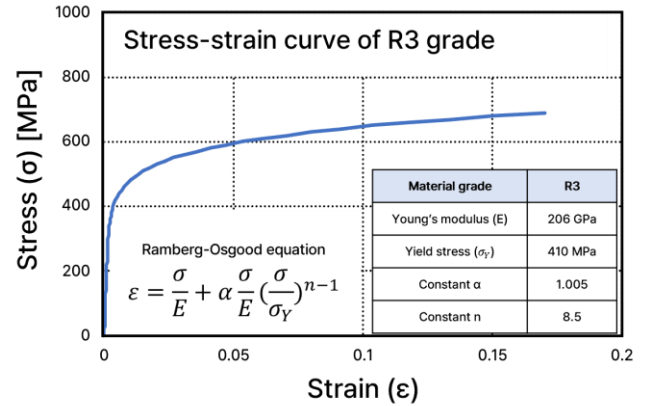


FIGURE 5: MATERIAL PROPERTIES OF THE STUDLESS CHAIN IN THE PRESENT STUDY

2.2. Construction of Analysis Model

Based on the defined geometric and material properties, finite element models were constructed. Figure 6 shows the developed analysis model, which consists of a three-link configuration composed of a full link in the centre and two half links at both ends. The finite element modelling and numerical analyses in this study were performed using the commercial finite element analysis software ABAQUS (Version 2019) [13].

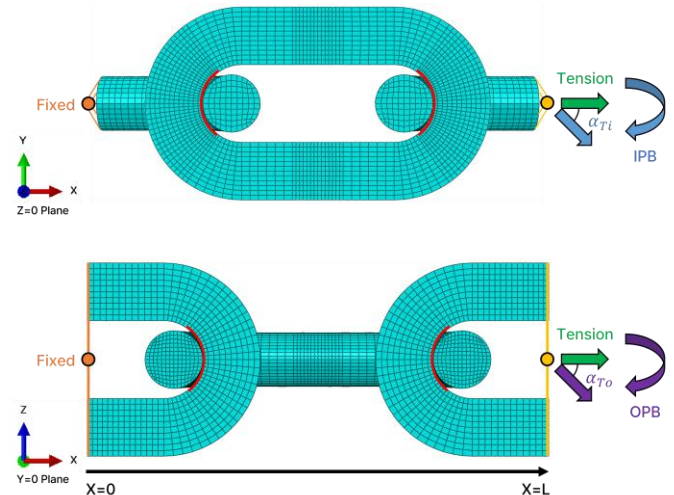


FIGURE 6: FINITE ELEMENT MODEL USED IN THE PRESENT STUDY

Two half models were constructed along the $z = 0$ and $y = 0$ planes, respectively, and symmetric boundary conditions were applied to each plane. The upper model captured the IPB

behaviour, and the lower model captured the OPB behaviour. The total model length in the x-direction was denoted as L . Control points were placed at the centroids of the cross sections at $x = 0$ and $x = L$, and tie constraints were applied through kinematic coupling between each control point and the respective cross section. The control point located at $x = 0$ was fully constrained with six degrees of freedom (DOFs) to define a fixed boundary condition, while the control point at $x = L$ was subjected to tensile loads. When a tension angle is introduced, frictional contact between the links induces either IPB or OPB behaviour. The tension angle causing IPB is denoted as α_{Ti} , while that causing OPB is denoted as α_{To} .

Table 2 provides detailed information on the finite element model, including the element data, contact parameters, and nonlinear analysis settings.

TABLE 2: DETAILED INFORMATION FOR THE FINITE ELEMENT MODEL USED IN THE PRESENT STUDY

Element data	
Element type	C3D8R
Number of defined elements	18,720
Number of internal elements generated for contact	15,432
Number of total elements	34,152
Contact parameters	
Tangential behaviour	$C_{friction} = 0.3$
Normal behaviour	Hard contact
Nonlinear analysis parameters	
Large deformation	Yes
Stabilisation factor	0.0002

The analysis models were discretised using 8-node linear brick solid elements with reduced integration (C3D8R). A total of 34,152 elements were generated, including those automatically created for the contact interfaces. For the contact definition, a hard contact formulation was applied in the normal direction, ensuring no interpenetration between the contact surfaces. The tangential behaviour was defined using a friction coefficient of 0.3, considering seawater conditions in accordance with the Bureau Veritas (BV) guidelines [14]. However, it should be noted that the friction coefficient may vary depending on surface conditions such as corrosion and contact pressure. Although the most commonly adopted value was used in the present study, the influence of varying friction coefficients will be investigated in future work.

To account for geometric nonlinearity, large deformation effects were included in the analysis. In addition, automatic stabilisation with a small stabilisation factor of 0.0002 was introduced in the nonlinear static analysis to improve convergence associated with contact nonlinearity.

2.3. Analysis for Mooring Chain under Cyclic Loads

Using the constructed finite element models, nonlinear finite element analyses were performed to investigate the behaviour of

mooring chains under cyclic loading conditions. The cyclic loading conditions considered in this study included cyclic tension and cyclic moment (IPB or OPB).

2.3.1. Cyclic Tension Condition

Figures 7 illustrates the applied load history for cyclic tension condition.

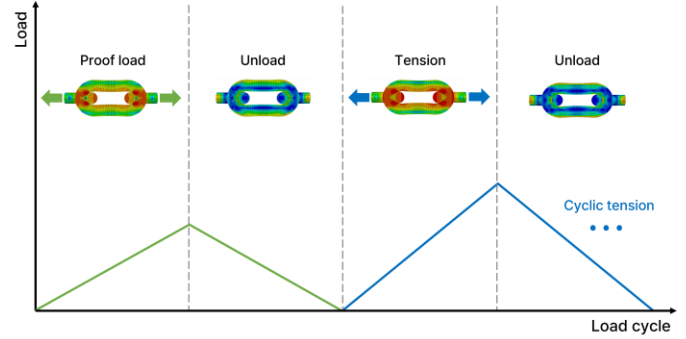


FIGURE 7: APPLIED LOAD HISTORY UNDER CYCLIC TENSION

Since the mooring chain is subjected to a proof load during the manufacturing stage, a tensile load corresponding to the proof load calculated from Eq. (1) [2] for the R3 grade with a diameter of 100 mm was applied and subsequently unloaded.

$$\text{Proof load} = 0.0148 \times D^2 \times (44 - 0.08D) = 0.0148 \times 100^2 \times (44 - 0.08 \times 100) = 5328 \text{ kN} \quad (1)$$

It should be noted that, as a half model was used in this study, only half of the actual load was applied to account for symmetry. Progressive plastic strain is expected to occur under tensile loads exceeding the proof load. Therefore, in this study, the break load of the chain was calculated using Eq. (2) [2], representing the maximum tensile capacity. Subsequently, cyclic tensile loads were applied with decreasing load amplitude from the break load down to the proof load.

$$\text{Break load} = 0.0223 \times D^2 \times (44 - 0.08D) = 0.0223 \times 100^2 \times (44 - 0.08 \times 100) = 8028 \text{ kN} \quad (2)$$

2.3.2. Cyclic Moment Condition

Figures 8 illustrates the applied load history for cyclic moment condition. Similarly, the proof load was first applied to the chain, followed by the introduction of pretension. When a tension angle was induced by the pretension, IPB or OPB moment was generated. For the cyclic moment, the tension angle was alternately applied at a fixed inclination and then returned to the initial parallel tension direction to simulate the repeated bending behaviour. Since the accumulation of plastic strain under cyclic moments is expected to occur when sufficient pretension is applied, the pretension magnitude was assumed to be equal to the proof load in this study.

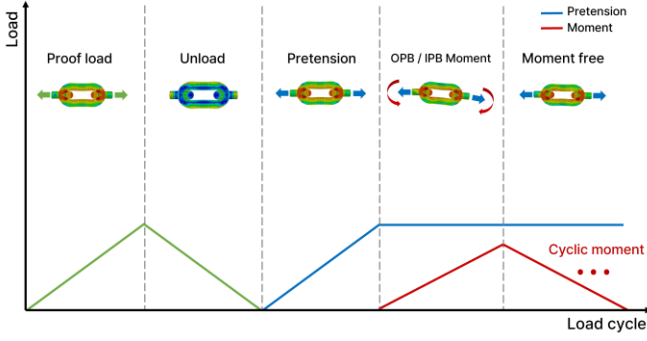


FIGURE 8: APPLIED LOAD HISTORY UNDER CYCLIC MOMENT

When a tension angle is generated, it is necessary to calculate the moment applying on the chain. In this study, the moment was evaluated using the direct tension approach (DTA) proposed by Choung and Han [3]. Figure 9 illustrates a schematic of the mooring chain subjected to IPB induced by a tension angle.

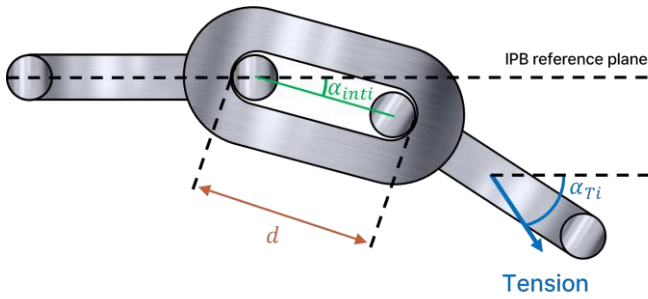


FIGURE 9: SCHEMATIC OF MOORING CHAIN SUBJECTED TO IPB INDUCED BY TENSION ANGLE [4]

The tension angle between the applied tensile load with a magnitude of T and the reference plane is defined as α_{Ti} , and the inter angle of the central link with respect to the reference plane is defined as α_{inti} . The distance between the inner contact points of the adjacent links is denoted as d . Based on these definitions, the IPB moment acting on the central link is calculated using Eq. (3). Similarly, the OPB moment is obtained using the same principle using the tension angle α_{To} and inter angle α_{into} , as shown in Eq. (4).

$$M_{IPB} = T \times d \times \sin(\alpha_{Ti} - \alpha_{inti}) \quad (3)$$

$$M_{OPB} = T \times d \times \sin(\alpha_{To} - \alpha_{into}) \quad (4)$$

2.4. Evaluation of Plastic Behaviour

Based on the numerical static equilibrium solutions obtained from the nonlinear finite element analyses, the evolution of plastic strain was analysed to evaluate the stability of plastic behaviour. This section describes the occurrence of plastic

deformation and the evaluation indicator adopted to quantify it. Figure 10 illustrates the mechanism of plastic strain development in a 1D stress–strain relationship.

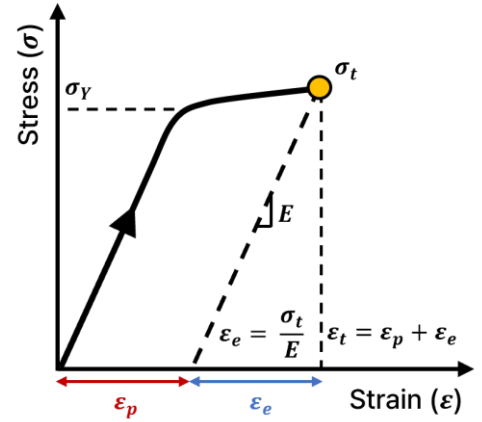


FIGURE 10: MECHANISM OF PLASTIC STRAIN DEVELOPMENT IN A 1D STRESS–STRAIN RELATIONSHIP [15]

When the applied stress exceeds the yield stress, plastic strain occurs, leaving a permanent deformation. As shown in Fig. 10, if the total stress in the current state is denoted as σ_t , and unloading is assumed to follow the elastic slope with modulus E , the plastic strain ϵ_p remains as permanent deformation. At this stage, the total strain ϵ_t can be expressed as the sum of the elastic strain ϵ_e that is recovered during unloading and the plastic strain ϵ_p .

When this mechanism is extended to three dimensions, the same strain decomposition can be applied using the stress and strain tensors. However, it is not straightforward to intuitively evaluate the plastic strain from the tensor components themselves, because each tensor component represents deformation in a specific direction, and the overall plastic deformation state depends on the combined effects of all components. Therefore, scalar indicators such as equivalent plastic strain (PEEQ) or plastic strain magnitude (PEMAG) are commonly used to quantify the plastic strain in a unified manner. Under proportional loading conditions, these two quantities are equivalent. In this study, PEMAG was adopted as the indicator of plastic strain, and it is calculated as a scalar quantity using the following expression:

$$\begin{aligned} \text{Plastic strain magnitude (PEMAG)} &= \sqrt{\frac{2}{3} \boldsymbol{\epsilon}^p : \boldsymbol{\epsilon}^p} \\ &= \sqrt{\frac{2}{3} \sum_{i=1}^3 \sum_{j=1}^3 \epsilon_{ij}^p \epsilon_{ij}^p} \end{aligned} \quad (5)$$

where $\boldsymbol{\epsilon}^p$ represents the plastic strain tensor.

In this study, the variation of PEMAG under cyclic loading was analysed. Figure 11 illustrates examples of the variation in PEMAG for different types of plastic behaviour. If PEMAG

converges to a stable value after a few cycles, the response is identified as elastic shakedown. If it fluctuates within a limited range, it is classified as plastic shakedown, whereas a continuous increase in PEMAG indicates ratchetting behaviour.

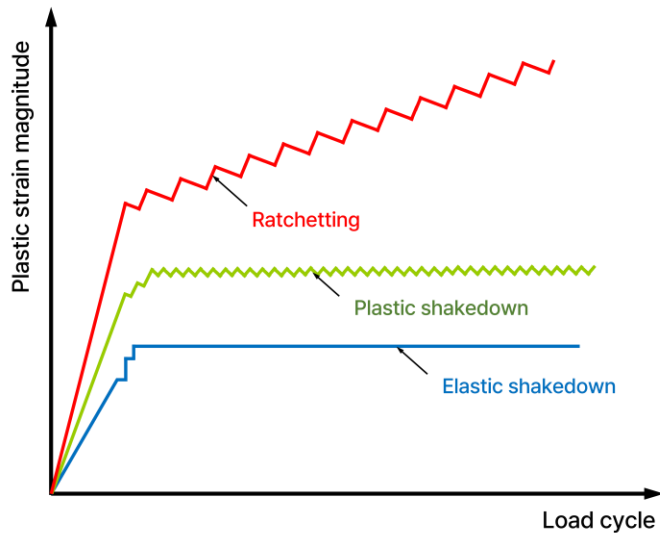


FIGURE 11: EXAMPLES OF PLASTIC STRAIN MAGNITUDE VARIATION FOR DIFFERENT TYPES OF PLASTIC BEHAVIOUR UNDER CYCLIC LOADING [16]

3. RESULTS AND DISCUSSION

The plastic behaviour of the mooring chain under cyclic tension, in-plane bending (IPB), and out-of-plane bending (OPB) loading conditions was analysed based on the nonlinear finite element results. The plastic strain magnitude (PEMAG) was used as a scalar indicator to evaluate the evolution and stability of plastic behaviour.

3.1. Plastic Behaviour of Mooring Chain under Cyclic Tension

Figure 12 shows the variation of PEMAG during 10 cycles of cyclic tension loading with a constant load amplitude after the proof load and unload. The tracked element corresponds to the one exhibiting the maximum PEMAG at the final load step. As illustrated in the contour plot in Fig. 12, the maximum plastic strain occurred on the side region near the link contact area.

The cyclic load amplitude was defined as a percentage of the break load calculated in Eq. (2) and was maintained constant throughout the loading cycles. When the applied tension reached the break load, the plastic strain increased rapidly, leading to structural collapse. At 90% break load amplitude, failure occurred after only the second load cycle. For the 85% break load amplitude, a progressive increase in PEMAG was observed, clearly indicating ratchetting behaviour that eventually led to failure. At the 84% break load amplitude, the response did not diverge but gradually increased in PEMAG throughout the 10 load cycles.

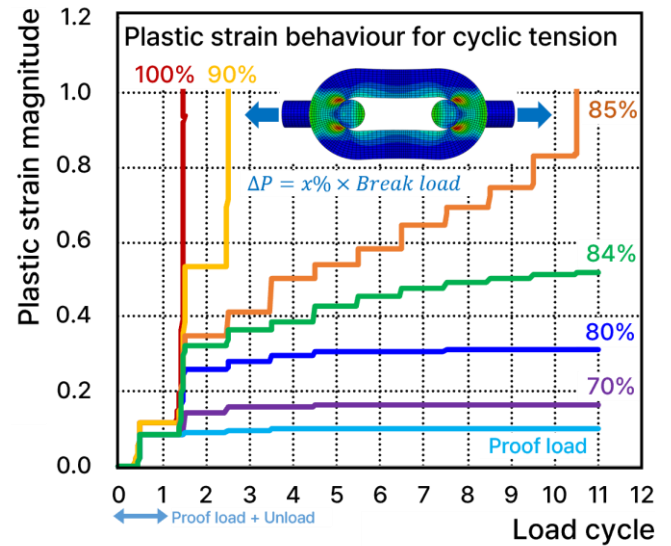


FIGURE 12: PLASTIC STRAIN MAGNITUDE VARIATION OF MOORING CHAIN UNDER CYCLIC TENSION

In contrast, when the load amplitude was reduced to 80% of the break load, the plastic strain stabilised and converged after several cycles, exhibiting elastic shakedown behaviour. Convergence was confirmed by verifying that the variation of PEMAG at the final loading step remained within 0.1% over successive cycles. Under the 70% break load and proof load amplitude conditions, the number of cycles required to reach elastic shakedown decreased further, and a stable plastic response was maintained thereafter.

From these results, it can be concluded that the R3 grade mooring chain with a nominal diameter of 100 mm achieved stability under cyclic tension with a load amplitude of approximately 80% of the break load. However, the corresponding plastic strain was significantly larger than that at the proof load, representing an extreme tensile condition that may not be acceptable for practical applications. Therefore, a conservative design approach is recommended, and the mooring chain should be used under low-cycle loading conditions, with plastic strain remaining below 20% and not exceeding approximately 70% of the break load.

3.2. Plastic Behaviour of Mooring Chain under Cyclic Moment

Figures 13 and 14 show the variation in PEMAG during 10 cycles of cyclic IPB and OPB moments after proof load, unloading, and pretension. In the analysis, the tension angle α_{Ti} or α_{To} was fixed at 3.0°, 2.0°, 1.0°, 0.5°, and 0.25°, respectively, and the cyclic moment was generated by repeatedly applying and releasing the inclined tension to return the chain to the parallel direction. Table 3 summarises the calculated IPB and OPB moments for each tension angle, obtained from the inter angle and the deformed length d using Eqs. (3) and (4) (see Fig. 9).

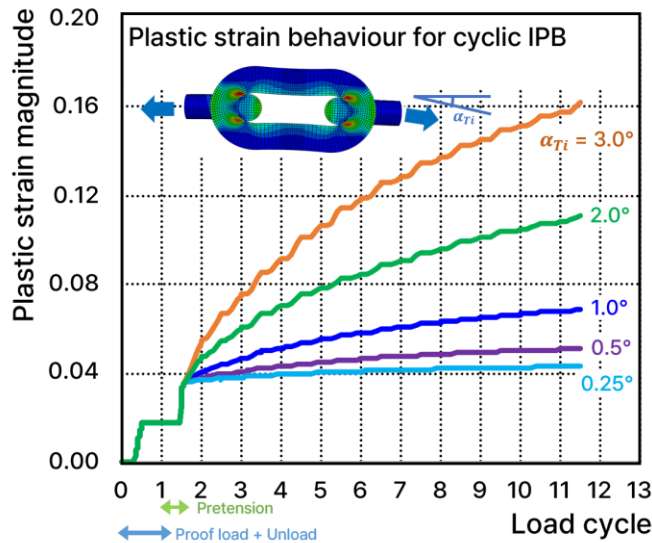


FIGURE 13: PLASTIC STRAIN MAGNITUDE VARIATION OF MOORING CHAIN UNDER CYCLIC IPB

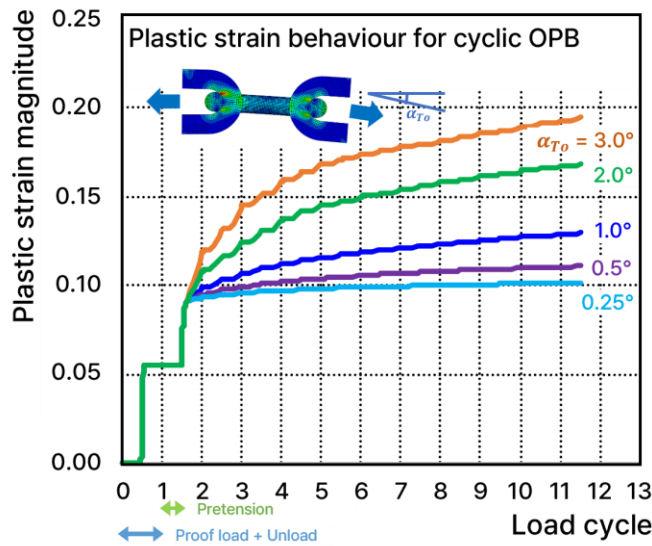


FIGURE 14: PLASTIC STRAIN MAGNITUDE VARIATION OF MOORING CHAIN UNDER CYCLIC OPB

Unlike the cyclic tension case, the element showing the maximum PEMAG at the final step varied depending on the magnitude of the applied moment and the load cycle. This occurred because, as the cyclic moment developed, the elements that initially had lower PEMAG values under the proof load experienced a progressive increase in plastic deformation, eventually surpassing the previous maximum after several loading cycles. Therefore, in this study, the results were analysed by tracking the element that exhibited the maximum PEMAG at the final loading cycle under the largest tension angle of 3°.

TABLE 3: CALCULATED MOMENTS CORRESPONDING TO EACH TENSION ANGLE

Results of inter angle and moment for IPB			
α_{Ti} [°]	α_{inti} [°]	d	IPB [Nm]
0.25	0.17	432.17	3340.60
0.50	0.33	432.23	6707.48
1.00	0.67	432.37	13090.78
2.00	1.38	432.64	24841.48
3.00	2.11	432.88	35651.95
Results of inter angle and moment for OPB			
α_{To} [°]	α_{into} [°]	d	OPB [Nm]
0.25	0.16	432.16	3683.19
0.5	0.32	432.26	7330.09
1.0	0.64	432.44	14371.10
2.0	1.33	432.89	27166.93
3.0	2.03	433.43	39234.00

At tension angles of 3° and 2°, PEMAG exhibited a distinct ratchetting behaviour, where plastic strain progressively accumulated with each loading cycle rather than stabilising after a few repetitions. This indicates that cyclic bending under such tension angles can cause irreversible strain accumulation even when the overall deformation per cycle appears relatively small. The progressive increase in PEMAG suggests that local yielding occurred repeatedly near the link contact region, leading to the accumulation of plastic strain over time.

When the tension angle was reduced to 1° or below, the variation of PEMAG between successive cycles decreased to within 0.1%, indicating convergence and stabilisation of the plastic response. This implies that even at intermediate tension angles between 1° and 2°, cumulative plastic strain may occur due to the generated secondary bending, particularly under sustained tensile loads close to the proof load. At the same tension angle, the OPB moment was slightly greater than the IPB moment because out-of-plane deformation induces additional torsional effects and a more complex contact stress distribution. Consequently, the plastic strain resulting from OPB loading was found to be more significant, indicating that out-of-plane bending can be more detrimental to the long-term structural stability of mooring chains.

These results indicate that, under tensile loading conditions comparable to the proof load, even a small inclination angle can induce progressive plastic strain accumulation in the mooring chain due to the bending moments generated at the inter-link contact regions. Therefore, under extreme conditions with high tensile forces, the influence of small angular displacements should be carefully considered in the structural design and safety assessment to prevent potential ratchetting or local failure of chain links during long-term service.

4. CONCLUSIONS

This study conducted nonlinear finite element analyses to evaluate the plastic behaviour of an R3-grade mooring chain

with a nominal diameter of 100mm under cyclic tension and cyclic moment loading. The findings of this study can be summarised as follows:

- Under cyclic tension, the mooring chain exhibited progressive plastic strain as the load amplitude, based on the break load, was gradually reduced. The results indicated that stable plastic behaviour was achieved at approximately 80% of the break load, while it is recommended that the load amplitude be limited to 70% or lower for safe operation.
- Under cyclic in-plane bending (IPB) and out-of-plane bending (OPB), the accumulated plastic strain increased with the tension angle. The OPB moments produced slightly higher magnitudes than the IPB moments at the same tension angle, leading to greater plastic strain. Ratchetting behaviour was clearly observed at a tension angle of approximately 3°, gradually transitioning to a stabilised plastic response as the tension angle decreased to between 1° and 2°. Therefore, under high-tensile loading conditions, the potential for ratchetting should be carefully considered in structural safety assessments.

Future work arising from the present study is as follows. The analyses were conducted for a specific material property and a single nominal diameter of the mooring chain. Therefore, further investigations considering different chain diameters, various material properties, and additional analysis parameters such as friction coefficients and boundary conditions are required to evaluate the influence of geometric, material, and modelling factors on the plastic behaviour and shakedown characteristics. In addition, ratchetting behaviour was observed under cyclic bending, but the number of cycles was limited because the applied tensile loads corresponded to an extreme condition equal to the proof load. A more extensive cyclic loading analysis is required to examine potential transitions to plastic or elastic shakedown behaviour. Furthermore, for practical offshore applications, it is necessary to establish a framework that links local chain analysis with global dynamic analysis. Future research will focus on incorporating the identified plastic behaviour characteristics into advanced computationally efficient analysis techniques [17] to ensure both accuracy and computational efficiency.

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