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BEYOND THE BREAKING POINT: INSIGHTS INTO DAMAGE ACCUMULATION FROM REPEATED IMPACTS ON STIFFENED SHIP GRILLAGES

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ABSTRACT

Naval vessels frequently operate in conditions that impose impact loads beyond their original design criteria, including ice-laden waters and collision-prone environments. This study examines the progressive damage accumulation in stiffened ship grillages subjected to repeated impacts, employing full-scale experimentation and numerical simulations to refine predictive methodologies for structural resilience. Using a custom-built double pendulum impact apparatus, five distinct impact scenarios were investigated to assess the transition from elastic shakedown, into pseudo-shakedown before leading to ratcheting and plastic collapse under higher energy loads. Results indicate that damage evolution is highly dependent on impact sequencing and spatial distribution, with non-coincident impact patterns leading to accelerated structural degradation compared to coincident strikes. The findings provide energy thresholds for damage progression, emphasizing a continued need for the study of adjacent and repeated impacts in damage evolution—something not captured in simpler specimen-level and quasi-static analyses.

KEYWORDS: Impact; Repeated impacts; Ratcheting; Structural response; Warship grillage.

INTRODUCTION

Naval structures are increasingly subjected to operational loads that extend beyond their original design constraints, with aging fleets facing prolonged service in high intensity theaters (Paik, 2003). While traditional fatigue assessments focus on high cycle loading effects, the progressive accumulation of plastic deformation under ultra-low cycle loading (ratcheting or ratchetting) remains a critical but underexplored aspect of structural assessment (Alsos and Amdahl, 2007) Analyzing multiple impact scenarios, the research identifies key transitions in structural response, offering insight into repeated impacts' influence on the structural resilience in built-up warship grillages. While extensive research has been conducted on isotropic, ductile material behavior under monotonic and cyclic loading, less attention has been given to the accumulation of plastic deformation in full-scale ship structures subjected to repeated, localized impacts and other built-up structures exposed to transient impact events and accumulated damage (Cho et al., 2014).

Early studies in ship structural integrity focused on static and quasi-static loading conditions, defining failure criteria based on yielding and ultimate strength considerations. However, as interest in ice-class and extended-service-life vessels has increased, there has been a shift toward recognizing the influence of ratcheting in ship structures (Abdel-Karim, 2009). Investigations by

Mansour et al., (1990) and Zhu et al., (2018) have highlighted the limitations of current design frameworks in accounting for the effects of repeated impacts. These studies suggest that traditional elastic-plastic design approaches may not fully describe the nonlinear accumulation of plastic strain, particularly in regions subjected to cyclic, localized impacts. The extent to which repeated impacts induce progressive structural degradation remains a key question in naval structural mechanics (Dong et al., 2019; Xu & Yue, 2006). Through a combined experimental and numerical approach, this research evaluates how impact sequencing contribute to structural deterioration.

RESEARCH CONTEXT AND OBJECTIVES

The response of naval structures to impact loading has been widely studied, particularly in the context of single-strike events. Prior research has established that ship structures can undergo both elastic and plastic deformation under impact loading (Jones, 2014). However, the long-term implications of sequential, non-coincident impacts (such as those encountered in ice-infested waters or combat scenarios) remain poorly understood. This study aims to investigate how damage accumulates in stiffened ship grillages subjected to repeated impacts and to characterize the progression. Using full-scale experimental data and finite element modeling, the objectives are to (1) identify damage mechanisms arising from sequential impacts, (2) evaluate structural degradation across multiple strikes, and (3) assess the predictive fidelity of numerical simulations against experimental benchmarks. The findings offer insight into failure evolution under repeated loads and contribute to the development of more resilient naval structures.

EXPERIMENTAL AND NUMERICAL APPROACHES TO REPEATED IMPACT ANALYSIS

Experimentation on repeated impact loading has primarily relied on drop-weight and pendulum impact tests, which offer controlled, repeatable conditions to assess response (Jones, 2014; Polocoșer et al., 2017). Pendulum-based impact testing provides a well-defined means of introducing localized, high-energy impacts, allowing for characterization of damage evolution in stiffened structures (Alam, 2012). Previous work by Zhu and Faulkner (2018) demonstrated that strain rate effects, strain hardening, and geometric stiffening play significant roles in determining impact response, yet their findings were largely limited to single-strike loading conditions.

Complementary to experimental methods, numerical simulations using finite element analysis (FEA) provide a means of extending observations to broader parametric studies. Explicit nonlinear FEA has been employed to model impact and indentation behaviors in ship structures (Paik et al., 2003; Xu & Yue, 2006). Simulations leverage advanced material models to approximate the complex interplay of strain accumulation, and load redistribution in stiffened panels. Recent studies have integrated nonlinear kinematic hardening (NLKH) models to better capture ratcheting effects in structural simulations (Paul, 2019). However, full-scale model validation remains limited, as most numerical studies rely on small-scale component testing (Paul, 2019).

PLASTICITY AND PROGRESSIVE DAMAGE IN SHIP STRUCTURES

The onset of plastic deformation in ductile materials is traditionally governed by yield criteria such as the von Mises and Tresca conditions, with strain-hardening behavior characterized by isotropic or kinematic hardening models (Chen & Han, 2012). While these models are well-established for monotonic loading, their applicability to multi-axial, cyclic impact conditions remains an active area of research. Experimental studies (Chen, 2005) have demonstrated that ship structures undergoing repeated impact loads exhibit behaviors beyond classical plasticity models, including:

- **Elastic shakedown** – initial plastic deformation stabilizes, and the structure subsequently responds elastically.
- **Plastic shakedown** – alternating plastic strains develop, leading to a stable cyclic response.
- **Progressive plastic accumulation (ratcheting)** – inelastic deformation increases with each cycle, leading to cumulative damage.
- **Instantaneous plastic collapse** – accumulated damage results in structural failure in fewer than 50 cycles.

While recognized that the mechanisms governing these behaviors are influenced by load sequence, impact energy, and strain path dependence (Dowling, 2007), the interaction of repeated impact loads with built-up ship structures remains insufficiently understood.

EXPERIMENTAL SETUP

The experimental campaign was conducted using a custom-built dual pendulum impact apparatus (Figure 1) designed to deliver controlled impact energies across a range of scenarios. The test setup consisted of two pendulum arms with mass units supported by rigid swing arms, ensuring minimal out-of-plane rotation during impact. The system was equipped with a braking mechanism to prevent multiple uncontrolled collisions, allowing discrete impact observations and measurements at varying energy levels. The test specimen consisted of a stiffened grillage representative of the port-side midship shell section of HMCS IROQUOIS, constructed from 5/16-inch mild steel with a yield strength of 420 MPa, the panel featured four transverse T-stiffeners spaced 610 mm apart. The grillage was secured using rigid boundary conditions ensuring that deflection and deformation were localized to the test specimen.

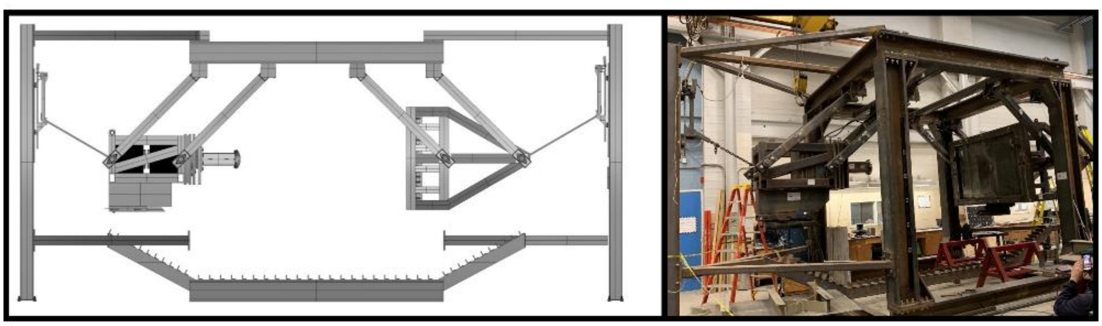


Figure 1. Dual pendulum apparatus (adapted from Robbins, 2020, incorporating data from Gagnon et al., 2015)

A rigid, spherical indenter fabricated from HS-100 steel (Figure 2, left) was used to apply impact loads. The indenter was designed to maximize energy transfer to the test specimen while minimizing modeling complexity in numerical simulations. Impact loads were delivered by releasing the pendulum arms from a predetermined angle, with an initial inclination of 50° selected to achieve sufficient impact energy for inducing plastic deformation.

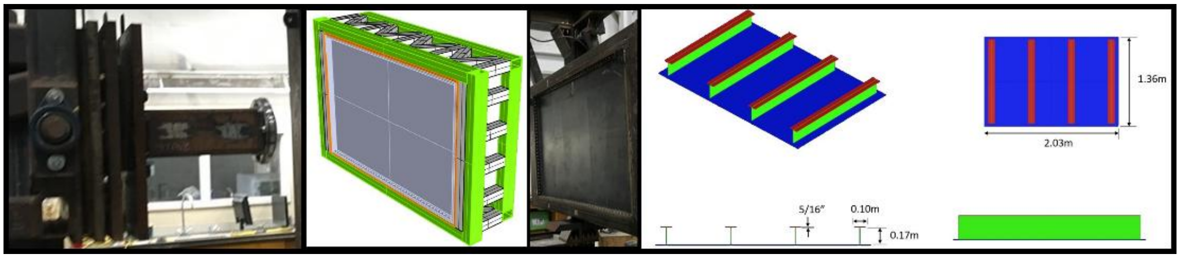


Figure 2. Spherical rigid indenter (left), Ring frame panel restraint (center) and numerical model geometry (right) (adapted from Robbins, 2020) incorporating data from Daley and Hermanski, (2009)

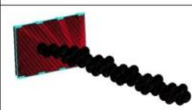
Load Scenario	Load Case Isometric View	Load Case Impact Pattern	Load Case Descriptor
1			Co-incident Indenter Strike
2			Rotational Clock-pattern Strike
3			Expanded Centralized Damage Area
4			Wave Pattern
5			Expanded Damage Area— Variation #1

Figure 3. Load case impact pattern summary (adapted from Robbins, 2020)

The study examined five distinct impact scenarios (Figure 3) to assess damage accumulation trends under different loading conditions. Instrumentation included high-speed cameras, FARO-brand coordinate measurement management systems for post-impact surface analysis, and strain gauges at critical locations to capture real-time deformation data. The test sequence involved up to four consecutive impacts per specimen, with deformation scanned and analyzed between each strike.

NUMERICAL MODELING & MATERIAL MODEL ASSUMPTIONS

Parallel to the experimental testing, an explicit dynamic formulation numerical model was built using LS-DYNA®, leveraging an explicit nonlinear finite element formulation to simulate impact responses. The material model incorporated a multi-linear kinematic hardening law, calibrated against uniaxial tensile test data. Model material validation was performed by comparing numerical deformation profiles with experimental measurements, as illustrated in Figure 4. The computational domain mirrored the experimental setup, with rigid boundary conditions replicating the bolted constraints to ensure deformation occurred within the grillage panel rather than the external supports. Although the numerical model successfully captured overall trends in plastic deformation, limitations such as the exclusion of strain rate effects, frictional losses, and damping influences suggest areas for future refinement.

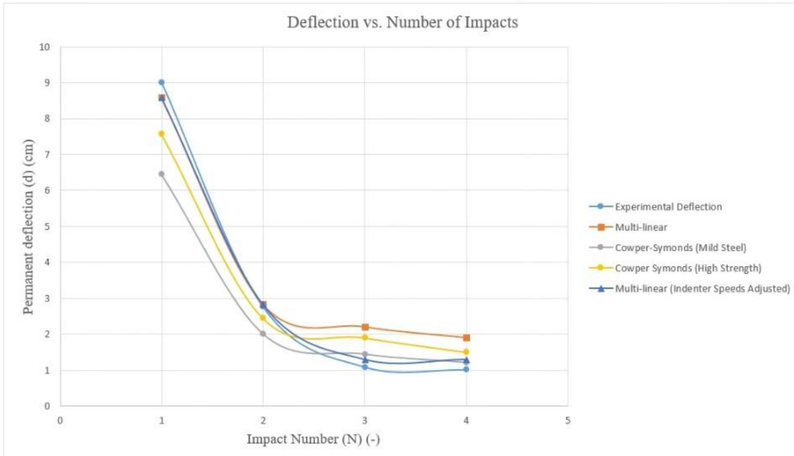


Figure 4. Permanent deflection vs. number of impacts for experimental and simulated grillage specimens under repeated loading. (adapted from Robbins, 2020).

To calibrate the material model used in the finite element simulations, uniaxial tensile tests were conducted on coupon specimens extracted from the same plate material used in the grillage. Figure 5 depicts the engineering stress-strain response for Specimen 3, representative of the base material. This curve informed the elastic modulus, yield strength, and post-yield behavior used in the plasticity definitions of the simulations. While Cowper–Symonds models were also explored for comparison, the multi-linear model based on these experimental results produced the best agreement with the deflection trends observed in testing.

MATERIAL MODEL SELECTION

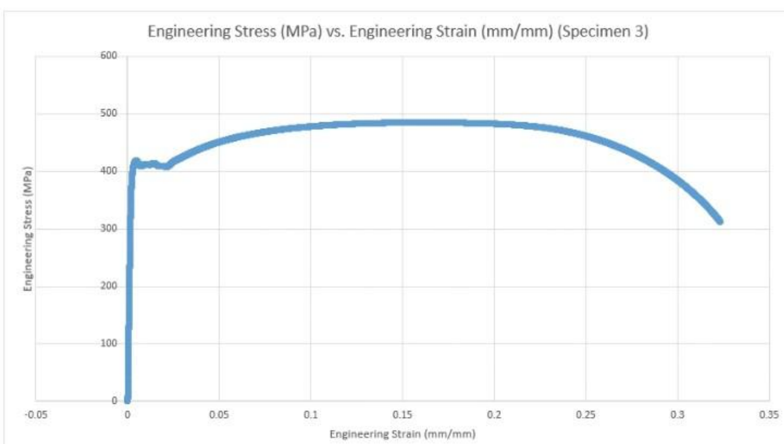


Figure 5. Engineering stress-strain curve for Specimen 3 of the grillage material, obtained from tensile coupon testing and used to inform the plasticity model for FEM simulations (adapted from Robbins, 2020).

The selected material model employed a multi-linear kinematic hardening law calibrated against uniaxial tensile test data. While NLKH models have demonstrated improved accuracy in predicting ratcheting behavior in cyclic loading scenarios, their application to repeated impact cases remains underexplored. Hardening model choice was driven by computational efficiency and experimental validation data availability. Strain-hardening behavior was incorporated based on steel properties fit to the yield curve of the test data depicted in Figure 5, with the model capturing progressive yielding and load redistribution following impact strikes. The grillage stiffeners and plating were meshed using quadrilateral shell elements optimized for computational stability. The selected mesh resolution was determined through a convergence analysis, ensuring sufficient refinement.

MODEL VALIDATION & COMPARISON WITH EXPERIMENTAL RESULTS

The numerical model's performance was validated by comparing simulated deformation patterns with physical test results. Figure 6 illustrates the correlation between simulated and experimentally observed panel deflections. The model captured key damage trends, including the depth of impact craters, buckling of stiffeners, and progressive strain accumulation over multiple cycles. Despite reasonable agreement, certain discrepancies were noted in strain localization near stiffener intersections, and a generalized overprediction of deformation response, suggesting that additional refinements, such as strain-rate dependent material modeling, could improve predictive accuracy. Friction and damping effects were omitted from the numerical model due to a lack of empirical validation data. However, these factors may influence strain distribution in real-world conditions, particularly in repeated impact scenarios where energy dissipation mechanisms play a role in damage evolution (Coffin, 1970).

Impact #	Accumulated Experimental Deflection (cm)	Relative change (%)	8-segement Multi-linear	Relative change (%)	8-segment Multi-linear (Cowper Symonds) C=40.4 P=5	Relative change (%)	8-segment Multi-linear (Cowper Symonds) C=3200 P=5	Relative change (%)	8-segment Multi-linear Differing (Indenter Speed Adjusted)	Relative change (%)
1	9.01	-	8.58	-	6.45	-	7.56	-	8.58	-
2	2.76	30.63263041	2.82	32.86713287	2	31.0077519	2.44	32.27513228	2.82	32.86713
3	1.09	39.49275362	2.2	78.0141844	1.44	72	1.9	77.86885246	1.3	46.09929
4	1.012	92.8440367	1.9	86.36363636	1.21	84.0277778	1.5	78.94736842	1.3	100
Total Deflection	**13.872**	-	**15.5**	-	**11.1**	-	**13.4**	-	**14**	-

Figure 6. A quantitative comparison of deflection error between the simulated and experimental profiles

RESULTS & DISCUSSION

The experimental and numerical results demonstrated a strong dependence of structural response on impact sequencing and spatial distribution. Three primary progression modes were observed: elastic shakedown, pseudo-shakedown, and ratcheting failure. Elastic shakedown occurred at low-energy impacts, resulting in minimal additional strain accumulation. Pseudo-shakedown emerged in intermediate-energy impacts, with strain accumulation slowing over multiple cycles. In contrast, ratcheting failure was observed in high-energy impacts, leading to structural degradation and eventual collapse. Figure 7 and Figure 8 illustrate the first load case impact study in graphical and qualitative visual form, respectively, and are representative of the progression modes observed across the impact studies. Table 1 summarizes the observed failure modes based on impact angles and energy levels.

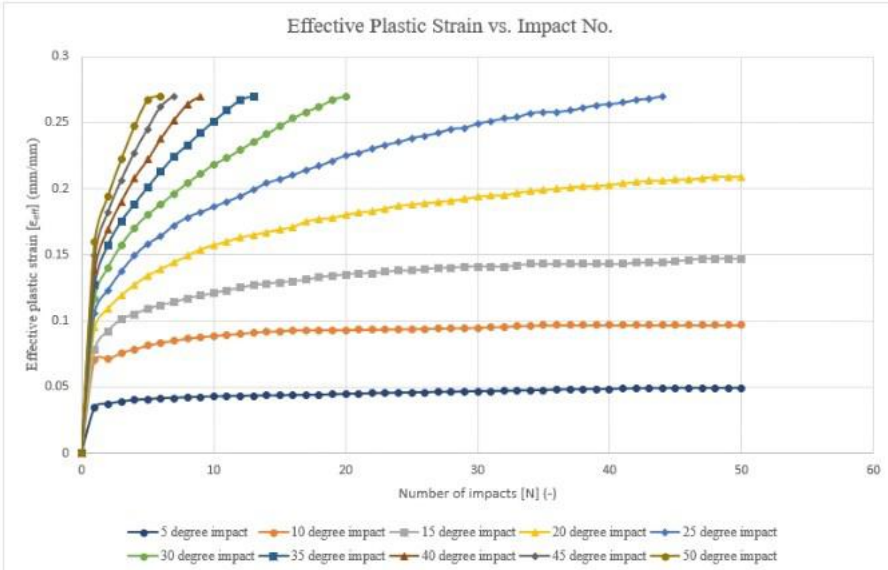


Figure 7. Load case #1: Effective plastic strain vs. impact number (adapted from Robbins, 2020)

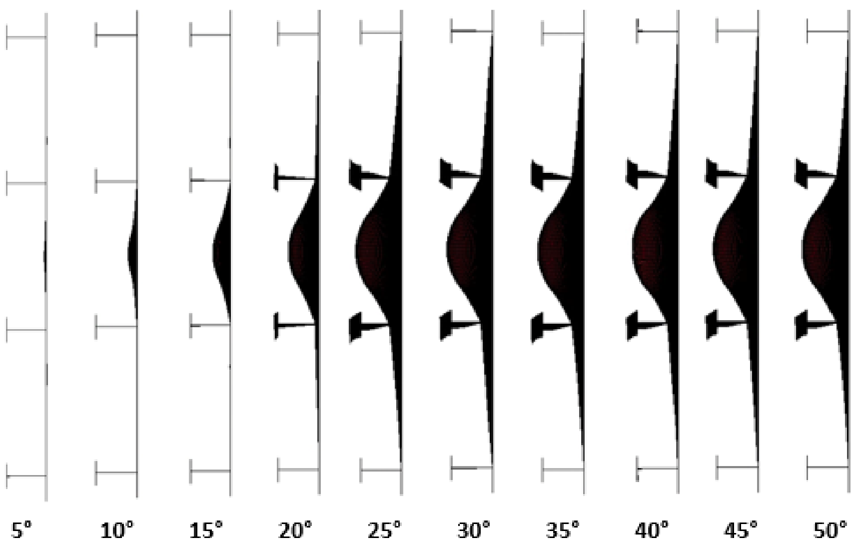


Figure 8. Load case #1: Accumulated damage pattern following 50 impacts or at failure strain attainment if occurring before 50 impacts (adapted from Robbins, 2020)

Table 1. Observed failure modes based on pendulum impact angles and energy levels

Impact Angle (°)	Indenter Speed (m/s)	Energy (kJ)	Structural Response
5 - 10	0.546-1.178	1.87 - 9.51	Elastic Shakedown
15 - 20	1.546-2.176	14.85 - 22.78	Pseudo-Shakedown
25+	>2.532	>29.74	Ratcheting Failure

The test grillage represents a longitudinally stiffened plate field from a naval hull structure, with material properties and boundary conditions scaled to match realistic ship construction details.

While the scale and degree of constraint differ from a full ship, the imposed loads were sufficient to induce meaningful plasticity and progressive damage accumulation, making the tests qualitatively and, in part, quantitatively representative of ship-ice interactions at service speeds. Further work is required to compare these results to higher-energy ridging events or impact scenarios involving more complex geometries and global structural interaction.

Among the five impact scenarios tested, coincident repeated impacts (Load Case 1) exhibited the slowest progression toward failure, as damage remained localized at the impact site. In contrast, non-coincident impact patterns, particularly the radially expanding (Load Case 2) and sinusoidal strikes (Load Case 4), accelerated structural degradation by redistributing plastic strain over a broader area. Impacts directly on stiffeners (Load Case 3) led to rapid localized buckling and tripping, significantly reducing the grillage's ability to sustain further loading. Quantitative findings identified key energy thresholds for damage progression. The onset of ratcheting effects was observed at impact energies exceeding 25°, with maximum recorded plastic strain surpassing standard design assumptions for naval grillages. The peak panel deflection under high-energy strikes reached 35 mm, demonstrating a progressive increase over repeated impacts.

In the coincident impact case (Load Case 1), where repeated strikes occurred at a single location, impacts at lower energies, associated with release angles between 5° and 20°, survived fifty strikes without reaching failure strain. In contrast, higher-energy impacts, at angles of 25° and greater, resulted in progressive failure in fewer cycles. As impact energy increased, indentation patterns evolved, with early increases in impact crater depth transitioning toward greater deformation in stiffeners rather than continued deepening of the central indentation.

In cases where impacts followed a radially expanding strike pattern (Load Case 2), initial strikes at the center of the plate, followed by subsequent impacts radiating outward, resulted in more uniform lateral damage expansion. At lower energy levels, individual impact craters remained distinct, but as energy levels increased beyond 20°, damage accumulation shifted from plate deformation to stiffener deformation, with pronounced plasticity in the stiffener web. The transition from localized indentation to broad-area plasticity indicated that a radially expanding strike pattern enhanced strain distribution, potentially delaying failure in certain configurations.

Progressive stiffener impacts (Load Case 3) introduced another distinct failure mechanism leading to immediate buckling effects. Unlike scenarios where plasticity primarily developed through plate bending, stiffeners in this case became the primary energy-absorbing components. Even at relatively low energy levels (10°–15°), stiffener webs experienced localized tripping and buckling, and at higher energies, failure strain was reached in fewer than 30 strikes.

The sinusoidal impact pattern (Load Case 4) presented responses at lower impact energies (5°–10°), resulting in the structure exhibiting a shakedown response, where plastic strain incrementally decreased with successive impacts. However, at moderate and high energy levels (15°–25°), strain accumulation accelerated once impacts occurred in proximity to stiffeners. At lower energy levels, damage remained uniformly distributed, but as energy increased, damage accumulation became concentrated at stiffener locations, leading to rapid plasticity growth and eventual failure.

Successive overlapping impacts (Load Case 5), where each strike was applied within the indentation region of previous impacts, exhibited a stepped progression in plasticity accumulation. Initial strikes resulted in significant strain increments, followed by successive non-growth strikes before another major strain increment occurred. This pattern closely mirrored the behavior observed in progressive stiffener impacts but with a greater focus on central indentation deepening.

As energy levels increased, the number of non-growth impacts decreased, suggesting that both impact pattern and energy magnitude influenced the rate of damage progression.

The analysis of impact cases demonstrated that structural failure progression depends on impact energy, location, and stiffener integrity. Load Case 1 (coincident repeated strikes) exhibited elastic shakedown at low energies, but above 20°, plastic damage accumulated in stiffeners, leading to buckling and tripping at 25°+, culminating in rupture. Load Case 2 (radially expanding impacts) unexpectedly accelerated failure at lower energies due to early stiffener stress exposure, aligning with classic impact mechanics. Load Case 3 (direct stiffener impacts) showed a clear energy-dependent failure progression, highlighting the need for quantitative hull damage assessment. Load Case 4 (sinusoidal patterns) revealed that stiffener intersections were particularly vulnerable, challenging the assumption that the stiffest regions provide the most resistance. Stiffener degradation significantly weakens overall structural integrity, with stiffeners influencing plasticity accumulation and damage evolution. These findings suggest the need to consider impact sequence, energy magnitude, and cumulative plasticity in naval structural assessments.

RATCHETING FAILURE

Contrary to initial expectations, repeated impacts in a single coincident location did not produce the most severe damage. Instead, damage progression that radiated outward from an initial strike led to a structurally weakened state more quickly. This progressive weakening likely results from repeated impacts introducing damage to both previously compromised and undamaged material, reducing the structure's ability to distribute loads effectively (Paul, 2019). A uniaxially stiffened warship grillage can endure accumulated damage, but at higher energy levels, plastic accumulation progresses cyclically until failure, manifesting as stiffener buckling, gross yielding in the plate field, or a combination of both failure mechanisms (Paik et al., 2003).

CONCLUSION & IMPLICATIONS

This study employed a simplified impact experiment using a multi-linear hardening model to characterize the dynamic response of a uniaxially stiffened warship grillage under repeated impacts. The numerical model, developed using LS-DYNA®, was validated against physical experiments conducted using a dual-pendulum apparatus. The comparison between permanent deflection in physical experiments and numerical simulations showed reasonable agreement, suggesting that the model can provide useful insights into plastic deformation behaviors.

The impact scenarios allowed for a detailed exploration of plasticity behaviors, highlighting potential relationships between applied energy and impact location. The findings indicate that plastic strain accumulates over multiple impact cycles, with plasticity either rapidly stabilizing or progressing incrementally until failure strain is reached. A uniaxially stiffened grillage exhibits three primary plastic damage behaviors under repeated impact loads: elastic shakedown, pseudo-shakedown, and ratcheting leading to progressive collapse. Lower-energy loads generally result in elastic shakedown, where plastic strain accumulation trends asymptotically. Mid-energy loads exhibit pseudo-shakedown, where damage accumulates but may not immediately reach failure, depending on the impact pattern. At all energy levels, initial plastic damage to stiffeners appears to significantly weaken the surrounding structure's ability to absorb subsequent impact energy.

IMPLICATIONS FOR FULL-SCALE STRUCTURAL APPLICATIONS

A key challenge in applying these findings to full-scale ship structures is the influence of global hull deformations and large-scale load redistributions (Paik and Thayamballi, 2007). While the experimental grillage represented a localized structural element, full-scale warships experience complex stress interactions due to hydrostatic loading, operational fatigue, and inertial effects in dynamic environments (Paik et al., 2003). This gap between the laboratory and the sea may be bridged through exploring non-dimensional scaling parameters. The stiffener-to-plate strength ratio, impact energy per unit thickness, and the transition from localized to global deformation modes are critical considerations for extrapolating results.

The role of mixed-material structures in ratcheting behavior also bears consideration. Many modern ships designs incorporate composite reinforcements, or high-strength steel in localized areas to improve impact resistance or reduce topside weight (Paik, 2018). Understanding how these materials interact under repeated loading conditions will be crucial for refining classification society guidelines and enhancing ship survivability. Incorporating refinements such as those detailed herein will ensure that the predictive methodologies developed in studies remain applicable to experimental setups as well as real-world naval and offshore structural challenges.

LIMITATIONS AND RECOMMENDATIONS FOR FUTURE WORK

While the numerical model captured key damage behaviors observed in the physical experiments, it was limited by a uniaxially stiffened grillage and a hardening model validated against a small number of full-scale impacts. The model did not extend beyond the ultra-low cycle fatigue regime and could not account for cyclic hardening or softening effects relevant to real-world service conditions (Dong et al., 2019). Additionally, the experimental setup lacked force sensors and rebound velocity tracking, limiting strain energy estimation and impact force prediction validation.

The simplified boundary conditions further constrain applicability to full-scale ships, where grillages interact with broader hull structures, weldments, and secondary reinforcements. To advance this work, future research should:

- Integrate nonlinear kinematic hardening (NLKH) models with stress-state-dependent plasticity to improve strain accumulation fidelity.
- Incorporate high-speed force measurement systems to validate dynamic response.
- Investigate material interactions between high-strength steels and composite elements under ratcheting loads.
- Study the combined effects of repeated impacts and sustained operational loads, such as ballast pressure, on structural degradation.
- Conduct full-scale cyclic testing under ASTM protocols and biaxial stress states to refine constitutive models for shipbuilding steels.

Addressing these areas will enhance predictive capabilities and contribute to the development of more resilient naval and offshore structures.

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