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Damage Tolerance Assessment of Multi-Hull Aluminum Vessels Using Global Finite Element Methods

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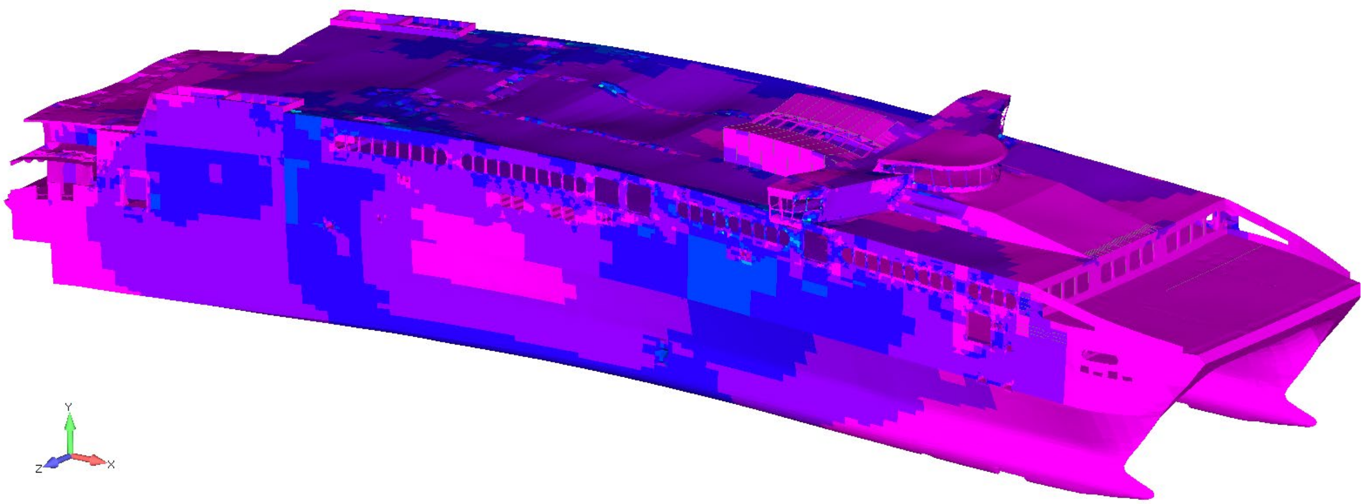

As aluminum high-speed multi-hulls continue to grow in size, capacity and operational sea state, a need is growing to understand the damage tolerance of these structures. This paper presents a Linear Elastic Fracture Mechanics (LEFM) approach to performing damage tolerance assessments of aluminum hull structures using the hydrodynamic analysis and global finite element model developed as part of a class Dynamic Loading Approach (DLA) notation. The LEFM approach is used to calculate the stress intensity factor (K) and the critical crack length throughout the model to screen the entire hull structure and identify fracture critical locations. This paper also investigates the use of elastic-plastic fracture mechanics to predict potential critical crack growth locations, rates, and directions. Fracture critical locations identified and visualized through the analysis provide the ship designer with tools to develop damage tolerant structures. The results of the analysis can also assist owners and regulatory bodies in developing structural inspection and repair plans.

KEY WORDS: aluminum; fracture mechanics; high speed craft; structural design; structural analysis

NOMENCLATURE

- DLA – Dynamic Loading Approach
- DLP – Dominant Load Parameter
- FEA – Finite Element Analysis
- LEFM – Linear Elastic Fracture Mechanics
- MPEV – Most Probable Extreme Value
- ABS – American Bureau of Shipping
- DNV – Det Norske Veritas

INTRODUCTION

High-speed aluminum vessels are designed and surveyed in accordance with Class Society rules (e.g. ABS, DNV) to avoid cracking, however due to complex and unpredictable loads at sea, vessels may be subjected to damage and possible cracks. This paper presents an alternative method to support in-service vessels when unforeseen cracking may occur and a method to predict the severity of cracks to allow vessels to remain at sea.

High-speed aluminum multi-hulls have grown in size, capacity and operating range over the past approximately 30 years. Fig. 1 shows a comparison of the length of Austal vessels delivered from 1990 to 2010. The increase in the number of vessels over 100 m in the past 10 years is mostly a reflection of expanded naval applications for large high-speed ships. Operating routes for large catamaran vessels include areas with significant seas, such as the Caribbean, Sea of Japan, Canary Islands, English Channel, Gulf of Maine, and for naval vessels, open ocean.

Increases in length, beam and displacement coupled with operating routes that include open ocean environments increase global and secondary structural loads. As a result, to ensure adequate strength of high speed ship structures, it is common for class societies to require a Dynamic Loading Approach (DLA) assessment of ship structure for new multi-hull designs or vessels over a certain size (DNV High Speed and Light Craft 2021 and ABS High Speed Craft 2021). The hydrodynamic load analysis and global finite element model created for the DLA can also be leveraged to investigate the damage tolerance of the structural design.

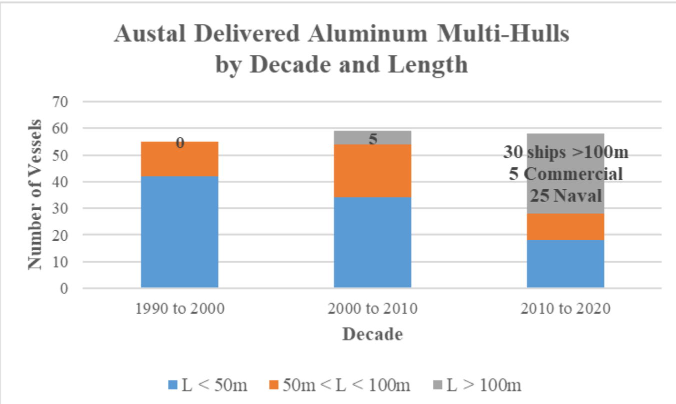

Fig. 1: Austal Delivered Vessels by Decade and Length

Using the DLA model in conjunction with Linear Elastic Fracture Mechanics (LEFM), an approach to evaluating and presenting damage tolerance of multi-hull aluminum vessels has been developed. While there are still many unknowns (e.g. residual stress, impacts of environmental degradation), the assessments available can inform the vessel design and in-service maintenance. Understanding critical crack length and crack growth rate allow the designer to improve structural safety by reducing stress or locating crack arresting systems. The designer and regulatory bodies can develop inspection and repair plans based on the critical nature of the structure and damage tolerance. When damage has occurred, operational limitations can be set that allow the vessel to safely operate until repairs can be executed. Finally, the assessment tool can aid forensic investigations.

Through a worked example, this paper provides an approach for performing a global structural damage tolerance assessment and how the results can be applied to design development and the structural inspection process.

DAMAGE TOLERANCE MODEL

The damage tolerance assessment applies a LEFM approach to the stress results calculated throughout a global FE model for the DLA loads. The LEFM approach is used to calculate the stress intensity factor (K) and the critical crack length throughout the model to screen the entire hull structure and identify fracture critical locations. This paper will also investigate the use of elastic-plastic fracture mechanics to predict potential critical crack growth locations, rates, and directions to assist the designer in the development of damage tolerant aluminum structures.

Sample Vessel and Operating Environment

To demonstrate the damage tolerance assessment method using a DLA model, a sample design was developed. The characteristics of the design are presented in Table 1. The vessel arrangements and structure are typical of a large catamaran transport vessel classed to ABS or DNV. The speed and wave environment selected for the analysis correspond to typical safe operating envelopes for these blue-water craft.

Table 1: Table of Design Characteristics for Sample Vessel

Principle Characteristics and Operational Profile	
Vessel Type	High-Speed; Aluminum; Catamaran; Transport Vessel
Length	~110 m
Beam	~27 m
Draft	~5.0 m
Displacement	~2,700 MT
Hull Material	Aluminum
Speeds	0 to 35 knots in 5 knot increments
Sea State	Up to Sea State 7 (low speed above SS5)

Hydrodynamic Assessment for Extreme Load Prediction

The hydrodynamic analysis was performed with the advanced, fully three dimensional hydrodynamic assessment program WASIM, which is developed and supported by DNV Software.

The mass of the vessel in the hydrodynamic analysis is represented with a distribution of mass elements in a finite element model tuned to match the longitudinal, transverse, and vertical weight distribution. The mass of fluids in the tanks is represented with a tank model, using filling ratios and fluid densities to accurately distribute the fluids throughout the tank volumes, and to generate representative static plus dynamic pressure loads on the tank boundaries and supporting structures.

To capture the inherent non-linear characteristics of a multihull vessel in significant seas, the extreme loads are developed from a series of non-linear time domain simulations in irregular Sea States. The time history data for each Dominant Load Parameter (DLP) is recorded and processed to calculate the Most Probable Extreme Value (MPEV) for the specific operating environment. The MPEV for each DLP are calculated using two and three parameter linear regression and moment methods, and the Weibull statistical method that produces the best Goodness-of-Fit of the Upper Region of data (GOFUR) is selected for the analysis.

The loads are transferred onto the global FE model using a modified equivalent wave approach, using the time step corresponding to the maximum observed DLP value from the non-linear irregular seas runs. The wave characteristics at the critical time step are linearly scaled until the MPEV is achieved, and the loads are transferred to the structural FEA model as pressures for the external sea pressure, internal tank pressure, and dynamic accelerations. The scaled irregular sea state time step for the maximum sagging MPEV DLP is shown in Fig. 2.

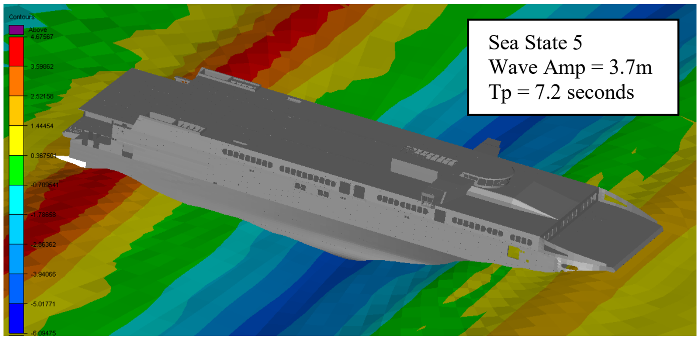

Fig. 2: Irregular Sea State Wave for MPEV Sagging Load

The hydrodynamic load cases used in this sample vessel assessment consist of a single static loading condition with four dynamic load cases; corresponding to maximum vertical bending moment (Sagging & Hogging), and maximum transverse bending moment (Pinching & Prying). In practice, the damage tolerance assessment would be performed on the maximum dynamic stress ranges calculated from the full set of DLP conditions typically developed, and used within a DLA.

Finite Element Model and Load Application

The sample vessel is modeled with a typical global FE model mesh density, with all stiffeners explicitly modeled, and one plate element between longitudinal stiffeners with aspect ratios close to one. All major structure, including the shell, decks, bulkheads, transverse frames, girders, and webs are represented with plate elements. All stiffeners in the structure are modeled with bar elements, using hybrid beam theory to account for the effective attached plating. The full global FE model of the sample vessel is shown in Fig. 3.

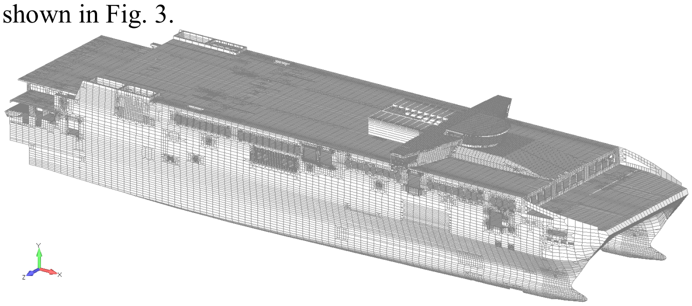

Fig. 3: Global Finite Element Model

Damage Tolerance Calculations

Viking Systems has developed a crack propagation tool within their in-house software suite, SAGA, which helps to automate the fracture mechanics calculations. The crack growth program integrated into the SAGA software performs a fracture mechanics analysis using the Paris law (Eq. 1).

$$\frac{da}{dn} = C_0 \Delta k^m \qquad (1)$$

Where:

C_0 = Fatigue Material Constant

m = Fatigue Material Constant

Where da/dn is the rate of crack growth per fatigue cycle, C_0 and m are material parameters, and k is the stress intensity factor related to the crack type. The material properties for the aluminum alloys used in the FEA model are provided in Table 2 (SSC Report 448):

Table 2: Aluminum Properties for Fracture Mechanics

Material (Grade)	**Ultimate Strength, MPa**	**Fracture Toughness, MPa √m**	**Paris Law Intercept (C_0)**	**Paris Law Slope (m)**
5083-H111	269	36.27	3.93E-11	2.65
5083-H116	276	36.27	3.93E-11	2.65

The crack propagation tool includes various expressions for the stress intensity factor (k), depending on the location of the initial crack or imperfection, with consideration for crack depth (surface elliptical cracks or through thickness cracks) and crack location (in the middle of a plate, or along the edge of a plate). For the purpose of this sample problem, a through thickness crack in the middle of a plate panel is used as the initial imperfection.

The dynamic stress amplitude is calculated by comparing the maximum principal stress from any of the dynamic load cases for a given element to the principal stress of the corresponding static condition. The stress intensity factor is calculated using the stress range and initial crack geometry (Eq. 2). The stress intensity factor for a through thickness center crack (Fig. 4) assumes that there is a defect in the middle of the plate that extends through the thickness of the material and crack length extends in the plate width. As crack length a grows, the stress intensity factor increases until K_I approaches the fracture toughness of the material and the crack becomes unstable (i.e. critical crack length).

$$\Delta K_1 = \sigma\sqrt{a\pi}\sqrt{Sec\left(\frac{a\pi}{W}\right)} \qquad (2)$$

Where:
K_I = stress intensity factor
a = crack length
W = width of plate

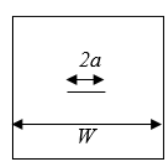

Fig. 4: Through Thickness Center Crack Terms

The crack propagation tool was initially developed to estimate the crack growth for a specific initial imperfection at a specific location. The tool was developed to calculate the time that it will take a known crack to grow to critical length, where the critical crack length is defined as the length at which the crack could become unstable, and grow without bound.

For initial design purposes, the crack propagation tool has been repurposed to serve as an initial crack sensitivity and screening tool, and determine the damage tolerance of the overall global vessel structure. The crack propagation tool is used to calculate the critical crack length throughout the vessel structure, based upon the distribution of dynamic nominal stresses and the initial imperfection geometry. Locations of the model with large critical crack lengths are more tolerant to damage, and cracks occurring in these locations are less likely to grow quickly, or achieve critical length before being identified during a visual inspection of the vessel. Locations of the model with small critical crack lengths are more critical, and additional consideration should be included at design to incorporate crack arresting structures in critical areas.

The critical crack lengths, calculated on the global model of the sample vessel are shown in Fig. 5 and Fig. 6.

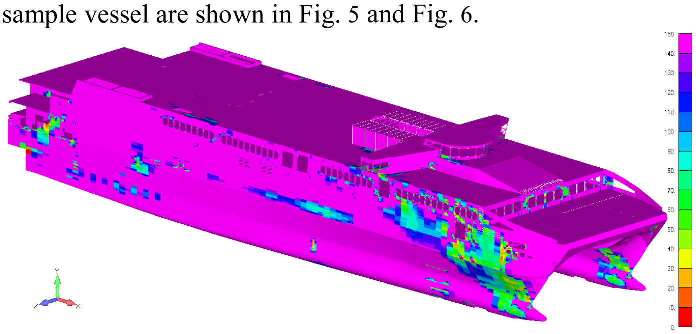

Fig. 5: Damage Tolerance Assessment Plots (Critical Crack Length, mm)

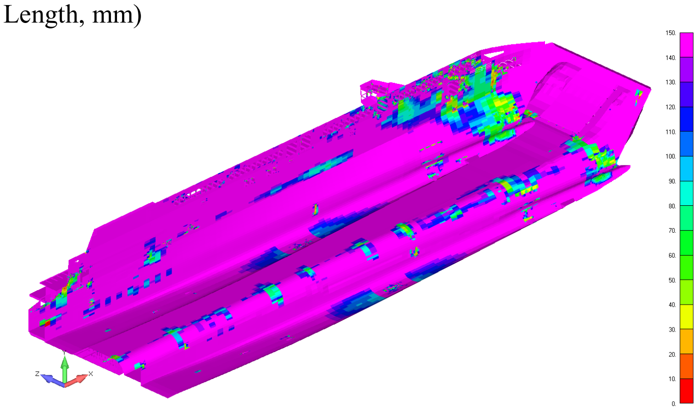

Fig. 6: Damage Tolerance Assessment Plots (Critical Crack Length, mm)

Crack Growth Rates

For critical areas, the crack propagation tool can be used to further refine the likelihood, and progression of an initial imperfection over time. This process can be used to assist in the design and placement of crack arresting devices in the initial design, or determine the implication of a defect observed in service.

The initial defect is defined with an initial length, crack type (surface crack, through-thickness, crack location, etc.), and the known dimensions of the plate panel around the crack. The crack is then subjected to a variety of loading stress intensities to determine the stability of crack growth. The dynamic stress range calculated from the DLA results is converted to a series of loading histograms using a Weibull distribution parameter. The various loading histograms are developed to represent various annual loading histograms, with high stress cycles biased to difference parts of the year. The annual stress distribution histograms all include the same number of cycles and stress levels, but apply the cycles in different order to account for the randomness of the stress application into the crack growth calculation. The crack growth for a 1mm initial imperfection, over a 10 year period, with each of the six stress cycle histograms is shown in Fig. 7. As shown, the initial imperfection grows to a maximum length of approximately 15mm over 10 years, and does not reach the critical crack length.

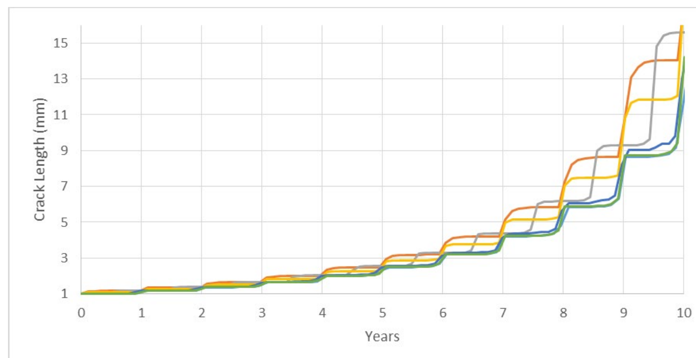

Fig. 7: Damage Tolerance Assessment Plots (Critical Crack)

The simplified crack propagation approach shown in Fig. 7 provides a reasonable estimate of the initial growth of small cracks, but the approach is limited in that it only considers crack growth in bare plate under consistent conditions. The crack growth estimate does not account for the variation in stress intensity at the crack tip as the crack approaches orthogonal supporting structures, changes of plate scantlings, or variations in the nominal field stress around the local geometry of the area of interest.

To improve the accuracy of the crack propagation calculations for larger cracks, the simplified crack propagation calculations have been integrated into local FEA using an iterative design approach to model the progression of the crack propagation, and update the local stress results to account for the continued crack growth. In this sample case, a fine mesh local FEA model has been created to evaluate the propagation of an initial crack in way of the large openings in the starboard side shell, near the bow, where the results of the global damage tolerance screening show critical crack lengths of less than 10 mm. The location of the critical openings is used for the iterative crack growth calculations shown in Fig. 8

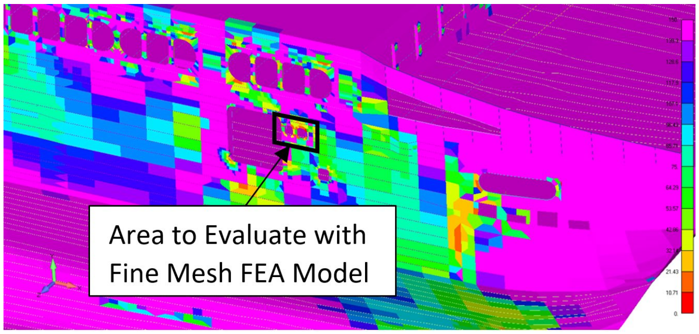

Fig. 8: Critical Openings for Fine Mesh FEA Crack Assessment

A fine mesh local FEA model is created in way of the openings, loaded with enforced displacements, inertial accelerations, and lateral pressures from the global model, and analyzed to calculate the local stress results in way of the area of interest. A plot of the major principal stress components shows high tensile dynamic stresses in way of the upper / aft corner (critical crack location No. 1) and the lower / forward corner (critical crack location No. 2), as shown in Fig. 9.

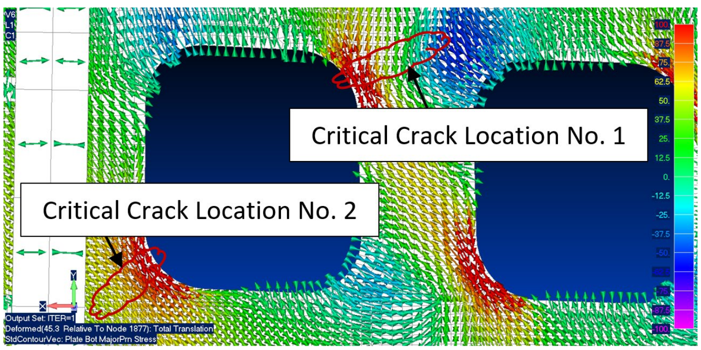

Fig. 9: Initial Major Principal Stress Distribution around Openings

The iterative crack propagation procedure is applied to the local FEA model, using the steps defined below:

1. Run the SAGA simplified crack propagation approach, using an initial edge imperfection and the elemental stress results from the fine mesh FE model to determine if an initial crack will propagate through the width of the element.
2. If the crack propagation exceeds the width of the element, locally re-mesh the fine mesh element to include the current crack length, using a crack propagation direction normal to the major dynamic principal stress.
3. Load and solve the updated local model to calculate the updated stress field in way of the crack tip.
4. Repeat Steps 1 through 3 until the crack propagation stops, the time associated with the crack propagation exceeds the period of interest (design life or service interval), or the crack is confirmed to grow unbounded.

The iterative crack propagation procedure has been applied to the two critical crack locations shown in Fig. 9.

For Location No. 1, the crack propagation runs through 12 iterations before the crack growth slows due to a significant reduction in the nominal stress in way of the crack tip resulting from the redistribution of load around the cracked structure. The final distribution of major principal stress in way of the final crack length is shown in Fig. 10.

For Location No. 2, the crack propagation runs through 15 iterations before the crack growth slows due to a significant reduction in the nominal stress in way of the crack tip resulting from the proximity to the transverse web frame supporting the side shell. The final distribution of major principal stress in way of the final crack length is shown in Fig. 11.

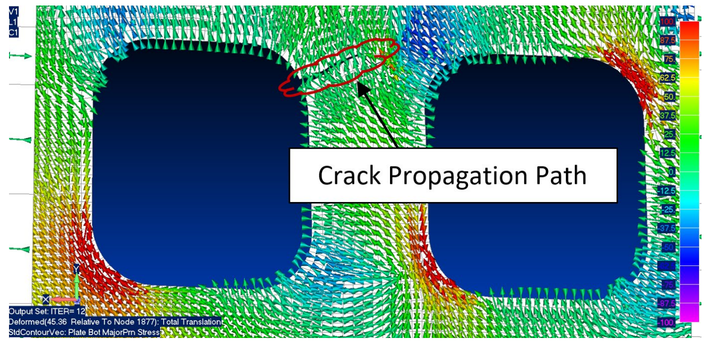

Fig. 10: Local Model - Major Principal Stress, Mpa (Fracture Has Completed)

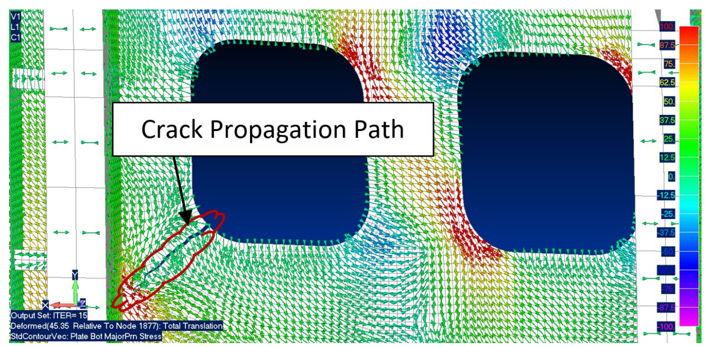

Fig. 11: Local Model - Major Principal Stress, Mpa (Fracture Has Completed)

The results of the local, iterative analysis show the areas initially identified to be critical in the damage tolerance screening to be more tolerant than initially thought. While the initial imperfections in the critical areas do continue to grow, they are bound by changes in the local stress distribution, or by the presence of orthogonal supporting structures. This method can be used to further evaluate critical structures, and ensure crack arresting structures are positioned appropriately to prevent unacceptable crack propagation.

APPLICATIONS TO ALUMINUM HIGH SPEED VESSEL DESIGN AND INSPECTION

Results from the damage tolerance assessment are in the form of critical crack length. Fig. 5, Fig. 6 and Fig. 8 show assessment plots indicating the critical crack length for different structural regions of the vessel. The plots are by plate panel as bounded by longitudinal stiffeners and transverse web frames. As noted previously, some conservativeness is inherent in the assessments as stress intensity reduction or crack redirection from stiffeners and frames are not considered in the global screening. Depending on the fidelity of the loading and fracture data, these plots can serve as either quantitative or qualitative assessment of the overall ship structure damage tolerance. These plots benefit both the initial vessel design and in-service vessel support.

Vessel Design for Damage Tolerance

In conjunction with global strength results and fatigue analysis, the damage tolerance assessment (crack growth rate and critical crack size) informs the designer of the overall safety of the design. Given the complexity of ship designs, unknowns in loading, departure from planned operating procedures and variation in welded fabrication, it is unrealistic to expect that ships will remain crack free through their lifetime. Designing blue-water/open ocean vessels for damage tolerance provides a measure of the resilience after damage has occurred.

There are two approaches that can be taken with the assessment plots: 1) The vessel can be designed to tolerate a certain crack size through increased scantlings to reduce stress; or 2) Crack arresting structures can be incorporated for additional load support that reduce high intensity stress locations susceptible to crack growth. Fig. 12 outlines an area where stress resulting from hydrodynamic pressure can be reduced by increasing plating thickness. Fig. 13 indicates locations where crack arrestors can be used to prevent cracks from propagating across openings.

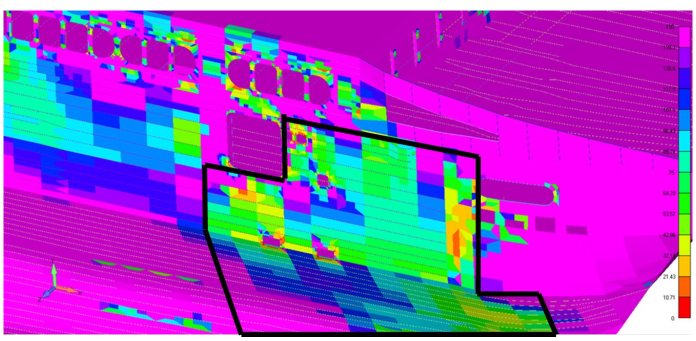

Fig. 12: Region Identified for Stress Reduction

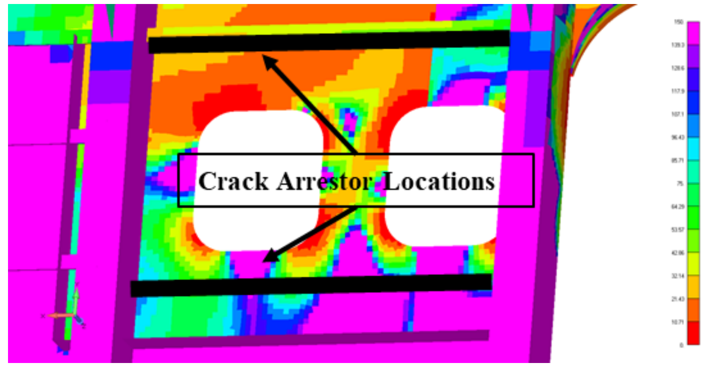

Fig. 13: Locations Identified for Crack Arrestor

For high speed craft controlling weight is always a top priority, so designing to stress less than class allowable to improve damage tolerance, except in localized locations, will likely sacrifice too much speed, range, or payload. The better approach to design for damage tolerance is to protect critical structures through the use of crack arrestors. The closely spaced stiffeners of aluminum ship construction, especially if they are integral plate and tee extruded panels, provide an inherent crack arresting system (Galanis and Papazoglou 2009; SSC 265) In way of sheer and deck strakes as well as large openings, the flexibility of aluminum extrusions allows for custom stiffener type crack arrestors to be developed.

Fig. 14 shows a possible crack arrestor design. In this arrangement, a large bulb section is joined integral to the shell plate through either gas-metal arc or friction stir butt welds. This abruptly thicker geometry arrests cracks by reducing stress intensity. Local crack growth models, as shown in Fig. 9 to Fig. 11 can be used to predict the direction of crack growth allowing arrestors to be strategically placed and their effectiveness evaluated. Further work is still needed to better quantify the performance of aluminum stiffener type crack arrestors (Galanis and Papazoglou 2009).

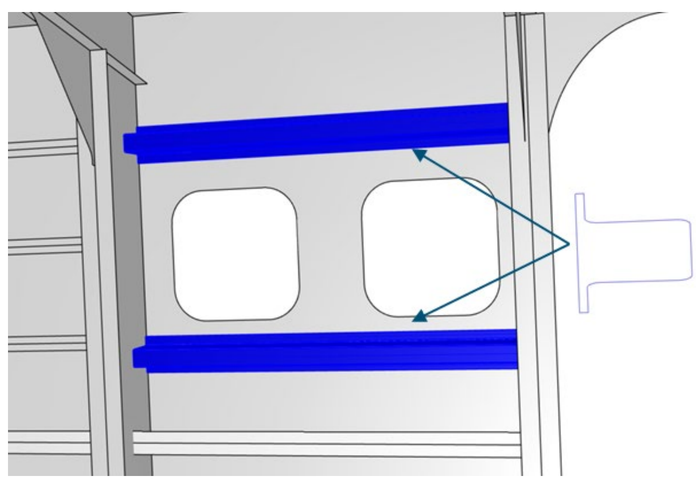

Fig. 14: Possible Crack Arrestor Solution

In-Service Support

Using the DLA, fatigue analysis and damage tolerance models, ship structural inspections schedules and required repairs can be developed based on three things: 1) the likelihood a structure will start to fail; 2) the speed at which an initial failure will grow; and 3) the consequence to the structural safety of the vessel should failure occur. Items 1 and 3, likelihood and consequence, are determined from strength and fatigue analyses. To have an economic inspection and repair plan, item 2, damage tolerance, needs to be understood. Damage tolerance assessment plots provide data on when a crack will grow critically. Local models determine whether critical growth is arrested by adjacent structure, including crack arrestors if fit.

Table 3 is a risk based inspection plan assessment for the structure in way of the openings shown in Fig. 13, both with and without crack arrestors. Notional ratings and inspection periods are provided to show how damage tolerance can be accounted in developing an inspection plan. It also shows how inspection periodicity may be extended by preserving a basic level of structural strength through damage tolerance design.

Table 3: Notional Inspection Plan Assessment

Structure Region	Likelihood Failure Initiates (1 to 5)	Damage Tolerance (1 to 5)	Conseq. of Failure (1 to 5)	Proposed Inspection Period
Fwd Side Shell (no arrestors)	3	4	4	6 months
Fwd Side Shell (with arrestors)	3	1	4	12 months

1 = least likely; most damage tolerant; lowest consequence
5 = most likely; least damage tolerant; highest consequence

Similar types of assessments can be used to provide operational advice to operators and class for a ship that has suffered damage from fatigue, collisions, over-load, etc. Again, using full ship damage tolerance models, the critical nature of the damage based on size, location and adjacent structures limiting crack growth can be assessed to determine whether the vessel should continue with full operations, with restricted operations, or cease operations. Understanding how damage will propagate can allow vessels to better plan and execute repairs within their normal service cycle, reducing interruptions to operations.

CONCLUSIONS

This paper has presented tools that can be used to design high-speed aluminum multi-hulls for damage tolerance. By leveraging existing DLA work, knowledge of vessel safety can be gained with minimal additional investment in modeling. The method is based on established LEFM and the best available material data. A great deal of work has been accomplished over the past 20 years on the fracture performance of marine aluminum alloys, however research needs still exist. To improve damage tolerance assessments of aluminum ship structures, the following areas of research are recommended:

- Measures of aluminum residual stress and methods to account for it in fracture analysis
- Further characterization on the effects of stiffening configurations on the fracture of aluminum structures
- Fracture mechanics data on sensitized aluminum
- ASTM G67 and DoS Probe sensitization measurements for assessing in-service ships

Through these damage tolerance assessments, strategic strengthening can occur during the design phase that improves the safety of high-speed aluminum ship design. For in-service ships, the global damage tolerance model aids inspection plans and operational recommendations. Collectively, this approach and potential applications will allow high-speed aluminum multi-hulls to continue to grow in size, capacity and open ocean operation.

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