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Research Needs in Aluminum Structure

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Abstract

The technology required for the design, fabrication, operation and maintenance of aluminum structures for ships and craft are reviewed to assess the needs for improvements in that technology. The areas reviewed are: material property and behavior, structural design, structural details, welding and fabrication, joining aluminum to steel, residual stresses and distortion, fatigue design and analysis, fire protection, vibration, maintenance and repair, mitigating slam loads and emerging technologies.

Keywords

Aluminum ship structures; Aluminum high-speed vessels.

Introduction

Aluminum has been used for the construction of ships and craft for more than a century. In many cases, the vessels have served well for several decades of use without any serious structural problems. However, there have been some difficulties. From the very beginning, and continuing up to very recently, there have been instances where the selection of the wrong aluminum alloy has led to corrosion problems so severe that the vessels had to be scrapped within a few years of construction. Aluminum has been used for the deckhouse structure of US Navy combatant and amphibious ships for more than 70 years. Those ships served well, but the aluminum structure was the source of significant maintenance problems, mostly from fatigue damage. Serious concerns for survival in shipboard fire and for maintenance reduction led to the discontinuation of the use of aluminum for major US Navy combatant ships in the 1980s.

Towards the close of World War II, some merchant ships built in the U.S. had aluminum in their deckhouses, and this practice continued after the war, primarily in the superstructures of passenger ships. Aluminum began to be adopted worldwide for fabrication of the superstructure of passenger ships, a practice that continues today. Aluminum began to be used in the 1940s for pleasure craft and for workboats, the size of which has increase greatly over the years. The use of aluminum for the hulls of high-speed merchant vessels began in the 1990s with increased construction of high-speed ferries. These vessels have become so technologically advanced that they have surpassed the capabilities of many naval vessels; many navies today are adapting derivatives of these high-speed vessels to combatant craft.

The interest in aluminum structure has increased greatly over the past decade. Evidence of international interest in aluminum ship structure is the International Forum on Aluminum Ships, the fifth of which took place in Tokyo in 2005. The Ship Structure Committee (SSC) has recently completed a number of projects concerning aluminum ship structures:

- SSC-410, Fatigue of Aluminum Structural Weldments
- SSC-438, Structural Optimization for Conversion of Aluminum Car Ferry to Support Military Vehicle Payload
- SSC-439, Comparative Structural Requirements for High Speed Craft
- SSC-442, Labor-Saving Passive Fire Protection Systems for Aluminum and Composite Construction
- SR-1434, In-Service Performance of Aluminum Structural Details
- SR-1446, Mechanical Collapse Testing on Aluminum Stiffened Panels for Marine Applications
- SR-1447, Fracture Mechanics Characterization of Aluminum Alloys for Marine Structural Applications
- SR-1448, Aluminum Marine Structure Design and Fabrication Guide
- SR-1454, Buckling Collapse Testing on Friction Stir Welded Aluminum Stiffened Plate Structures

Additionally, the US Navy's Office of Naval Research has begun a multi-year research program, Aluminum Structure Reliability Program, aimed at improving the technology for design construction, operation, and maintenance of high-speed aluminum naval vessels.

This paper is based on the aluminum guide and on the ONR program. Research needs will be discussed in the following areas:

- Material property and behavior
- Structural design
- Structural details
- Welding and fabrication
- Joining aluminum to steel
- Residual stresses and distortion
- Fatigue design and analysis
- Fire protection
- Vibration
- Performance metrics, reliability and risk assessment
- Maintenance and repair
- Structural health monitoring
- Emerging technologies

Material Property and Behavior

There is vast experience with aluminum alloys in both the 5xxx and 6xxx-series; the most commonly used marine alloys. However, there are still fairly large knowledge gaps in basic knowledge on these alloys. The most common gap is in fatigue properties and fracture toughness, particularly dynamic fracture toughness, with much of the existing fracture data coming from non-standard tests with invalid data.

An important discrepancy in basic material properties is the variation among different sources on the strength of welded aluminum. Table 1 illustrates this discrepancy for several alloys. The differences come in part from different standards for determining the yield strength from a “dog bone” sample cut across the weld in a plate. Some use a 50-mm gage length that measures only weld metal and heat-affected zone (HAZ), but others use a 250-mm gage length sample that includes base metal.

Perhaps even more important than the difference in yield strength is the manner in which this property is used in design. The welded strength is typically 30 to 50 percent of the strength of the base metal, and this reduced strength is used for most design calculations. There are indications that the approach is overly conservative. In studies on the compressive strength of welded panels, Paik et al (2006) used a weighted average based on the relative volumes of base metal, weld metal, and HAZ. In a simplified analysis of a welded panel in tension, Collette (2005) found that the yield strength of a 5xxx-series welded plate was close to the yield strength of the base metal, although for a 6xxx-series alloy, the strength was closer to that of the HAZ. Research in this basic material property could result in significantly increased allowable stresses and reduced weight.

Table 1: Yield Strength of Some Alloys as Specified by Different Authorities (MPa)

Alloy	Authority				
	ABS	DnV	Aluminum Association	AWS Hull Welding	US Navy
5086-H116	131	92	95	131	152
5083-H116	165	116	115	165	
5383-H116	145	140			
5456-H116	179		125	179	179
6061-T6	138	105	105	138	

Aluminum alloys, particularly those of the 5xxx-series have shown excellent corrosion resistance in service, with some bare hulls operating for more than 30 years without discernable corrosion. However, there is a general reluctance to place 6xxx-series alloys in similar service. Indeed, classification societies and the U.S. Navy prohibit most uses of 6xxx-series alloys in contact with seawater. A review of available corrosion data fails to provide any experimental basis for this prejudice against 6xxx-series alloys.

The 6xxx-series alloys generally have excellent resistance to general corrosion over the surface, but compared to 5xxx-series exhibit more localized pitting. Most of the corrosion testing of aluminum in seawater occurred in the 1950 through the 1960s. Goddard et al. (1967) report that the maximum pit depth in three 5xxx-series alloys (5052, 5056, and 5083) was 0.18 and 0.86 mm after five and ten years of immersion in seawater, respectively. In the same tests, 6061-T6 had 1.30 and 1.65 mm of pit depth when samples were removed after 5 and 10 years of immersion. Although the 6061 had twice the depth of pitting in this test, the rate is not necessarily unacceptable. Other 6xxx-series, such as 6082 have less copper that 6061 and should have better corrosion resistance, although data is lacking

The 6xxx-series are beginning to be used more extensively in integrally stiffened deck panels, and there is a desire to use these light panels for general hull structure. A systematic comparative test of different alloys in corrosive environments will demonstrate if more extensive use of the 6xxx-series alloys is possible and if this can be safely done will result in significant weight and cost savings.

While the 5xxx-series alloys have generally shown to have excellent resistance to corrosion, there is concern that material is becoming sensitized over time to intergranular corrosion and stress-corrosion cracking, particularly when subjected to higher service temperatures on exposed decks. An accelerated test that would be based on the thermal profile of the decks of operational ships must be developed to screen the material.

There are also indications that there are reductions in corrosion resistance in the heat-affected zones of welds in the 5xxx-series alloys such as shown in Fig 1. The standard ASTM G 67 NAMALT test is designed to measure weight loss in a relatively large surface area, not in the narrow band of the HAZ of a weld. A standard for weight loss in the HAZ should be developed to allow comparison and optimization of welding methods.

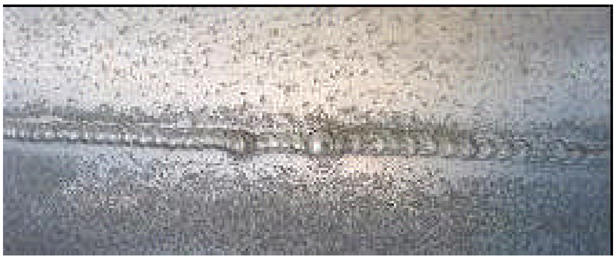

Fig. 1: Corrosion at a weld in 5xxx-series plate.

Testing in accordance with ASTM G 67 as well as the ASTM G 66 G66 (ASSET) test to determine susceptibility to exfoliation are required for marine-grade 5xxx-series aluminum alloys ordered in accordance with ASTM specification B 928, which was developed following extensive stress corrosion cracking that was experienced in 5083-H321 material ordered in the late 1990s (Bushfield et al, 2003). However, recent experience (Kieth and Blair, 2007) showed some 5083 H321 that had been ordered to ASTM B 928 to have considerable excess magnesium precipitating as a secondary phase, Mg_2Al_3 or β-phase, in the grain boundaries of the metal. The β-phase is an electrochemically active phase. When the β-phase forms as a continuous and complete network on the grain boundaries, the material becomes “sensitized” or susceptible to intergranular forms of corrosion. The 5083-H321 may have had more than 15 mg/cm^2 mass loss in ASTM G 67. This experience indicates that further research into sensitization of higher-magnesium 5xxx-series alloys may be needed.

Structural Design

Methodologies for computing the compressive strength of plates and welded panels are well established and validated for steel structure. For welded aluminum structure, that is not the case. The work of Paik and by a few others such as Rigo et al. (2003, 2004) represents a good start on this validation, but many questions remain such as the effect of transverse welds and the effect of localized heat-affected zones resulting from welded attachments. There is limited guidance on how to incorporate such welds into finite element models. A conservative approach is to treat such a panel as all-HAZ material; however this may incur a large weight penalty and does not shed any light on strain concentration and other effects from the differences in material properties over the panel.

Other design issues include:

- Ultimate strength of plates and panels undergoing combined loading such as biaxial compression in multi-hull cross decks, or a combination of in-plane compression and lateral pressure in the slamming zone of high-speed vessels.
- The effect of initial imperfections and residual stresses on the strength of common aluminum structures needs further validation, including guidance on how to incorporate these values into finite-element models for ultimate strength along with simplified methods able to incorporate a range of imperfection magnitudes in ultimate strength prediction.
- Guidance on how to incorporate HAZ effects on ultimate strength calculations needs to be defined, including techniques for incorporating HAZ into finite element models, including estimates of the effect of strain concentration on tensile ultimate strength, and estimates of the effect of various types of HAZ (GMAW, Laser, FSW) on in-plane and lateral loads of panels.
- Simplified methods for predicting the load-shortening curves of plate and panels under combined loading for use in overall hull-girder ultimate strength calculations.
- Ultimate strength methods for advanced extrusions, where the plate thickness may not remain constant.

Structural Details

Although many structural details that have been used over the year with steel ships are acceptable in aluminum construction, many are not, particularly because of concern for fatigue strength. Likewise, many details that boatbuilders have used for years on smaller craft are not acceptable on larger craft because of longitudinal strength and fatigue concerns. The Ship Structure Committee has sponsored many projects over the years on the suitability of different steel structural details and their fatigue strength, but has not yet produced significant guidance for aluminum details. Fig. 2 shows one of the new types of details being used in aluminum structures today—a detail of questionable strength.

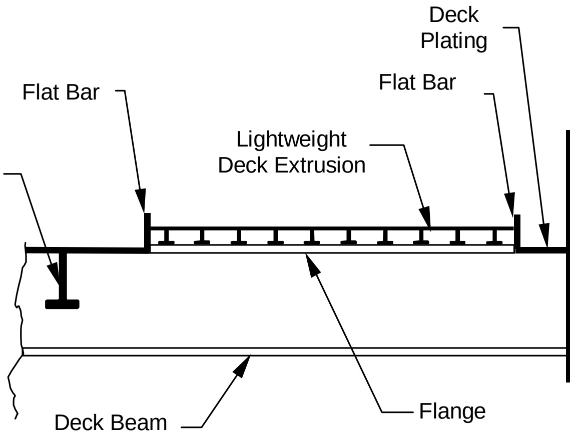

Fig. 2: **Detail with lightweight deck extrusions.**

Joining Aluminum to Steel

Many ships combine an aluminum superstructure with a steel hull. The standard for performing the joint between the metal is the roll-bonded or explosively bonded bimetallic (actually trimetallic strip), which has to be at least four times wider than the thickness of the plate that it joins. If 10-mm aluminum plate is to be joined to similar thickness steel plate, the bimetallic strip has to be about 40 mm wide, which is unsightly and somewhat difficult to paint, and it must be painted to avoid galvanic corrosion. Kimapong and Watanabe (2004) explored a simpler method to use friction stir welding to join 2-mm 5083 plate to mild steel of the same thickness. This work should be continued to produce a less expensive and cleaner joint between the two dissimilar metals.

Residual Stresses and Distortion

The residual stresses and distortions associated with welding aluminum structures have advantages and disadvantages compared to steel. The elastic modulus of aluminum is one-third that of steel, but the coefficient of thermal expansion is about twice as much. This means that the strains that occur from the cooling of the welds and surrounding areas will produce lower residual stress in aluminum. However, the reduced elastic modulus means that when residual stresses do occur, they will tend to produce greater distortion than in steel structure. Because aluminum conducts heat anywhere from 2.5 to 9 times faster than steel, the area heated during welding processes is greater but not as intense. In general, welded aluminum structure tends to exhibit greater overall distortion than steel structure, and tolerances for ship construction reflect this, with greater allowance for distortion being permitted in aluminum structure than in comparable steel structure. Although there has been much research done on the residual stresses and distortion of steel ship structure, particularly by the National Ship Research Program, much comparable work is needed for aluminum.

Fatigue Design and Analysis

Design of aluminum structure to resist fatigue damage is severely limited by a lack of information on the fatigue strength of typical structural details used in aluminum high-speed vessels. Several organizations have compiled databases relating to the fatigue strength of aluminum structural details and have published design codes. The most recent of these codes is Eurocode 9, which was developed by merging data from most of the other sources and developing new data from testing of medium-scale specimens typical of the details used in civil engineering structures. These codes all assume that the fatigue strength of welded details is the same for all aluminum alloys, and that mean stress effects are not significant.

The data from which these design codes were developed does not reflect many of the structural details currently used or proposed for use in construction of high performance aluminum marine vehicles. Rather, they are for the structural details used for civil engineering structures such as buildings and bridges, for which aluminum is sometimes used. Comparison of the limited data that is available for the structural details used for ship structure with the Eurocode 9 standard shows that the international standard is far more conservative than the data for ship details indicate. A testing program is needed to address these deficiencies. Some of the details used today for which no data is available include joints in extruded aluminum sandwich panels and other complex details commonly used with other lightweight extruded panels.

A deficiency in Eurocode 9 is illustrated by Fig.3, which has experimental data for a common ship-type aluminum structural detail compared to the more conservative fatigue strength of Eurocode9. In the figure, the dotted line represents the lower 5 percent limit of the data, and the solid line represents a Eurocode 23, 3.4 fatigue classification, which would apply to a detail of this sort. The Eurocode 9 standard is considerably more conservative than the data would suggest. This illustrates the need for more fatigue data on specific ship structural details.

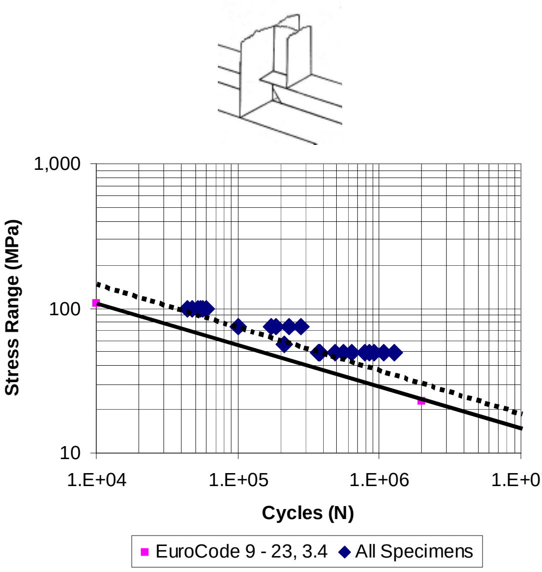

Fig. 3: **Fatigue data for stiffener intersection compared to Eurocode 9.**

To perform fatigue analysis during structural design, an accurate fatigue-loading spectrum is needed, which is typically developed in the latter stages of design through the use of hydrodynamic analysis or model testing. However, fatigue considerations frequently control many of the scantlings of aluminum vessels, including hull girder strength and methods of performing fatigue analysis in the early design stages are needed. Although the format of fatigue allowable stress levels developed by classification societies for initial guidance in the design of steel ships for fatigue has some merit, the method is too restrictive for the design of most aluminum vessels because of their high speeds and sometimes unusual hull forms. Rather, a simplified way to develop a fatigue-loading spectrum is needed, perhaps tied to the various methods of estimating hull girder loads during early design stages.

The different multi-axial loadings occur at different phases during a loading cycle, and a means of combining all of the different loads to assess the fatigue strength of structural details is needed. There is currently no universal parameter for correlating cyclic multiaxial stress/strain with fatigue life for marine structures. Very few methods have been investigated for welded joints as a group, particularly in aluminum, and additional validation efforts are required before they can be recommended for application to marine structures. Potentially useful tools for extrapolating the responses of aluminum structural details from one stress state to another and for life correlation in high cycle multiaxial regimes include the use of maximum shear stress for crack initiation and maximum principal stress for crack growth.

Aluminum has a crack propagation rate under fatigue loading that can be as much as 30 times greater than that of steel under the same applied stress intensity factor range. Fig. 4 illustrate a fatigue crack growth calculation for a steel hull and an aluminum hull that were designed to the ABS HSC guide, with the section modulus of the aluminum hull increased significantly over minimum rule requirements because of a fatigue crack initiation analysis. An initial 24-mm crack in the aluminum propagated to 50 mm in 24 months of service, but the same size initial crack in the steel propagated to only 30 mm. When a crack reaches appreciable size in an aluminum hull, it can grow quickly and lead to catastrophic hull failure.

In steel hulls, placing significantly tougher grades of steel in critical areas to serve as crack arrestors reduces the chance of catastrophic hull failure from fast fracture. Recognizing that that fatigue crack growth resistance and fracture toughness are entirely different metallurgical phenomena, an effective means must found to arrest a crack in an aluminum hull before catastrophic failures occur.

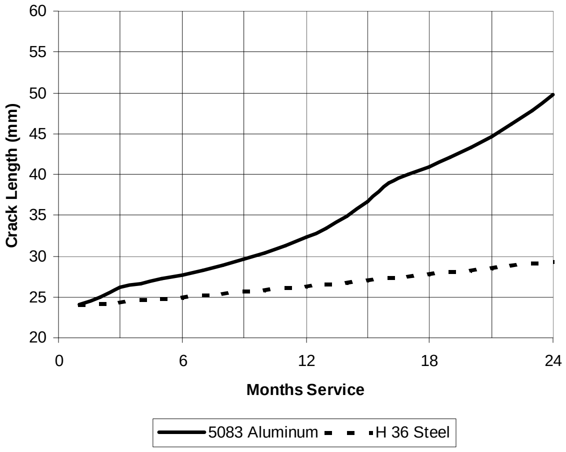

Fig. 4: **Predicted crack growth for a 4.39-m 32-knot craft.**

Riveted seams may be an answer to crack arrest, but they represent a significant maintenance problem in aluminum structure because they can lead to crevice corrosion and are prone to leakage. Solutions such as welding thicker bars of aluminum that will temporarily reduce the stress intensity may be effective, but the concepts need to be analyzed and experimentally verified prior to use.

Fire Protection

The structural insulation requirements for aluminum are more extensive than for steel because the aluminum structure itself must be protected from the heat of the fire by using fire protection insulation to prevent the aluminum from softening or melting during the fire. The goal of aluminum fire protection insulation is to prevent the aluminum being heated to more than 230 °C.

Table 2 shows the results of two comparative studies that were made of the weight of aluminum structure. The first is a 42.7-m, 32-kt crew boat and the second is the deckhouse of a naval combatant. In the first study the aluminum structure alone weighed 56 percent of the weight of the steel structure, but the total weight of aluminum structure and fire protection insulation was 62 percent of the weight of the steel structure. In the second study the aluminum structure alone weighed 49 percent of the steel, but 84 percent of the weight of the steel when the insulation was added, negating much of the weight advantage of aluminum.

Table 2: Comparative Weights of Aluminum and Steel Structures with Fire Protection Insulation (tonnes)

Ship	Items	Steel	Aluminum	
		Weight	Weight	% of Steel
42.7-meter 32-kt Crew Boat	Structure	84.4	47.5	56%
	Insulation		4.5	
	Total	84.4	52.0	62%
Naval Combatant Deckhouse	Structure	134.9	66.2	49%
	Insulation		46.6	
	Total	134.9	112.8	84%

The weight increase for the crew boat is probably acceptable, especially as a conservative assumption was made in the study to insulate all transverse bulkheads and the bottom of the entire main deck, which is not always required for a vessel of this size. Insulation provided IMO A-60 protection and weighed 8.64-kg/m^{2}to cover both sides of a transverse bulkhead. For the combatant's deckhouse, the U.S. Navy N-30 protection was provided, with the insulation weighing 18.94-kg/m^2 with both sides of a bulkhead covered.

The U.S. Navy N-30 protection is designed to withstand the heat of a hydrocarbon fire as well as the fire from the residual fuel of an unexpended missile, a more significant threat than the wood fire that is the basis of A-60 protection. However, hydrocarbon fires are a threat for commercial vessels, particularly above vehicle decks on ferries, where some builders use a steel framework to support the deck above rather than using IMO H-60 insulation, which weighs only slightly less than N-30 insulation. There is a clear need for the development of better fire protection methods for aluminum structure.

The National Shipbuilding Research Program has conducted a study of improved fire protection insulation for aluminum structure aimed particularly at the vehicle deck of ferries (NSRP, 2001). The product studied under project was estimated to weigh about 0.2 to 0.4 pounds per square foot (1.0 to 2.0 kg/m2), and have an installed cost ranging from $0.07 to $1.00 per square foot. Because the product was tested in hydrocarbon fires, it seems promising to meet the IMO H-30 and the U.S. Navy N-30 requirements. However, regulatory bodies have not yet approved the product.

Reductions can be made in the placement and configuration of structural fire protection insulation through modeling potential fire scenarios, and examining how the structure responds with different types of insulation. This is in line with established IMO procedures for alternate design and arrangements for fire safety that are used for Class A fires. However, the experimental basis for such evaluation with hydrocarbon fires is not as well established, especially for structure surrounded by fire, such as stanchions and deep girders. SNAME Technical and Research Bulletin 2-21, Aluminum Fire Protection Guidelines, was issued in 1974 and should be updated through a program that included analysis and testing.

Vibration

Vibration problems can be more acute in aluminum structure than in steel because aluminum has greater potential for fatigue damage. Structural details located in areas not normally subjected to significant stresses can develop fatigue cracks if the structure vibrates significantly.

Although aluminum has one-third the elastic modulus of steel, it also has one-third the density. The natural frequency of a system is proportional to the square root of the stiffness divided by the mass, so similar aluminum and steel structures will have similar modes of vibration. Because the scantlings for aluminum structure are generally greater than for steel structure designed to the same criteria, aluminum structures will have higher natural frequencies than steel structures unless a significant amount of mass is associated with the mode of vibration, such as machinery foundations.

The methodology for analyzing structure for vibration is well developed and equations reflect both density and elastic modulus, so that calculations for aluminum structure are as valid as for steel structure. One area of concern is for structural damping when making forced response calculations, for which information is scarce for aluminum ships.

For ship structures, there is greater uncertainty into the magnitude of the forcing function for such sources as waterjet propulsors, and research is needed in order to properly design structure subjected to such loading.

Performance Metrics, Reliability and Risk Assessment

A need to apply quantifiable performance metrics to evaluate the capability of a structural design has influenced research into applying formal reliability analysis and risk assessment to marine structural design. These methods offer an advantage for aluminum marine structures because there is little experience with design and long-term operation of many of these ships. Traditional design methods may lead to over-designed structures or a higher level of risk than desired. Development of the methodology for applying performance metrics to ship design requires research in several areas:

- Development of specific aluminum limit states, and the uncertainty associated with the variables in these limit states.
- Development of an automated process to calculate and document the probabilities associated with individual failure modes.

- Application of the methodology to existing ship designs to establish baseline values of these metrics.
- System level aggregation of each reliability-based performance evaluation.

Research in several key areas is needed for further application of reliability assessment to aluminum vessels:

- Development of ultimate strength and fatigue analysis methodologies as mentioned above.
- Obtaining better information on the mean values and stochastic properties of the variables used in ultimate strength and fatigue analysis, including basic material properties.

Application of risk assessment to design of ship structures is less advanced than its application to other ship systems, but it offers a systematic method of assuring equivalence between aluminum and steel structures. There are several ongoing efforts in this area, including the POP&C, MARSTRUCT, and ASRANet projects that should be monitored to see how they could be applied to aluminum ships and craft.

Maintenance and Repair

Properly designed and maintained, aluminum marine structures can see many years of service with minimal problems. Aluminum can be very prone to fatigue crack propagation if cracking of structure does occur. Corrosion of aluminum, once initiated, tends to be rapid and concentrated, generally requiring immediate action to restore structural integrity. Although the 5xxx-series aluminum alloys do not generally require painting to avoid corrosion, improper painting procedures can lead to corrosion problems. Contact with most other metals, which are anodic to aluminum, can lead to rapid wastage of aluminum. Use of improper alloys, especially those containing copper, will also lead to rapid corrosion, against which coating systems offer little protection if the aluminum is constantly exposed to seawater.

The research needs for fatigue analysis methods in design were mentioned above, and are equally important for repair, where little time or money is generally available for the repair of fatigue cracks. The Ship Structure Committee has sponsored work in the past on improving the fatigue life of common structural details on steel ships, and that work should be extended to include aluminum. Knowledge of the corrosion resistance of marine aluminum alloys is needed to determine if a structural problem is material related.

Structural Health Monitoring

Structural health monitoring systems have seen application to some aluminum vessels, including the simple installation of accelerometers that warn ship operators when to reduce speed or take a more favorable heading when design levels of loads are being exceeded. These systems are sometimes misunderstood or are perceived as being too sensitive, and components such as audible alarms are frequently turned off.

The lack of confidence of the operators in such monitoring systems demonstrates the need for improvements in those systems. There are other needs that are more specific to aluminum vessels, particularly for the early detection of fatigue cracks. Because aluminum structures may have more insulation than ships built with steel, early detection of cracks by visual inspection is more difficult, although it is more important because of the rapid fatigue crack propagation rates in aluminum. Methods for early crack detection such as installation of trip gages should be explored for use on aluminum vessels.

Monitoring of the structural health of an aluminum vessel over its lifetime would be enhanced by the development of methods of analyses of the fatigue of the structure over the operational lifetime of the vessel. Such a model would be updated during the life of the ship from information gathered on actual fatigue cracking events, indicating if the forecasted behavior is optimistic or pessimistic.

Emerging Technologies

Friction stir welding of aluminum ship structures has gained rapid usage over the last few years, with new applications and methods under exploration. The research issues are similar for other welded properties. Paik is investigating the effect of the different properties on the compressive strength of panels, but the effect on other failure modes needs to be determined too. The basic material properties for all alloys being joined need determination, including their statistical properties. The effect of friction stir welds on corrosion strength is being investigated by NSWCCD, but this needs to be done in the context of standardized testing of aluminum alloys for marine service.

Conclusions

Aluminum has become the material of choice for many types of vessels, particularly high-speed vessels where lightweight structure is important for meeting design goals. The methods of design and fabrication of aluminum contain many areas of conservatism that if overcome by aggressive research will lead to even greater performance at reduced cost.

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