DAMAGE ASSESSMENT UNDER REPEATED SLAMMING AND CREEP OF FOAM CORE SANDWICH COMPOSITES

By

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ABTRACT

Sandwich composites are increasingly being used in the ship hull design due mainly to (i) their high strength to weight ratio, and (ii) the ability to functionally grade them for a broad range of commercial and naval applications. Sandwich composite are composed of widely differing constituent materials that can lead to substantial instabilities along the interfaces when subject to external loading and/or environmental effects. However, due to the layered nature of the material, damage in sandwich composites generally remains hidden along the interfaces and thus out of sight until reaching catastrophic dimensions – which make damage detection a very challenging task. Ship hulls routinely undergo a wide range of loading conditions that can compromise their safe operational life. With the main objective of understanding damage progression mechanisms, this thesis takes two of the most detrimental but least understood loading scenarios relevant to service life of the ship hull, namely, repeated slamming and cyclic creep in seawater of foam core sandwich composites.

A test program designed and carried out to mimic the ***repeated slamming*** of the bow section of fast moving small vessel on the ocean surface provided some unique observations in terms of failure mode transition and associated changes in the lifetime. Testing was performed on flat rectangular specimens that contained symmetric semi-elliptical edge flaws produced near the end of the specimen held by the rotating cam. Damage progression and modes of failure were evaluated for two types of sandwich composites with comparable global strength and stiffness but different foam density and facesheet strength. In-spite of comparable mechanical properties, lifetime of *Type 2* specimens was found to be over two orders of magnitude greater than *Type 1* specimens – indicating that the lifetime is highly dependent upon the constituent materials. *Type 1* specimens (softer core/stronger facesheet) consistently failed by interface and through the

thickness core shear, independent of the flaw size. On the other hand, a gradual decrease in the flaw size (i.e., decreasing stress intensity) in *Type 2* specimens (denser core/weaker facesheet) produced a striking transition in the mode of failure, from local buckling in the vicinity of the flaw site along with exponentially increasing lifetime, to interface shear failure at the free end accompanied by a dramatic drop in lifetime. These results are quite unique as a decrease in stress intensity is expected to lead to increasing lifetime and not to a decrease as currently observed. This curious phenomenon is attributed to a complex transition in the mode of failure from local buckling to interface delamination as a function of flaw site stress intensity.

Foam core sandwich composites were also subjected to ***creep to failure and cyclic creep*** in seawater which has never been reported in the literature. The instantaneous and secondary responses varied dramatically depending on the environment and loading type. Compared with creep to failure tests performed in air, about 15% higher deflection and over 50% reduction in lifetime was witnessed in specimens subjected to seawater, which is quite a dramatic loss of life especially in light of the a maximum of 2.3% water gain observed. However, seawater with high salt content has the propensity to breakdown the cell walls due to plasticization and thus deteriorates the interfaces. Cyclic creep was performed in order to mimic an actual ship hull service lifetime scenario whereby cargo and passengers are loaded for extended periods of time and subsequently unloaded. The specimens were loaded for 24 hours while the unloading times varied from 24 to 6 hours. Significantly reduced life and extensive damage were observed under cyclic creep as compared with creep to failure specimens. Counter intuitively, lifetime and number of cycles to failure were found to decrease as a function of increasing unloading periods, which is explained in terms of stress relaxation and cyclic behavior of the sandwich composite. Modes of failure were predominantly indentation and core compression.

RESUMEN

Los materiales compuestos tipo sándwich se utilizan cada vez en el diseño del casco de embarcaciones debido principalmente a (i) su alta relación de fortaleza a peso, y (ii) la capacidad de funcionamiento para una amplia gama de aplicaciones comerciales y navales. El compuesto sándwich se compone de materiales con propiedades diferentes que pueden conducir a inestabilidades sustanciales a lo largo de las interfaces cuando se somete a carga externa y / o el medio ambiente. Sin embargo, es debido a su constitución de laminado que el daño en materiales compuestos se mantiene oculto a lo largo de las interfaces, por lo tanto fuera de la vista hasta llegar a dimensiones catastróficas. Más aun la coraza de los barcos se somete rutinariamente a una amplia gama de condiciones de carga que pueden comprometer su vida útil. Con el objetivo de entender los mecanismos de la progresión del daño, esta tesis tiene dos de los escenarios más perjudiciales y más relevantes para la vida útil de la coraza de un barco. Esto es el impacto repetitivo de las olas acompañado de pruebas de fluencia a un esfuerzo constante.

Un programa de prueba diseñado y realizado para imitar el impacto repetitivo de las olas a la coraza del barco el repetido proporciona observaciones únicas en términos de transición de modo de falla y los cambios asociados a la vida útil. Las pruebas se realizaron en muestras rectangulares planas que contenían defectos de borde semi-elípticos y simétricos producidos en la base del espécimen que estaba sujetado a un eje de rotación. La progresión del daño y los modos de fallo fueron evaluados para dos tipos de materiales compuestos tipo sándwich con propiedades de fortaleza y rigidez similares pero con diferente densidad de la espuma y grosor de las caras del compuesto. Se encontró que a pesar de las propiedades mecánicas similares, el espécimen del Tipo 2 Tipo (más denso núcleo / cara más débil) demostro tener una vida útil de más de dos órdenes de magnitud en relación al Tipo 1(más suave núcleo / cara más fuerte),

indicando que el tiempo de vida es altamente dependiente de los materiales constituyentes. Los especímenes Tipo 1 (más suave núcleo / cara más fuerte) fallaron consistentemente por la interfaz, independiente del tamaño del defecto. Por otro lado, una disminución gradual en el tamaño del defecto (es decir, la disminución de intensidad de tensiones) en muestras Tipo 2 (más denso núcleo / cara más débil) produce una transición notable en el modo de fallo, de pandeo local en la vecindad del sitio del defecto a una delaminación en el extremo libre alejado del defecto, acompañado de un aumento exponencial de su vida útil solo en el punto de transición, ya que al pasar ese punto hay una baja notable en la vida útil. Estos resultados son bastante únicos ya que se espera una disminución de la intensidad de tensiones para llevar a incrementar el tiempo de vida y no a una disminución como se observa actualmente. Este curioso fenómeno se atribuye a una transición compleja en el modo de fallo de pandeo local a una de delaminación en la interfaz como una función de defecto de intensidad de tensiones sitio.

El compuesto sándwich de núcleo espuma también fue sometido a esfuerzo fijo hasta la ruptura así como a esfuerzo fijo con lapsos alternados con descanso en agua de mar con el fin de imitar el escenario que presenta el casco del barco en su vida útil, todo esto nunca antes reportado en literatura. . Las respuestas instantáneas y secundarias varían dramáticamente dependiendo del entorno y de tipo carga. Al compara las pruebas de esfuerzo fijo hasta la ruptura realizadas en el aire, la desviación es aproximadamente 15% mayor la deflexión y más del 50% en cuanto a la reducción en el tiempo de vida, de lo que se observó en muestras sometidas a agua de mar. Tomando en consideración que el máximo de ganancia de masa de agua fue de un 2.3% notamos que el agua de mar con alto contenido de sal tiene la propensión a la ruptura de las paredes celulares, debido a la plastificación y por lo tanto se deteriora las interfaces. En la prueba de esfuerzo fijo con lapsos alternados con descanso, los especímenes fueron cargados durante 24 horas mientras que los tiempos de descarga variaron de 24 a 6 horas. Un considerable daño y una significativa disminución de la vida útil del espécimen fue observado en las pruebas con lapsos de descanso alternado, esto es si lo comparamos con los de esfuerzo fijo hasta la ruptura. Curiosamente, la vida y el número de ciclos hasta la ruptura se vio disminuida al aumentar los períodos de descarga. Los modos de falla fueron predominantemente de indentación y la compresión del núcleo.

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DEDICATION

My kids

That although not physically present,

They have always been on my mind

A mis hijos

Que aunque no están de cuerpo presente,

Siempre han estado en mi mente

ACKNOWLEDGMENTS

A mis profesores

A mi familia

A mis compañeros de maestría

A mis amigos

A Dios

INDEX

LIST OF FIGURES

LIST OF TABLES

CHAPTER I: INTRODUCTION

There is an ever growing quest for lightweight, high strength and impact resistant materials in the ship building industry. As a result, sandwich composites have emerged as the material of choice due mainly to their ability to be tailored (functionally graded) to address a broad host of applications, while keeping the weight and cost to a minimum. However, the damage detection capability has not kept up with the increasing use of sandwich composites which is critical for the safe operational life. Damage detection has primarily been based on years of experience mostly with conventional metallic or wooden ships. However, damage mechanisms in sandwich composites differ vastly from the conventional alloys and thus, the experience based safe life prediction is increasingly proving inadequate. Therefore, a concerted effort is required to address this highly relevant damage detection and service life reliability aspect of sandwich composite ship hulls – and this thesis work is streamlined towards achieving that goal.

The type of core (polymer, metallic, foam, honeycomb, density, thickness), facesheet (glass, carbon, graphite, weaving pattern, tow size, etc.) and interface (binding agent) play a determining role in the mechanical and fracture properties of the sandwich composites. Polymeric foam core sandwich composites have successfully been implemented in the ship hull construction due to cellular consistency, ease of fabrication, sizing and economic viability. However, large disparity in the fracture properties of the various constituents of the sandwich composite can also lead to instabilities along the interfaces. Furthermore, the shift in the modes of failure and associated changes in lifetime are highly dependent on the properties of the constituents of the sandwich composites and thus do not lend themselves to a simple analytical formula. The problem of damage detection in sandwich composites is further exacerbated under dynamic loading conditions, such as, slamming, due to complex stress wave interactions or when subjected to hostile marine environment in combination with extended loading-unloading periods. Needless to say, the information regarding damage initiation, propagation and modes of failure is crucial in making a meaningful service life assessment and to avoid disasters. However, discerning damage in sandwich composites is a highly elusive process as the damage remains hidden along the interfaces only to manifest on the surface when nearing catastrophic dimensions.

Ships are routinely subjected to a wide range of loading conditions, such as, deadweight, fatigue, creep, impact, etc. as well as environmental effects, particularly seawater and vast temperature gradients that can potentially lead to reduced service capability. Each loading or environmental parameter leave a distinct damage signature, however, assessing the synergistic effect of various loading and environmental parameters is a daunting task. It is common knowledge that cyclic loading can be more detrimental to a material as compared with quasi-static or sustained loading. This thesis, therefore, takes two of the most detrimental but least understood loading scenarios relevant to service life of the ship hull, namely, repeated slamming and cyclic creep in seawater of foam core sandwich composites.

Repeated slamming has been known to impose life limiting consequences on the marine vessels operating in rough seas. Bottom slamming represents a violent impulsive event when the fore section of the vessel emerges out of water and slams the ocean surface upon reentry giving rise to very high acceleration rise time (approaching 10g's) in a timescale in the order of milliseconds that can impair the vessel's ability to operate safely – fortunately such events are not very common. However, bow flare slamming which represents the impact with oncoming waves is highly cyclic in nature, even though it is not as detrimental as the bottom slamming.

The current work embodies an effort towards capturing the damage mechanisms under bow flare slamming.

The analytical and empirical literature is quite abundant on the slamming of ship hulls, however, it has an overwhelming focus on:

1. *Bottom slamming* – far more detrimental than bow flare slamming but a rare occurrence, whereas bow flare slamming is highly cyclic in nature and with a typical design life of >40 years can impose extensive impact fatigue damage.
2. *Single slamming* of wedge shaped symmetric ship hull cross section panels – slamming is highly cyclic in nature and single slamming cannot be extrapolated to gain an insight into the repeated slamming induced progressive damage and resulting transient behavior.
3. *Peak pressure* and pressure distribution measurements - granted that ship hull design is primarily based on the peak pressure measurements along critical vessel components coupled with classical plate theories; pressure distribution cannot adequately predict the long term failure occurrences and modes of failure that are indispensable for service life reliability.

The problem of damage assessment in sandwich composites under repeated slamming is highly relevant to ship hull design and safe operational life while the current state of knowledge is limited on this very important subject. With an objective of simulating bow flare repeated slamming, the first part of this thesis undertakes a careful evaluation of damage mechanisms in two types of foam core sandwich composites with comparable strength and stiffness but vastly differing core and facesheet properties. The results provided in Chapter II offer a unique perspective on the complex interaction of lifetime and modes of failure as well as of their strong dependence on the constituent properties as opposed to the global properties of the sandwich composite material.

The thesis also makes a rigorous attempt at understanding damage and lifetime characteristics of foam core sandwich composites under **creep to failure and cyclic creep** in seawater – which has no reference in the literature and is therefore a unique task. Ships are designed to carry passengers and cargo that must remain loaded for extended periods of time followed by an unloading period thus introducing repeated sagging stresses on the ship hull. Creep represents the response of the material under long terms sustained loading, which has traditionally been associated with high temperature applications in conventional engineering materials and therefore, ignored under ambient conditions. However, polymeric foam cores are well known to be susceptible to viscoelastic effects that can further accelerate in the presence of seawater due to plasticization and subsequent breakdown of the interfaces between the core and the facesheet.

In-spite of abundant literature on the subject of creep, there appears to be a significant gap in the creep and cyclic creep of sandwich composites as outlined below,

i) *Creep of sandwich composites* - significant lack of research on this subject while foam is highly viscoelastic in nature and thus prone to creep effects.

ii) *Cyclic Creep* – no literature on this highly critical aspect of damage in sandwich composites.

iii) *Creep in air and water* - testing in air and water is performed separately and synergistic effects are never simulated.

The understanding of the damage mechanisms in foam core sandwich composites under cyclic creep is highly relevant to the safe operational life of the ships. The second portion of this thesis, therefore, seeks to address damage mechanisms and lifetime issues due to creep to failure and cyclic creep of sandwich composites in the seawater, as this scenario is most relevant to ship hulls. The work is unique, as the literature on this very important subject is extremely scarce.

The research outcomes as detailed in Chapter III provide a vivid illustration of how the creep life can be seriously compromised when the material is subjected to seawater even when the water ingress may be very limited. Results in Chapter III also illustrate the criticality of the unloading periods in the cyclic creep scenario.

CHAPTER II: REPEATED SLAMMING

2.1 BACKGROUND

The term ‘slamming’ is generally used when forward bottom of the hull emerges out of the water due to large pitch and heave motions and slams the water upon re-entry. Whereas, the term ‘flare slamming’ refers to the occurrence of frontal impact between the bow flare and the oncoming wave. Even though the analysis techniques are somewhat similar, bow flare slamming event is generally not as severe as the bottom slamming – yet on the other hand bottom slamming is not nearly as common as the highly cyclic bow flare slamming [1]. Other types of slamming loads include, ‘breaking wave impacts’ that are generated by the superposition of incident wave and bow wave hitting the bow of a blunt ship that can occur even for small ship motion and ‘wet-deck slamming’ that takes place when the relative heaving amplitude is larger than the height of a ship’s wet-deck. Figure 1 illustrates various types of slamming described here.

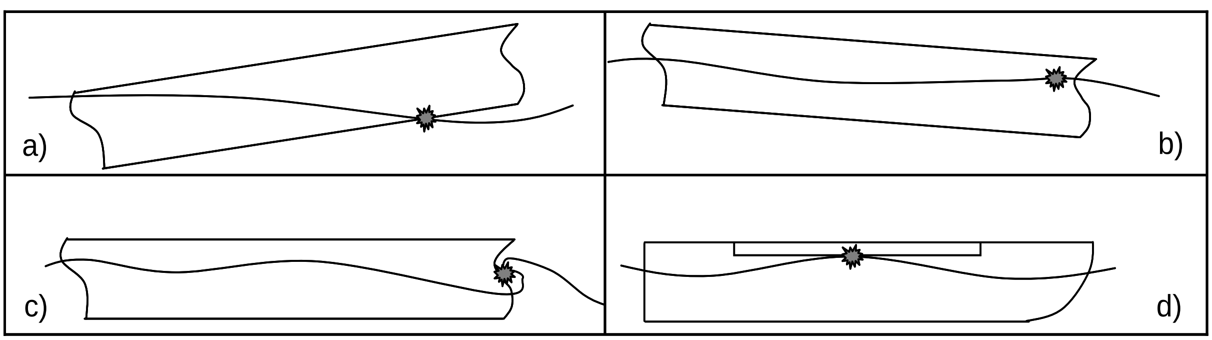


Figure 1: Basic slamming classification, a) Bottom slamming b) Bow-flare slamming c) Breaking wave impact d) Wetdeck slamming (Catamaran)

High speed lightweight marine craft operating in rough seas undergo complex loading conditions principally as a result of repeated slamming of the ship hull on the ocean surface.

Therefore, the hulls must be light and yet stiff enough to withstand these loads. Wave slamming is a violent impulsive event with peak pressures occurring when the ship's bow hits the water at high re-entry velocities; the resulting acceleration rise time of almost 10g and duration in the order of milliseconds makes the test design, instrumentation and in-situ data collection a difficult task [1-9].

2.1.1 Analytical Work

In-spite of abundant literature on the slamming of ship hulls, aside from scarce work on repeated slamming [8-11]; analytical [1-7,11-16] and experimental [2-6,11,17-20] research is largely limited to single slamming with an overwhelming focus on discrete pressure measurements. Granted that the pressure distribution is a key design parameter, it nevertheless does not offer any damage or service relevant information [1]. Furthermore, in light of the scatter that is commonly observed, it is somewhat questionable to treat the measured pressure distribution data in a deterministic manner [3,14,17]. The pressure data is also highly discrete, however, the issue was addressed by Rosen [1] who developed a robust interpolative numerical scheme capable of taking a few discrete pressure data points and generating the entire pressure profile. In addition, Zhao and Faltinsen [6] concluded that the impact pressures are at their peak during the initial phase corresponding to first half oscillation period and this is the most important result from a practical point of view.

The assessment of repeated slamming is in an analytical framework appears to be essentially impossible without quantitative cyclic damage progression and a relevant failure theory – which is yet to be reliably established. Therefore, analytical literature remains devoted exclusively to single impact with an almost exclusive focus on the various aspects of discrete pressure estimations. Some of the earliest reported wave impact studies were motivated by landing sea planes and planning crafts [12,13] pioneered by Wagner and Von Karman to predict the pressure distribution along the wedge shaped (bow) samples that have become the basis of much of ship hull design and analysis ever since. Wagner [12] simulated a wedge (bow) setup (as seen in Figure 2) as a boundary value problem to acquire results corresponding to slamming pressure distribution that depend on structural form and time dependent water entry velocity. Wagner's model can be provided in the following simplified form[12],

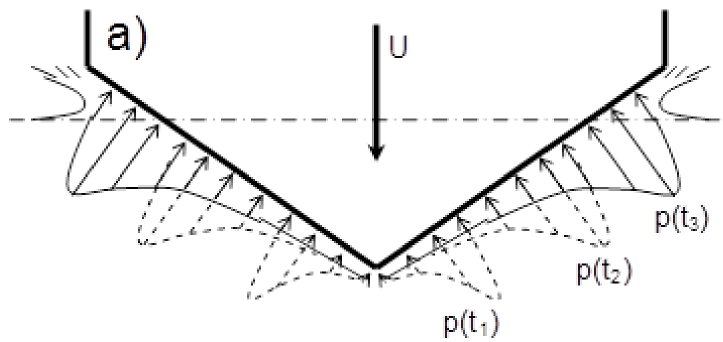


Figure 2: Wave slamming pressure distribution along V shape Wedge

$$p - p_a = \rho V \frac{c}{\left(c^2 - x^2\right)^{1/2}} \frac{dc}{dt} + \rho \frac{dV}{dt} \left(c^2 - x^2\right)^{1/2} \quad (1)$$

where p denotes the slamming pressure and p_a refers to the added mass pressure that incorporates the hydrodynamic forces ($p=p_a$ on the free surface). The transversal coordinate 'x' is measured from the keel of the wedge, c is the wetted half beam expressed as $c(t) = \pi Vt / 2\tan\beta$, where β is the deadrise angle. *dc/dt* corresponds to rate of change of wetted surface and V appears from the velocity potential as $\frac{\partial \varphi}{\partial z} = -V \ , \varphi = -V\left(c^2 - x^2\right)^{1/2}$. According to Eq. 1, the maximum pressure is limited to $P_{\max} = \frac{1}{2}\rho\left(\frac{dc}{dt}\right)^2$ when the velocity is constant. Using the conservation of momentum principles, Von Karman [13] also analyzing a symmetric wedge entering a calm body of water described the average pressure imposed on the wedge in the following form,

$$p = \frac{\rho V^2}{2} \frac{\pi \cot \beta}{\left(1 + \frac{\gamma \pi x^2}{2W}\right)^3} \tag{2}$$

where p is the maximum pressure taking place at the keel at the moment of first contact and W is the weight. Eq. 2 suggests that the maximum pressure takes place at x=0 (along the wedge). Wagner and Von Karman analysis results in similar analytical outcomes with the main difference being that Von Karman neglects the local uprise of water upon impact that leaves the wetted surface to be smaller.

Since Wagner and Von Karman's initial work, many other researchers have made significant contributions to the subject of wave slamming. The problem of analytical fluid structure interaction is generally made difficult by continuously moving boundaries between the hull and the water surface and coupling of hydroelasticity and structural response [15-19]. The problem can be greatly simplified by assuming inviscid, incompressible and irrotational potential flow, as well as by limiting the degrees of freedom of motion, reducing the general three dimensional problem to a series of two dimensional sections and most importantly by assuming that the loads can be applied quasi-statically, i.e., and no hydroelastic interaction occurs and the hydrodynamic loads and structural response can be treated separately [12-19].

Hydroelasticity essentially represents the fluid and the structure interaction, i.e., during the impact, the water pressure acts on the structure and the structure deforms while simultaneously the structure induces pressure and deforms the water domain. It may be tempting to ignore hydroelasticity to justify quasi-static analysis, however, the hull then must be assumed rigid which risks dangerously overestimating the pressure response [1,20-22]. In reality it is impossible to formulate a uniform design pressure which is equivalent to the real hydrodynamic loads, especially in sandwich composite structures where the margin of failure is so different in various constituents of the material. If, however, the structure can be assumed rigid then quasi-static analysis can be performed and with pressure taken from Wagner's theory, Eq. 1 [13] and elementary beam theory, the panel deflections and strains can be written as [8,20],

$$w = \mu \frac{\rho \pi^2 V^2 l^4}{1536 EI \tan \beta} \qquad or \qquad \varepsilon = \frac{\sigma}{E} = \frac{My/I}{E} = \frac{\frac{Pl^2/8}{I}}{E} = \frac{\rho \pi^2 bzV^2 l^2}{32 EI \tan \beta} \tag{3}$$

In an attempt to justify the much simpler quasi-static analysis, researchers have offered some guidelines, however, they remain a subject of ongoing debate. For example, Bereznitski [18] based on his FEA hydroelastic analysis found that the ratio between the duration of the impact and the first period of the natural frequency is the key parameter that determines whether the effects of hydroelasticity are significant enough to be considered in the analysis; if the ratio is greater than 2.0, the effect of hydroelasticity may be ignored. Faltinsen et.al. [5] highlighted the importance of hydroelasticity using hydroelastic orthotropic plate theory and presented structural response in relation to loading period and wet natural period of the structure. This theoretical work substantiated by experimental verification suggested that during bow flare, the effects of hydroelasticity are not locally significant, but global influences are manifested in the form of whipping (transient hydroelastic response -vibration). However, when the local loads become very high during slamming, effects of hydroelasticity could become significant. Stenius [5] following an analysis similar to Faltinsen [5], concluded that if the ratio of loading period and natural period is greater than 5, then the hydroelastic effects may be ignored. As a general guideline, if the first natural period of vibration is distinctly smaller than the shortest loading period, then the structural deformations are small and the structure can be assumed rigid and treated with the quasi-static loading assumption, on the other hand, if the quasi-static theory is not applicable, the problem has to be treated as a hydroelastic problem, which means solving coupled non-linear differential equations [1].

2.1.2 Experimental Work

Even though the phenomenon of wave slamming has been under investigation for nearly a century, fully instrumented experimental verification did not surface until a few decades ago. Testing of complete hulls in the marine environment have been performed, however, it remains a cost prohibitive proposition [1]. Therefore, aside from very limited work on repeated slamming [7-9,24], experimental research has largely been limited to single slamming [2,4-6,12,16,17.23] with an overwhelming focus on hydrodynamic pressure distribution. Testing is performed on rectangular flat panels instrumented with pressure sensors, strain gauges and accelerometers; the panels are mounted on wedge shaped rigid supports to simulate the bow section of the ship and dropped in a free or controlled manner onto a body of calm water (Figure 2). The test results almost unanimously point to an increasing hydrodynamic pressure as a function of increasing bow flare [1-9,17,20-21].

While design procedures account for slamming events by considering peak pressures at critical locations in the vessel, the damage assessment during service life has largely been based on years of experience (with metallic ships) and routine visual inspections [7,8,11,22]. Sandwich composites offer substantial advantage over metals due primarily to their high strength to weight ratio [4,20-22], however, sandwich composites are composed of various constituents of highly diverse mechanical and chemical properties; this mismatch is a major source of localized instabilities along the interfaces that can lead to premature failure. Furthermore, damage detection is inherently more complex in sandwich composites [6-12]. Loading, environment and type of material (core and facesheet shape, density and composition) have significant effect on the complex and varied modes of failure of the facesheet (cracking, buckling, wrinkling), and the core (through the thickness and interface shear). Therefore, an increasing use of sandwich composites in ship hull construction has not only made this experience based safe life prediction unreliable, it has also made damage detection an elusive process [21-22]. As a consequence, there is a growing interest in the damage assessment resulting from repeated hull slamming.

To exacerbate the situation, the lack of viable damage detection instrumentation has made damage detection and an elusive process [8,19,20-22,36]. Optical monitoring techniques provide limited detection capability as the damage remains out of sight and hidden mostly along the interface between the opaque and stiff facesheets and the softer core, only to manifest itself on the surface when nearing catastrophic dimensions. Aside from contact issues, acoustic emission sensors fail to consistently record a broad spectrum of acoustic frequencies emanating from highly violent and repetitive slamming impact [7-8,18]. The widely used strain gauges prove inadequate under repeated slamming as, i) they produce highly discrete and erratic data, ii) they fatigue themselves, thus giving rise to the cyclic noise and necessitating frequent recalibration during the testing, iii) it is difficult to keep the gauges isolated from water, therefore, short circuiting becomes an issue that forces sporadic test interruptions to replace the strain gauges [8]. Finally, post slamming assessment via residual strength or lifetime testing proves unreliable due primarily to inherently large scatter in the data that obscures any slamming induced damage [21,23-24].

2.1.3 Modes of Failure

Modes of failure provide the most crucial information regarding lifetime damage characteristics. Any change in the material composition or loading type has a potential of leaving its distinct signature in form of failure mode. For example, clear evidence exists about the shift in modes of failure in sandwich composites from single to repeated slamming. It would, therefore, be erroneous to use the more common single slam testing results to extrapolate modes of failure of a ship which is designed and subject to repeated slamming throughout its service life. While single slamming may lead to interface failure and core shear, repeated slamming is additionally subject to damage accumulation, localized core densification and localized facesheet buckling causing a global reduction in the load carrying capability [5-8,12,24].

Literature also provides ample information regarding the modes of failure and shift thereof in foam core sandwich composites, however, it is quite restricted to flexure induced by quasi-static loading, conventional fatigue loading, some explosions/implosions, vibration and highly localized impacts [23-35]. None of these situations provide sufficient insight into high energy repeated slamming induced damage into the sandwich composites. For static loads, the composites can easily be tailored to fail in a given mode by changing the constituent properties (core density and facesheet strength), loading type or scantlings [28-33]. For example, under static loading, it has been shown that core failure occur first in short span beams and then it triggers facesheet failure, whereas, for long spans, facesheet failure may precede core failure [30,33]. In theory, failure modes may be predicted from the elastic stress analysis coupled with the appropriate failure criteria which generally suit the facesheets quite well but not so much the foam core which exhibits non-linear behavior or the complex interactions of failure modes. Therefore, experiments remain the method of choice to extract the modes of failure [30-31].

Dynamic loading adds further complexities, for instance, it has been shown that the energy absorption in sandwich composites depends more on the mode of failure as opposed to constituent properties, therefore, facesheet may have a tendency to absorb more energy than the core shear failure [28,33]. Modes of failure under dynamic loading have also been reported to shift, e.g., a change in the magnitude of load can cause a shift in the modes of failure from core shear to facesheet rupture under fatigue loading [28,29]. Similarly, failure mode can transition from core shear to facesheet fracture depending on the shape and size of the projectile, impact energy, core density, facesheet thickness or a ratio of interfacial to core shear strength [25-26,33]. In terms of quantitative assessment, quasi-static analysis fails to predict impact induced failure modes due to stress wave propagation, therefore, dynamic FEA is generally implemented which requires that a failure criteria be established, the strain rate dependency of the material be checked and strain to failure data be available, which is not readily the case [33].

2.2 OBJECTIVE

The primary goal of this research is to understand the complex nature of damage progression and modes of failure in sandwich composites subject to repeated slamming on water in an effort to mimic the bow section of a small fast moving marine vessel.

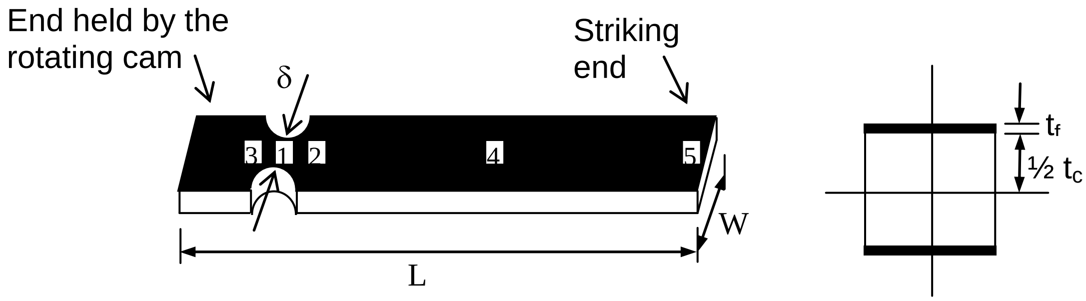
2.3 JUSTIFICATION

There is little disagreement that repeated slamming can seriously compromise the integrity of the sandwich composite ship hull, however, literature is extremely scarce on the repeated slamming induced damage characterization. This program is, therefore, designed to gain some insight into the damage and failure modes of sandwich composites under repeated slamming. The work is unique as the problem is highly relevant to the service life reliability of ship hulls, while the current state of knowledge is limited on this important subject.

2.4 METHODOLOGY

Two type of specimens were fabricated, *Type 1* and *Type 2* with a 1:4 ratio of polyurethane foam density (64 and 260kg/m^3) but similar $[0^o/90^o]_1$ glass fiber facesheet average elastic modulus and ultimate tensile stress. The flat rectangular specimen had a constant core thickness of 6.35mm, whereas, the facesheet thickness varied as 1.84mm and 1.02mm making the overall dimensions of 38cm x 5cm x 8.2mm and 38cm x 5cm x 7.37mm for *Type 1* and *Type 2* specimens, respectively. The quasi-static flexural test results found average load to failure and stiffness of the sandwich composite to be 587-649N and 246.1kN/m for *Type 1* specimens and 551-810N and 187.4kN/m for *Type 2* specimens. Therefore, there was substantially larger disparity between core and facesheet strengths of *Type 1* specimens as compared with *Type 2* specimens. Facesheets were bonded to the foam core with a 600cps epoxy resin. *Type 1* specimens had relatively thicker interface as the resin has a tendency to penetrate deeper into the lower density core during the manufacturing process. Specimens were fabricated using VARTM process.

Specimens were slam tested into a 152cm diameter and 122cm deep water tank. Impact velocity was measured using a Kistler 100mV/g with 25ks/s sampling rate accelerometer that was mounted on the back face of the model specimen. Flexiforce pressure transducers of 5.7kHz sampling rate installed on the impact faces of model specimens at critical locations exhibited a nearly linear distribution from fixed to free end with very little evidence of the hydroelastic effect. The 120 Ohm strain gages capable of 25ks/s sampling rate mounted on the back faces (tensile side) of the specimen in configuration shown in Figure 3 resulted in highly erratic response. Damage was primarily monitored optically. In some cases, florescent dyes were



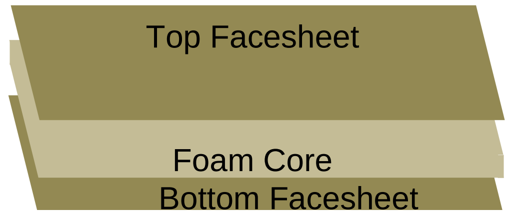


Figure 3: Specimen Configuration. [1] to [5] represent the locations of the strain gauges while pressure transducers were placed at locations [3] to [5] on model specimens

injected at the core/facesheet interface at various stages of damage propagation to facilitate damage tracking.

Testing was conducted at slamming velocity (at the free end) of 20m/s at a frequency of 1hz on an apparatus designed in-house. Rubber padding was placed on the back side of the end of the specimen held by the cam to smooth out load transfer. The slamming mechanism resembled a rotating link where the length of the link (arm) controlled the velocity of impact with 0^o representing a vertical position and 90^o the striking position (i.e., the surface of the water). Therefore, the velocity of impact varied from '0' at the fixed end to 20m/s along the free end. At impact, the specimen was designed to penetrate the water to an additional 5^o rotation with respect the water surface. The setup is more realistic than commonly adopted free drop testing and mimics a scenario for small high speed ships where the bow section continuously slams the water while moving forward. A picture of the test setup is shown in Figure 4.

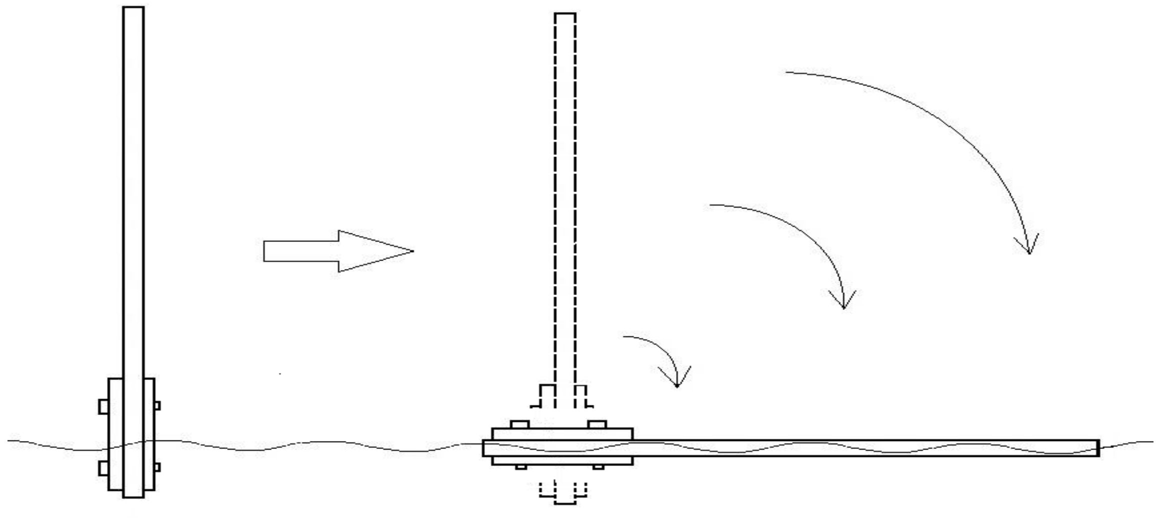


Figure 4: Repeated slamming apparatus and specimen

Specimens were designed in order to localize and control the stress level by cutting out symmetric semi-elliptical edge flaws near the end of the specimen held by the rotating cam (Figure 6). At each flaw size, slamming cycles to damage initiation, subsequent progression and catastrophic failure were recorded. By doing so, an S-N type curve representing flaw size (stress level) and number of slamming cycles to failure was generated. At least three specimens were tested under each condition.

2.5 RESULTS AND DISCUSSION

2.5.1 Type 1 Specimens (softer core/stronger facesheet)

The *Type 1* specimens consistently failed due to *interface shear* typically initiating at the free end independent of the flaw size, as seen in Figure 5. Facesheets being significantly stronger quickly lost contact with much softer foam core when subjected to high energy repetitive impact. The interface shear failure of the compression side facesheet accompanied by widespread core tearing was almost instantaneous; suggesting that it was caused by flexure

Figure 5: Typical interface and through the thickness shear failure in *Type 1* Specimens

induced shear stresses between the facesheet and the core coupled with stress wave interaction.

The observed behavior can be appreciated from the basic mechanics of layered materials of widely differing stiffness that produce instabilities along the interface [31,37]. The results are also consistent with some reports that have suggested that when prone to shear under dynamic

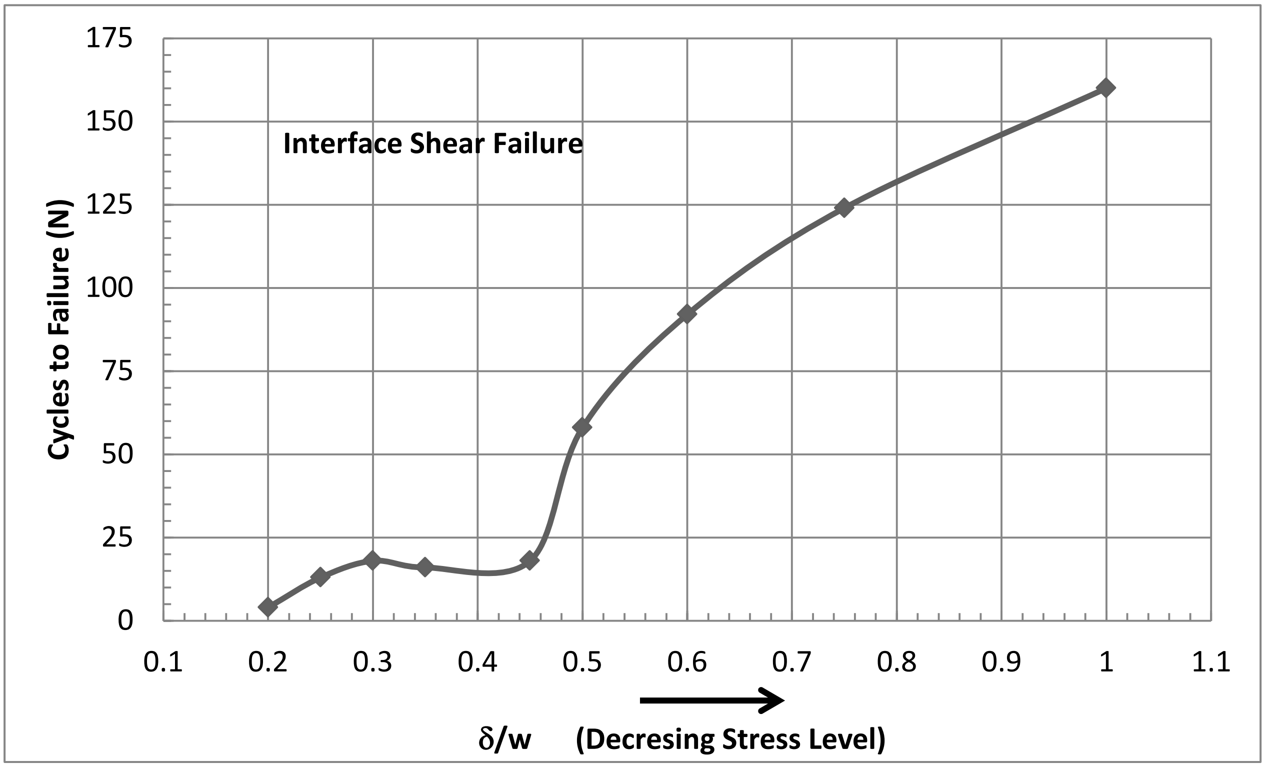


Figure 6: Average number of cycles to failure as a function of flaw size for *Type 1* specimens. No shift in modes of failure

loading, the tendency in sandwich composites is for the interface shear to precede [33]. Figure 6 indicates that the lifetime had an increasing trend as a function of decreasing flaw size (reducing stress concentration), which follows the expected behavior. Overall, the scatter in the data was minimal at $\delta/w<0.5$ and was observed to increase a little with decreasing flaw size.

2.5.2 Type 2 Specimens (denser core/weaker facesheet) The results of *Type 2* specimens suggest that a decrease in the flaw size led to a gradual increase in the number of cycles to failure up until nearing a critical point [δ_{cr}/w~70%), beyond which a surprising exponential decay in the number of cycles to failure was observed, as seen in Figure 7.

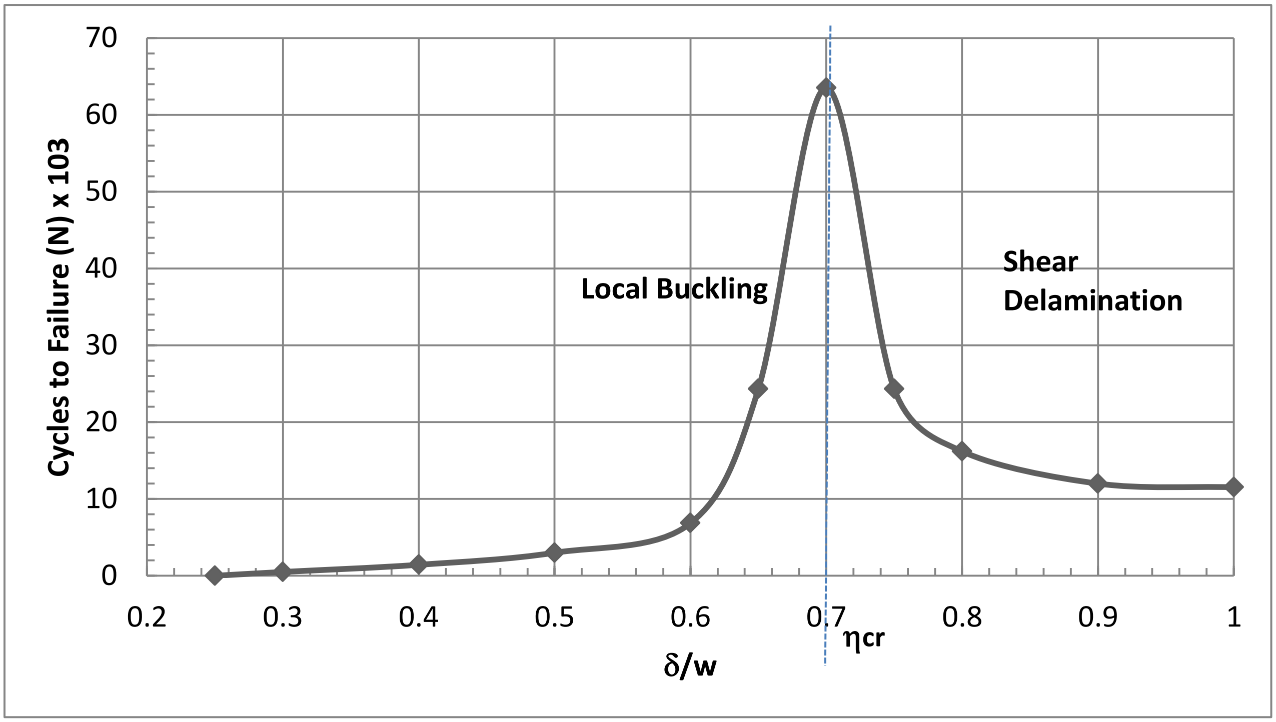


Figure 7: Average number of cycles to failure as a function of flaw size for *Type 2* specimens. Shift in mode and site of failure at the transition point δ_{cr}/w

This counter intuitive shift in the lifetime pattern was also accompanied by a vivid shift in the mode of failure from *local buckling* in the vicinity of the site of the flaw prior to δ_{cr} to *interface shear* emanating from the free end beyond δ_{cr} – as pointed out in Figures 7 and 8. Even though the flexural strengths and stiffness of *Type 1* and *Type 2* specimens were comparable; *Type 2* specimens lasted more than two orders of magnitude in lifetime as compared with *Type 1* specimens. The scatter in the data provided in Figure 7 was fairly small up until nearing δ_{cr}, however, it was in no way large enough to cast any uncertainty regarding the dramatic drop in lifetime observed beyond δ_{cr}.

The specimen failure due to *local buckling* provided some prior warning in the form of wrinkling on the compression side just before failing catastrophically. There was clear evidence of foam densification due to local buckling while the associated wrinkling led to widespread resin cracking, interface failure and fiber breakage on the compression side facesheet. The damage was highly localized near the site of the flaw and there was no evidence of any damage elsewhere. The specimen failure due to *interface shear* typically initiated at the free end of the specimen and propagated within several hundred cycles whereby compromising the two-phase action and allowing through the thickness shear failure in the foam – in this case, there was no evidence of damage near the site of the flaw. Although the mechanics of core and facesheet failure is well understood, the dynamically induced interface shear failure remains less clear. The prevailing thoughts are that local buckling failure can occcur when core has sufficiently high stiffness in through the thickness direction and that interface shear failure occurs when a flaw is present that can be propagated through shear or axial stresses [31,30] – however, these ideas are not quite consistent with the current results as they are largely based on quasi-static test results and do not account for dynamically induced stress wave interactions.

Figure 8: Typical (a) local buckling at the flaw site and (b,c) shear failure along the free end in *Type 2* Specimens

It is a common observation that damage accumulation and subsequent failure under cyclic loading in typical engineering materials reaches endurance limit below which the lifetime is considered to be infinite [23-24]. This threshold in the current case may point to the exponentially increasing life observed while approaching δ_{cr}. However, unlike any previous observations, instead of continually increasing life, the mode and site of failure shifted accompanied by significant drop in the lifetime beyond δ_{cr}. Mode transition in sandwich composites are not uncommon [28-34], however, finding literature support for the currently observed shift in the site of failure and accompanying reduction in lifetime is difficult. The authors are unaware of any failure criteria (including the widely used Tsai-Wu or Hashin) that are likely to substantiate the observed phenomena, as most phenomenological failure criteria are based on quasi-static maximum stress/strain conditions. Furthermore, literature on slamming is largely devoted to discrete pressure measurements on the wedge shaped specimens which offers little help to decipher the observed shift in failure modes [1-21]. Repeated slamming under free drop conditions as a function of impact energy has indicated local buckling to be the primary failure mode, however, in this case no flaw was introduced in the flat rectangular sandwich composite plates [8-9]. A recent study pertaining to simulated repeated slamming by adjusting the flexural fatigue waveform to mimic the slamming pressure profile has indicated the mode of failure to be flexure induced shear, however, such study fails to incorporate the dynamic features of slamming that likely lead to shift in the modes of failure [10].

The current results also suggest that the longevity in sandwich composites subject to repeated impact on water may be related to localizing stresses to cause failure by local buckling. Failure is generally anticipated in a region where the generated stresses overcome the yield strength. Local buckling stresses are predominantly related to flexure that is highest near the fixed end (held by the rotating cam) of the specimen, however, where the velocity of impact is zero. In sandwich composites, bending stresses are generally carried by the facing while core takes care of the shear stresses [30,33,37]. Therefore, it appears that as long as the localized flexural stresses were high enough to surpass the yield strength of the facesheet in compression (i.e., at larger flaw sizes), the failure was dominated by the local buckling – thus flaw site absorbing bulk of the impact energy. On the other hand, the interface failure generally develops in regions where the shear stresses are high and the out of plane compression is relatively low. Therefore, unless interface shear stresses surpass this compression, interface failure cannot take place as observed in the case of local buckling at the flaw site. On the other hand, when the flaw site stress magnitude dropped below what was required to cause facesheet compression, the slamming energy absorption was taken over by the free end of the specimen, thus causing interface shear failure where out of plane compression was minimal but the velocity of impact was maximum. Therefore, in the absence of any flexure at the free end, the interface shear failure must be initiated/propagated due to stress wave phenomena – however, a detailed stress wave analysis is quite complex in this case and outside the scope of this work.

The extensive literature on the low velocity impact of composite materials also fails to offer any insight regarding the shift observed in the mode and site of failure [25-26]. However, low velocity impacts are largely limited to highly localized point loads causing insignificant flexure; and in that respect, do not conform to the current impact scenario. Nevertheless, it is a common observation that when a projectile strikes the composites, it tends to cause local interface shear failure on the back face, the extent of which depends on the velocity of impact, shape of the projectile and the material properties, which is in some ways consistent with the current observations whereby the interface shear started on the back-face along the free end (at the site of maximum impact velocity) [22,24-27].

The fracture mechanics based justification for the shift in the observed modes and site of failure as a function of flaw size is not well formulated. Therefore, linear or non-linear FEA is not expected to provide support for the observed phenomena, as the analysis would not point to any damage at the free end as along as flexure is involved and a flaw is present to concentrate stresses. Furthermore, classical impact analysis is restricted in the sense that it can account for damage under point/line loads quite well based on the exiting failure theories but not versatile enough to incorporate slamming induced damage. In fact impact related damage assessment is overwhelmingly empirical in nature in mechanical and structural systems [24-27,33-36]. Finally, for any mathematical modeling, it would be erroneous to use quasi-statically obtained strain to failure data which is difficult to obtain under slamming [21].

The results are, nevertheless, quite relevant to sandwich composite marine vessels as they not only provide a clear demarcation from local buckling to shear delamination as a function of flaw size, they also show that even though the global strength and stiffness of the sandwich composites may be comparable, a change in the constituent properties can lead to significantly different paths to failure, as observed by comparing *Type 1* and *Type 2* specimens (Figures 5-8). The current results thus offer a unique perspective on the complex ship hull structure which is composed of primary, secondary and tertiary structures of highly varying scantlings and material properties that are put together and supported by stiffeners, girders, stringers and longitudinals, etc.

2.6 CONCLUSIONS

Two types of sandwich composite specimens were tested under repeated slamming. *Type 1* specimens (weaker foam and stronger facesheet) failed exclusively due to interface and through the thickness foam shear independent of the flaw size. Whereas, *Type 2* specimens (higher core density and lower facesheet strength) pointed to a curious and dramatic shift in the mode and site of failure from local buckling to interface shear at a distinct flaw site stress level. In-spite of comparable flexural strength and stiffness of the sandwich composites, the *Type 2* specimens lasted over two orders of magnitude longer as compared with *Type 1* specimens. Longevity of the specimens under slamming, therefore, appears to be related to designing composite structures to fail by local buckling. The results offer unique perspective on the damage assessment of sandwich composite ship hulls.

CHAPTER III: CYCLIC CREEP

3.1 BACKGROUND

Creep and stress relaxation are two of the most common ways of studying viscoelastic behavior, however, creep (constant loading) is more convenient experimentally. Typical creep of engineering materials undergoes distinct primary, secondary and tertiary phases, as depicted in Figure 9.

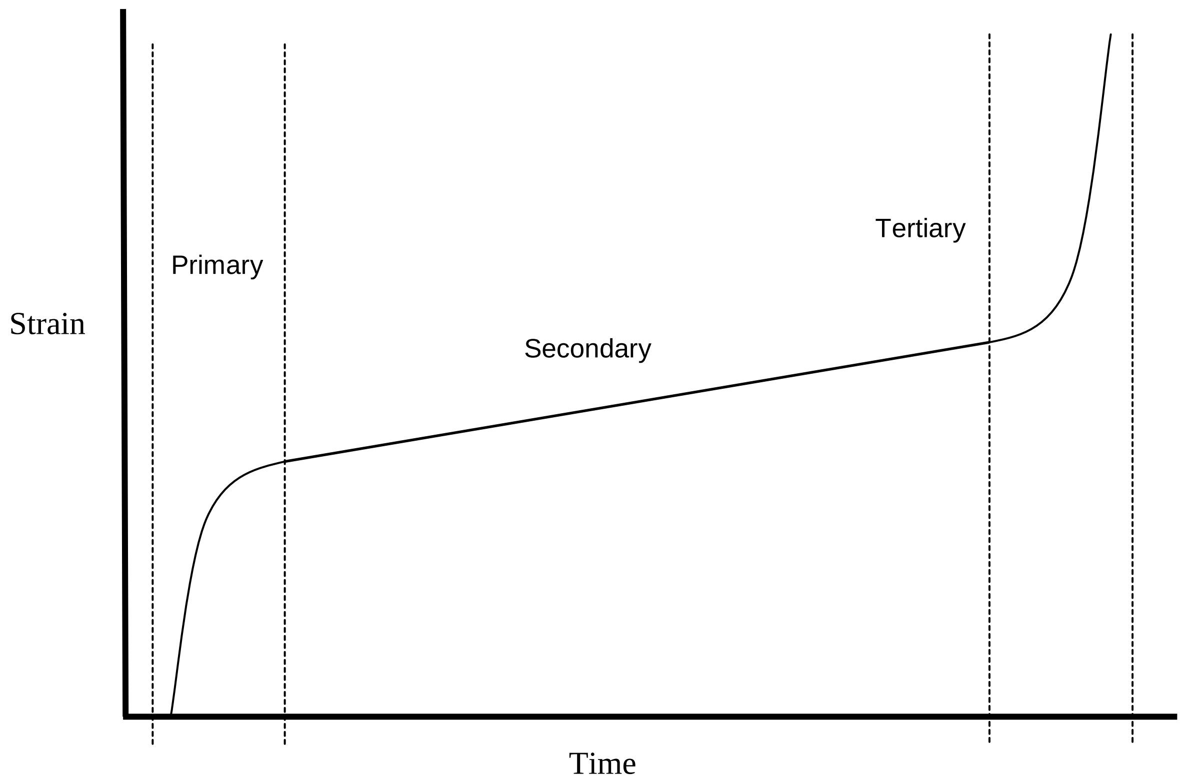


Figure 9: Typical creep phases

Primary phase refers to a sudden jump in deflection upon loading; the duration of this phase depends on the material composition. The slow and steady increase in deflection is referred to as the secondary phase which shows up as a linear portion of the curve in many engineering materials – in sandwich composites, the growth is generally unsteady accompanied by periods of stalling punctuated by hops. The secondary phase can consume well over 90% of the life of the material. The relative flexural deflection in this phase is commonly measured as $\delta_r = \frac{\delta_t - \delta_i}{\delta_e}$, where δ_r , δ_t and δ_i represent the relative, total and instantaneous creep deflections, respectively. The final phase is the tertiary phase, which corresponds to the yielding of the material and catastrophic failure. Duration of each phase in sandwich composites depends on the composition of the various constituents and on the type of impending failure mode. Viscoelastic behavior is commonly modeled using a sequence of dashpots (viscous) and springs (elastic) elements. The constitutive law for the viscous component (following Newtonian fluid) is $\sigma = \mu \frac{d\epsilon(t)}{dt}$, and for linear elastic behavior is $\sigma = E\epsilon$. Viscoelastic models of various complexities exist such as, Maxwell, Kelvin-Voigt and Burger, to name a few, however, Burger's model has been shown to suit best for the creep of polymers and polymer core composites [43,50,60,67].

Sandwich composites are known to be susceptible to viscoelastic effects that can be aggravated when operating in synergy with the hostile marine environment [45-51]. The mechanical properties (strength, modulus, toughness, etc.) and lifetime are also noticeably compromised when the sandwich composite is subjected to a combination of severe temperature gradients and moisture [46,48,52-59]. Furthermore, it is well known that cyclic loading can be more damaging to a material as compared with quasi-static or sustained tension or compression loading [46-44]. Therefore, cyclic creep can impose deleterious consequences on the sandwich composite ship hull, however, literature has not focused on this very important and relevant loading scenario [60]. The cyclic creep reported in the literature is primarily limited to conventional fatigue testing whereby loads are held stationary at the peak of trapezoidal waveform for just long enough to elicit creep response (typically less than half an hour) [43,61-63].

Joshi and Mulina [69] presented perhaps the only report on the combined effects of moisture and creep by analytically studying the effect of moisture content on the viscoelastic properties of foam core sandwich composites. However, their analytical model made several assumptions without any experimental verification; for example, they assumed a compliance curve based on the idea of water ingress through the facesheets, whereas, neat resins are known to be a good deterrent to moisture diffusion [62,70]. Nevertheless, the results indicate a classical creep curve with initial rapid deterioration followed by a stable and slow growth until catastrophic failure [69]. With a clear gap in the literature regarding the problem of creep in the presence of sea water, the work proposed herein will be the first to investigate the effect of moisture on the viscoelastic behavior of sandwich composites.

In actual marine vessels, the real time inspection aside from being costly is difficult to implement as the damage tends to remain hidden along the facesheet-core interfaces only to manifest on the surface when nearing catastrophic dimensions [38,44,51,64-65]. The lack of time dependent strength and stiffness parameters in the various constituents of the sandwich composite poses an enormous challenge to the lifetime prediction capability. As a result, existing models attribute viscoelasticity solely to the polymer foam core, thereby, ignoring contribution from the various constituents of the sandwich composite (especially the interface between the core and the facesheet) that may be considerable under combined environmental influences and mechanical loadings [43,50,53-54,66-67].

3.2 OBJECTIVE

The objective of this portion of thesis is therefore, i) to assess the effect of seawater on the creep lifetime of foam core sandwich composites, ii) evaluate the influence of cyclic creep in the presence of seawater as a function of unloaded time, iii) understand the water ingress mechanisms.

3.3 JUSTIFICATION

In-spite of abundant literature on the subject of creep, there appears to be, i) significant lack of research on the creep of sandwich composites [43,45,49-50,65,67-68], ii) literature is almost completely devoid of any cyclic creep in sandwich composites, and iii) creep testing is generally performed in air [43,45,49-50,65,67-68] and moisture absorption tests are performed separately in water [46-48,52-57], while cyclic creep testing of sandwich composites in the seawater has never been performed. This research, therefore, seeks to address damage mechanisms and lifetime issues due to creep to failure and cyclic creep of sandwich composites in the seawater, as this scenario is most relevant to ship hulls. The work is unique, as the literature on this very important subject is extremely scarce.

3.4 METHODOLOGY

Specimens with polyurethane foam core density of 64kg/m^3 and $[0^o/90^o]_1$ glass fiber facesheet were fabricated using the VARTM process. Facesheets were bonded to the foam core with a 600cps epoxy resin. With the core and facesheet thickness of 6.35mm and 1.84mm, respectively, the flat rectangular specimen had the overall dimensions of 30cmx5cmx8.2mm. The quasi-static flexural test results found load to failure and average stiffness of the sandwich composite to be 587-649N/246.1kN/m (*Type 1*). Creep testing was performed in a 70x70x180 cm^3 tank that permitted six specimens to be tested simultaneously, as shown in Figure 10. The tank was filled with actual seawater; a commercial water filter was used to keep it free of contamination.

Figure 10: Creep testing apparatus

Creep to failure was performed in air and seawater while cyclic creep testing was limited to seawater. For creep to failure tests, a constant load was placed on the specimens until catastrophic failure. In cyclic creep testing, the loading time was held constant at 24 hours while unloading time was varied at 6, 12 and 24 hours. Testing was conducted at 50% of the average ultimate static load in order to ensure a substantial creep life. Preliminary testing indicated a drastically reduced creep life at higher loading magnitudes; for example, at 70% of the ultimate static load, the specimen consistently failed within a few minutes and at 60% of life, the failure ensued within a few hours. The deflections in the primary, secondary and tertiary phases along with associated damage were closely monitored and recorded for analysis. Each specimen was weighed before and after the testing to assess water absorption. Additional tests were performed in order to measure water absorption as a function of time whereby the specimens were taken out at various intervals, lightly vibrated after the surfaces along with the edges were wiped off before weighing in the specimens. Three to eight specimens were tested under each loading condition.

3.5 RESULTS AND DISCUSSION

3.5.1 Creep to Failure

The average creep life and corresponding deflection was found to be 254h/27.9mm and 612h/24.2mm for specimens tested in seawater and air, respectively, as seen in Figure 10. The instantaneous response was found to be ~7.6mm for both air and seawater testing while significantly steeper response of 0.05mm/h was observed during the secondary phase in seawater as compared with 0.015mm/h in air (Figure 11).

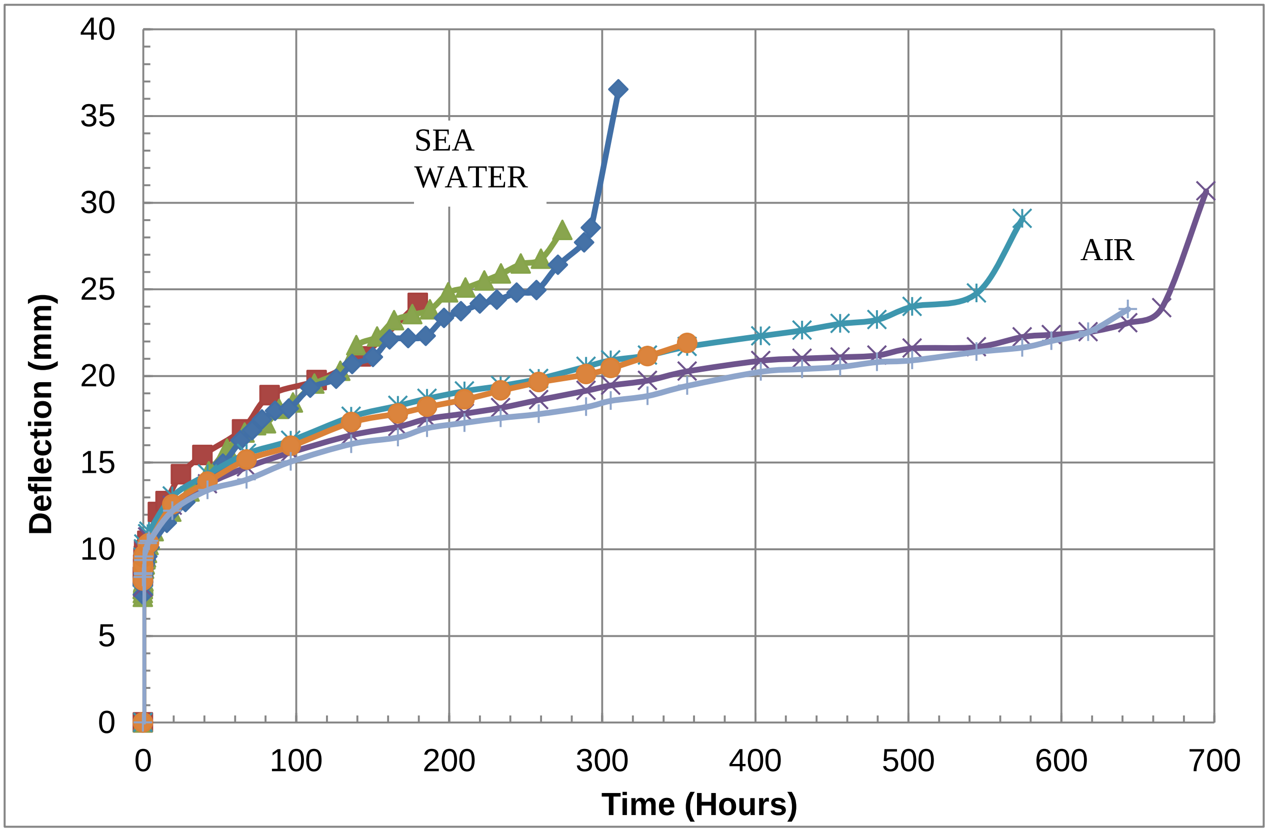


Figure 11: Comparison of Creep to failure in air and seawater

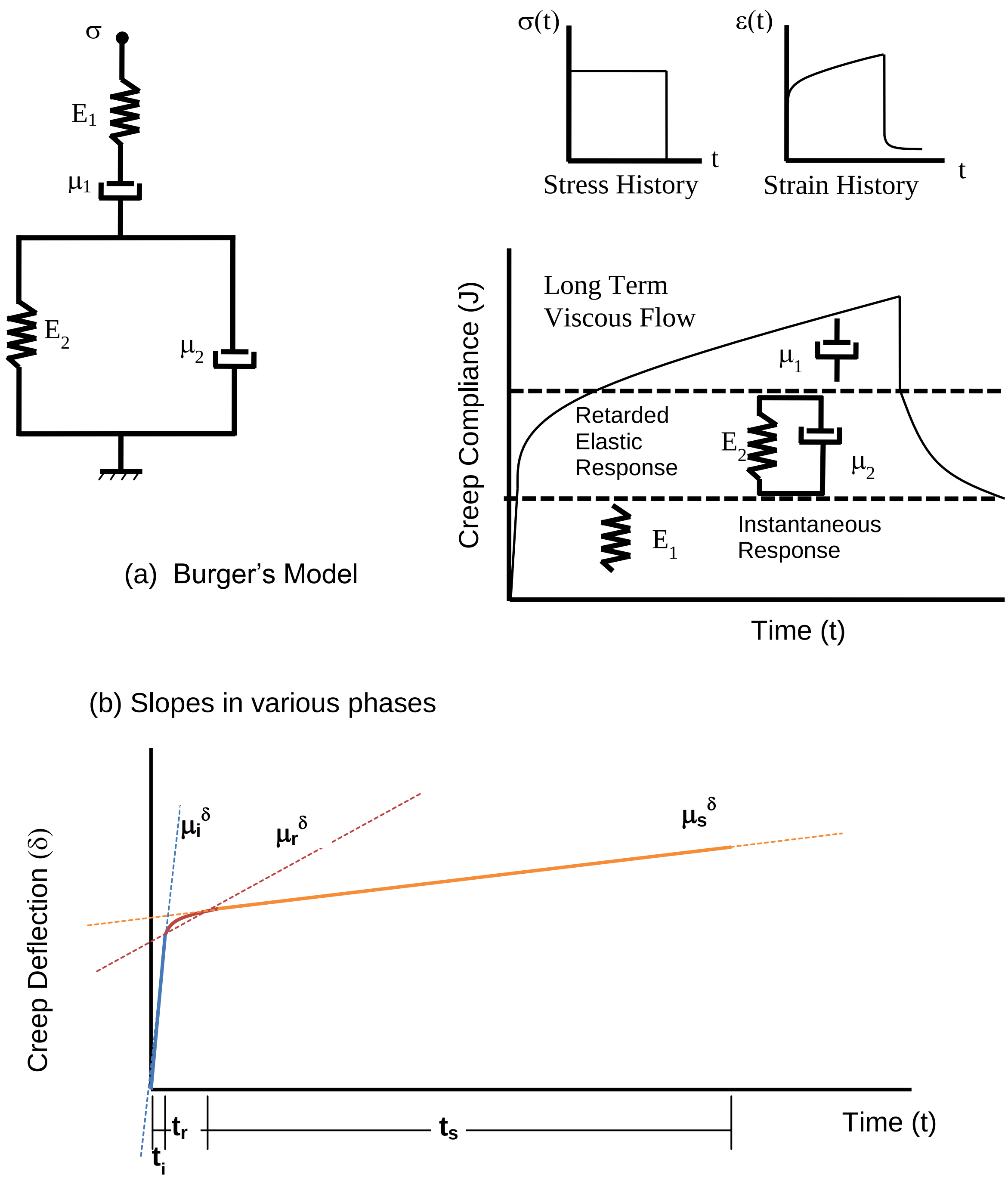


Figure 12: (a) Burger's model illustrating various stages of creep,
(b) δ-t curve and corresponding slopes.

There is a unanimous agreement that the instantaneous response is a function of facesheet properties [42-47], while long terms viscous response is associated with the foam core which can also be appreciated from the ideas embedded in the widely used Burger's Model provided in Figure 12 and Eq. 4 for reference [43,50,60,67],

$$\mathbf{J(t)} = \left[\frac{\mathbf{1}}{\mu_i} + \frac{\mathbf{1}}{\mu_r}\left(\mathbf{1} - \mathbf{e}^{-t/\lambda}\right)\right] + \left[\frac{\mathbf{t}}{\mu_s}\right] = \frac{\epsilon(t)}{\sigma} \tag{4}$$

where μ_i represents instantaneous elastic response, μ_r and λ correspond to the retarded portion, i.e., primary to secondary creep transition; whereas μ_s is the secondary creep rate and represents the inverse slope of the 'J(t) vs t' curve. The creep compliance function J(t) is defined as the time-dependent strain divided by the applied stress and measures the resistance of a material to creep deflection. In terms of practical implications, J(t) is most useful in establishing a relationship between ε(t) and δ(t) which is otherwise difficult. J(t) parameters for air and seawater testing respectively were found to be μ_i=4.16/4.69, μ_r =5.11/6.02, λ =18.8/6.98 and μ_s =2500/625.

The total creep deflection is typically obtained from superposition of instantaneous facesheet bending response (δ_i) and secondary core shear induced deflections (δ_s) [6,12-14]. For a TPB specimen,

$$\boldsymbol{\delta}_{\mathbf{total}} = \boldsymbol{\delta}_{\mathbf{i}} + \boldsymbol{\delta}_{\mathbf{s}} = \frac{\mathbf{PL^3}}{\mathbf{48D}} + \frac{\mathbf{PL}}{\mathbf{4U}} \tag{5}$$

In terms of creep compliance, the secondary deflection response for constant loading can be re-written as,

$$\boldsymbol{\delta}_{\mathbf{s}} = \frac{\mathbf{PL}}{\mathbf{4}\left[\frac{\mathbf{bd^2}G(\mathbf{t})}{\mathbf{c}}\right]} = \frac{\mathbf{P}}{\mathbf{bd}}.\frac{\mathbf{LcJ(t)}}{\mathbf{4d}} = \boldsymbol{\tau}\frac{\mathbf{LcJ(t)}}{\mathbf{4d}} \tag{6}$$

In Eqs. 5-6, P is the applied load, E_f is the facesheet stiffness, G(t) represents the core shear modulus [compliance J(t)=1/G(t)], d=f+c is the specimen thickness, b is the specimen width and L is the span length; whereas, D [$=E_f\frac{bf(c+f)^2}{2}$,[50] or $E_f\frac{(d^3-c^3)b}{12}$,[49] and U are functions of facesheet stiffness and core shear rigidity, respectively and are obtained from experiments and standard elastic analysis [40].

Based on Eq. 5, the instantaneous response was found to be about 15-30% off the experimental results depending on the form of 'D' used. However, for the secondary (core shear dominated) response, it is worth noting that the Burger's parameters are obtained from experimentally generated 'J(t) vs t' based on Eq. 6 [i.e., $J(t) = 4\delta_s d/\tau Lc$] and subsequently, fit the experimental results well. Furthermore, with the assumption of linearity, there is one to one correspondence between the secondary deflection and time. As a matter of fact, since J(t) in any event requires going through the experimentally obtained δ-t curve, applying the same assumption of linearity to instantaneous, retarded and secondary response, the total deflection can conveniently be obtained directly from δ vs t curve as,

$$\boldsymbol{\delta_{total} = \delta_i + \delta_r + \delta_s = \mu_i^{\delta} t_i + \mu_r^{\delta} t_r + \mu_s^{\delta} t_s} \qquad (7)$$

where, $\mu_i^{\delta}(P,D)$, $\mu_r^{\delta}(P,D)$, $\mu_s^{\delta}(P,U,\varphi)$ represent the slopes of the instantaneous, retarded and secondary response with $t_{i,}$ t_r and t_s the corresponding times lapsed (Figure 12b). The first two terms of Eq. 4 are functions of the applied load, scantlings and elastic properties while the last term additionally depends on environmental factors, such as, presence of seawater. As the instantaneous response does not depend on the environment or compliance parameters, it can be directly obtained from the elastic solution,$\delta_i = \frac{Pl^3}{48D}$, however, the current analysis suggest that the results are more accurate if they are based on the δ-t curve (Eq. 4).

In terms of modes of failure, the specimens underwent a dramatic core compression while the facesheets suffered very little damage until localized bending/indentation in the tertiary phase, as illustrated in Figure 9. Aside from some evidence of core compression during the later stages of the secondary phase, however, in general, damage was mostly hidden along the face-core interface which manifested on the surface only when nearing catastrophic dimensions. Specimens consistently failed in the vicinity of the loading point (where bending and shear stresses are maximum), with no evidence of damage at the supports.

Furthermore, the modes of failure did not appreciably change from seawater to air testing. The deflection (and associated damage progression) was intermittent with frequent but brief stalling in the secondary phase that consumed over 95% of the creep life, similar observations have been reported in the literature [43,49]. There is not much discussion in the literature about modes of failure in sandwich composites under creep, however, failure modes under quasi-static loading are well established and appear to support the current observations [38-39,69-71].

Foam is prone to viscous effects which may be exacerbated in the presence of seawater. Closed cell foam is designed not to absorb water, which is further impeded by up to 75% when facesheets are bonded to it thus dramatically reducing the surface area exposed to water [56-57,72]. However, the results shown in Figure 13 indicate that water absorption even though quite limited with a maximum 2.3% of the specimen weight, increased linearly with a substantial jump in the tertiary phase. Furthermore, a failure to reach a plateau indicates that the process was likely dominated by continual filling of the outer cells of the foam core aided by intermittent cell wall collapse [72]. Although the literature on seawater exposure of sandwich composites is limited and the outcomes are highly dependent on the material composition and manufacturing process; the current results are in general agreement with the cited seawater interaction/absorption phenomena in closed cell foams in sandwich composites [56,72].

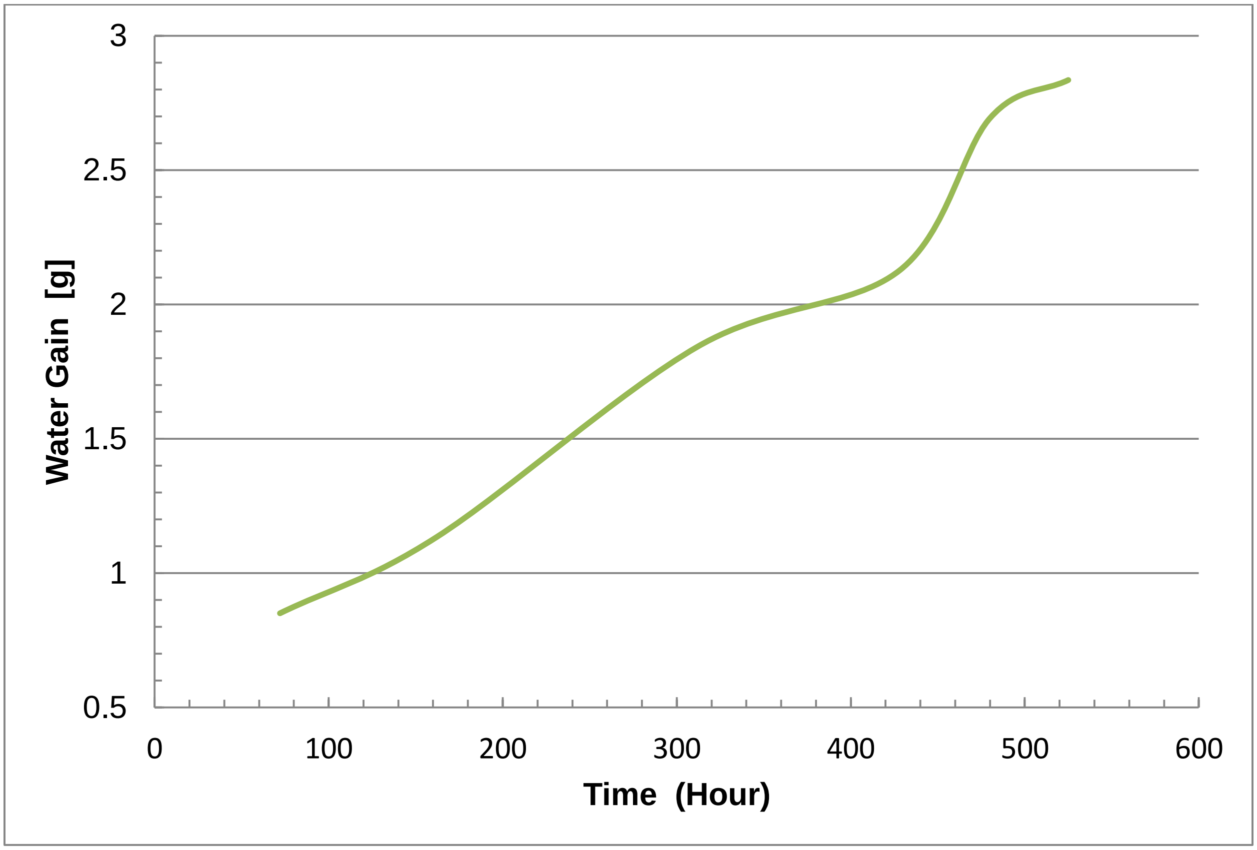


Figure 13: Typical water absorption as a function of time

In-spite of limited water gain, a comparison shows about 15% higher deflection and over 50% reduction in lifetime when specimens tested in seawater were compared with tests performed in air (Figure 10). Therefore, even a small amount of seawater ingress can have deleterious effects and is most likely linked to (foam) cell deterioration along the interface. Even though literature is not available on creep of sandwich composites in seawater, some relevant studies have shown that presence of seawater can cause a volumetric expansion in the foam and lead to weakening of the core-facesheet interface causing a substantial reduction in the fracture energy [58-59,72], which may explain the reduced life observed in the current case. It has been reported that after the initial water uptake, additional water absorption is generally more difficult in closed cell foam [57,72], however, the fact that the water continues to get absorbed over time (as currently seen in Figure 13, points at possible cell wall deterioration/collapse).

The most likely scenario is a synergistic effect of internal pressure produced as the first cell layer is filled up thus forcing additional water through narrower cavities, and external stress which would tend to intensify this process through gradual core compression thus aiding in foam cell deterioration. Furthermore, high level of inhomogeneity at the microstructural level of the core near the interface can entice water molecules to become attracted to the polar sites whereby the O-H radicals can preferentially react with the carbon chains and form hydrogen bonds with the polymer matrix causing breakdown of foam cell walls. This hydrolysis can further lead to plasticization of the foam matrix by disrupting the hydrogen bonding as well as rupture of the cell walls due to swelling induced surge in the internal stresses [57]. Also, whenever dissimilar materials are involved, there is a propensity of electrochemical reaction that can lead to dissolution of the interface, which can be greatly accelerated under localized stress. However, further electrochemical examination is warranted in order to better understand the role of seawater in the observed degradation of sandwich composites. The results are nevertheless quite relevant to sandwich composite marine vessels as they show that synergistic effect of seawater and sustained loading can be detrimental to service life of foam core sandwich composites (Figure 10).

3.5.2 Cyclic Creep in Seawater

The results reveal an intriguing trend whereby decreasing the unloading time from 24 to 6 ' ours caused an increase in the number of cycles to failure as well as in the overall lifetime, as seen in Figures 14-16. For the instantaneous response, Figures 14-17 and Table 1 suggest, (i) the 24, 12 and 6 hour unloading resulted into one, two and three life cycles along with an average of 56, 84 and 95 hours of total life, respectively, (ii) instantaneous loading and unloading responses increased slightly with increasing number of cycles and increasing unloading periods, and (iii) the deflection gradients (i.e., peak deflection to relaxation) increased with higher unloading periods. During the secondary phase of each cycle (which accounts mainly of the viscoelastic response of the foam)

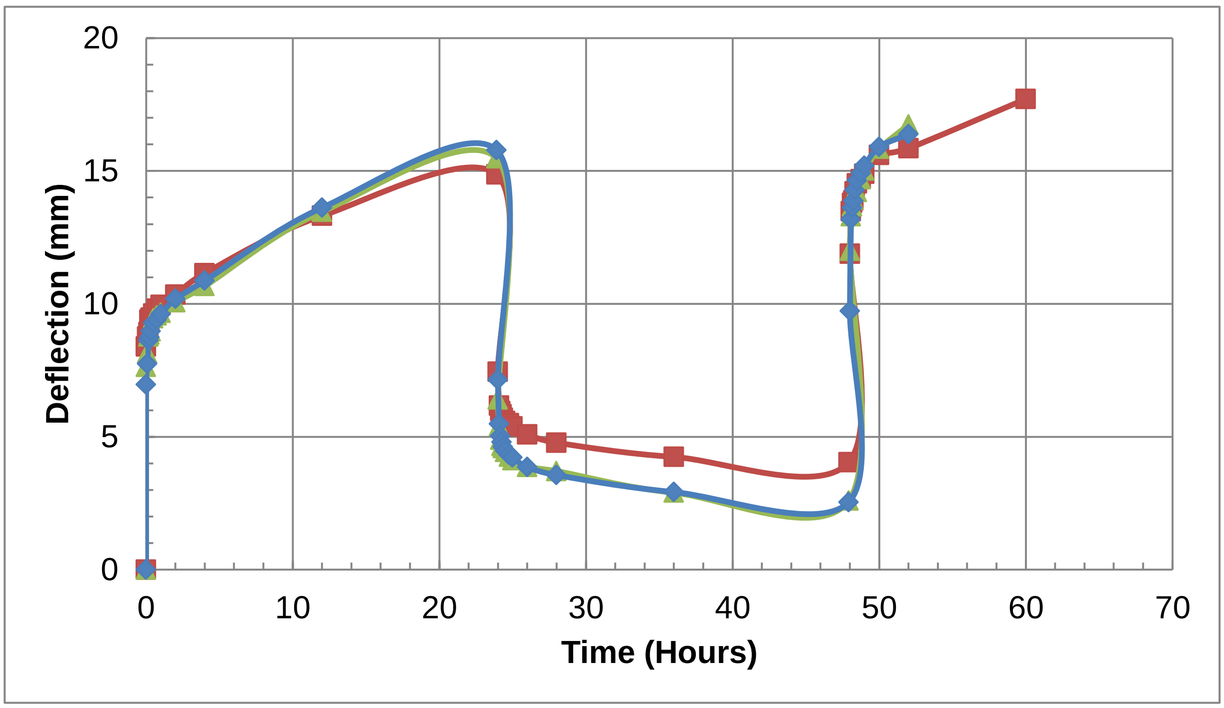


Figure 14: 24 hour loading and 24 hour unloading cyclic creep results

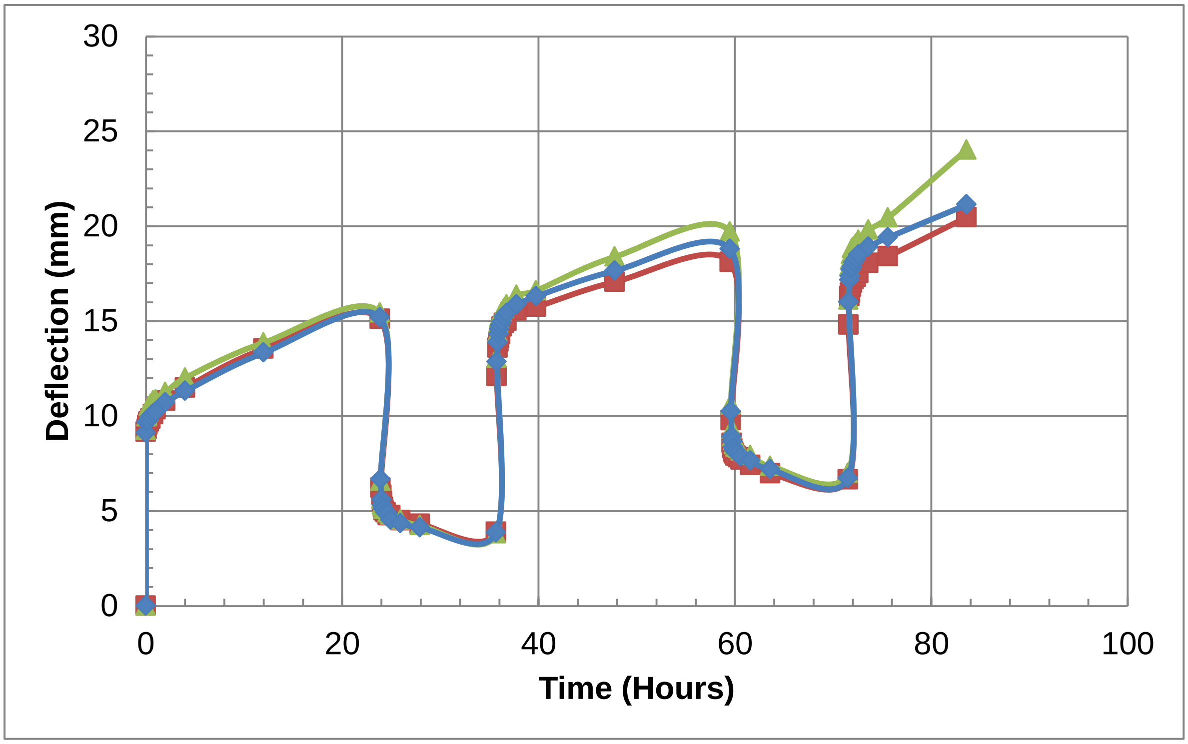


Figure 15: 24 hour loading and 12 hour unloading cyclic creep results

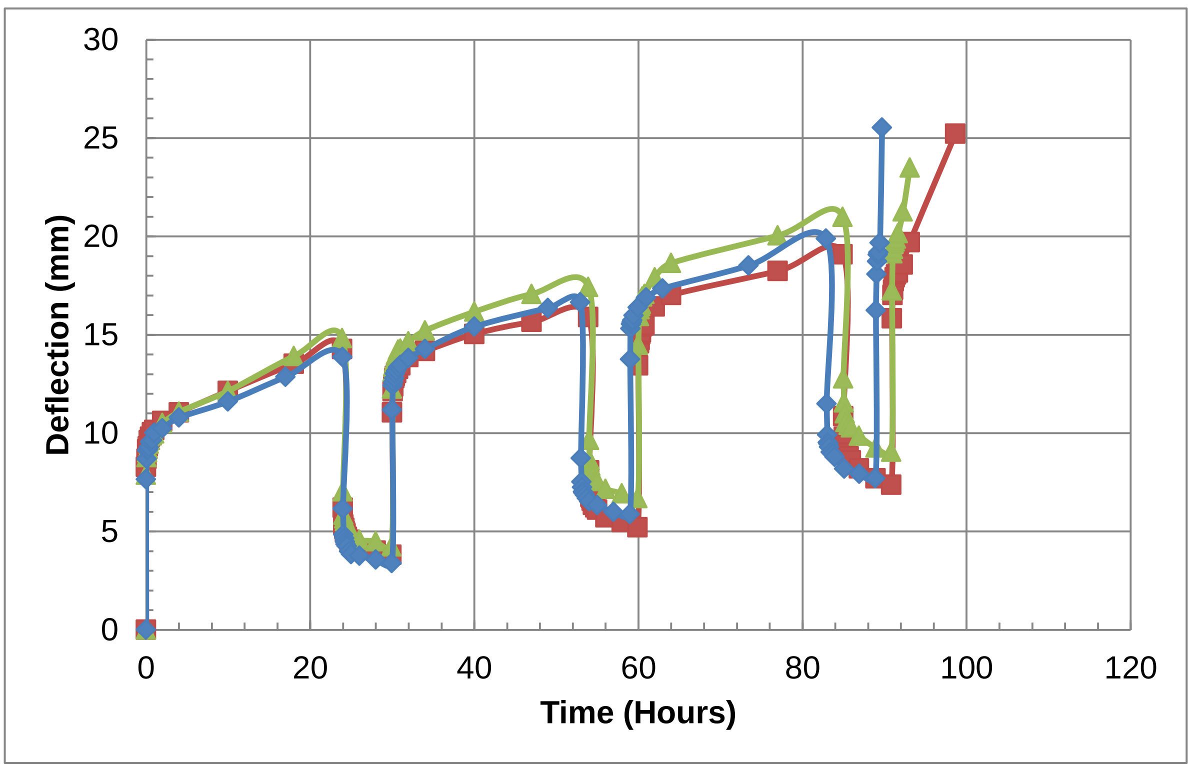


Figure 16: 24 hour loading and 6 hour unloading cyclic creep results

Figures 14-17 and Table 1 indicate, (i) the loading slopes were consistently higher than the creep to failure curve, with higher unloading times producing slightly higher slopes, (ii) both the loading and unloading portions of the curves indicated a fairly linear trend beyond their respective retarded portions, (iii) the loading slopes were found to be higher than the unloading slopes in most cases, (iv) the loading slopes consistently decreased while the unloading slopes increased (rapid relaxation) with increasing # of cycles. The Burger's Model (Eq. 2) or approach suggested in Eq. 4 applied to loading and unloading segments satisfactorily account for the experimental results (Figures 14-17 and Table 1).

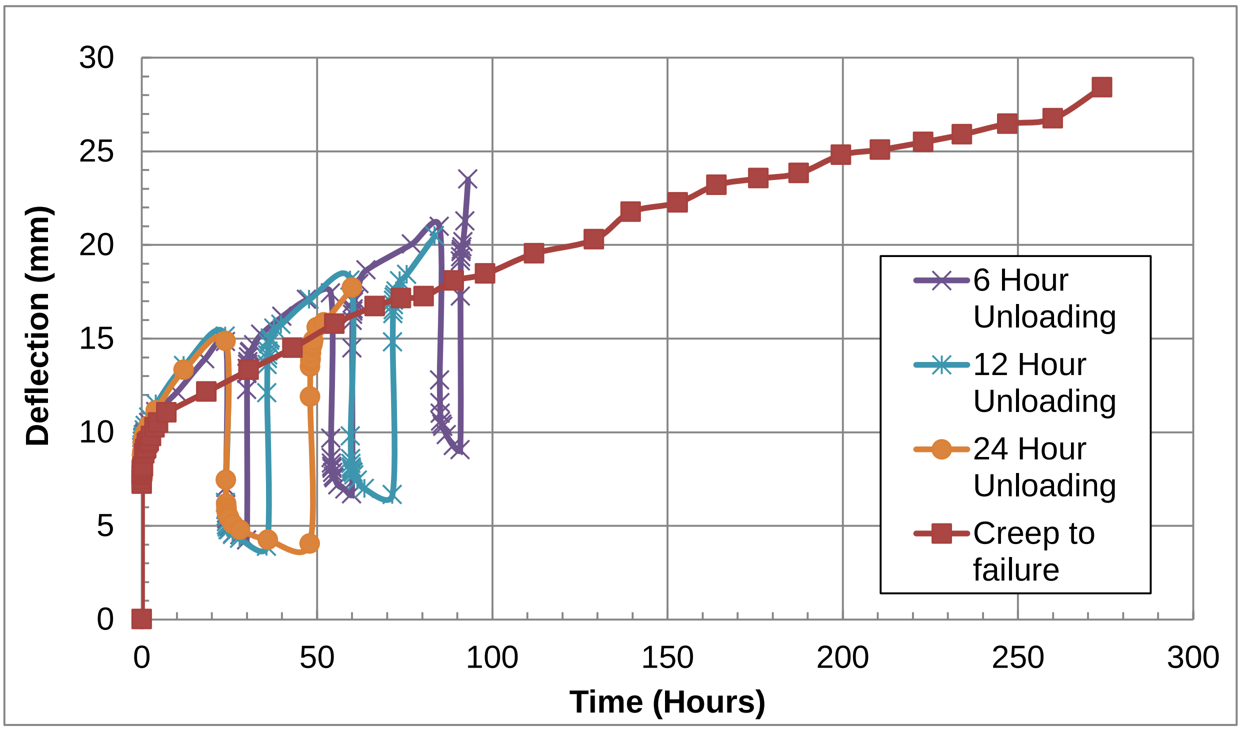


Figure 17: Comparison of typical creep to failure and cyclic creep

It can be seen that upon cyclic unloading, the specimens never totally recovered, i.e., a certain amount of irrecoverable creep remained, which agrees well with the reported results of creep loading and unloading [43,61-62] and fatigue loading [44,64]; however, this is the first

First Cycle Response							
Time (h)	Inst. Loading Response (mm)	Loading Slope (mm/h)	Peak Deflection (mm)	Inst. Unloading Response (mm)	Unloading Slope (mm/h)	Maximum Drop (mm)	Deflection Gradient (mm)
24	8.9408	0.2032	15.7734	4.8006	0.0508	2.54	13.2334
12	9.779	0.1956	15.1892	5.3086	0.04953	3.8608	11.3284
6	9.1948	0.188	14.8082	5.6642	0.08636	4.2164	10.5918
Second Cycle Response							
24	13.8684		16.383				
12	13.8811	0.1194	18.796	8.9154	0.091948	6.731	12.065
6	13.1064	0.1245	17.4244	8.3312	0.12319	6.6802	10.7442
Third Cycle Response							
12	17.1704		21.6408				
6	16.2814	0.1118	20.9804	10.9982	0.207518	9.0424	11.938
Fourth Cycle Response							
6	19.3548		23.495				

Table 1: Analysis of cyclic creep

study of its kind and literature on the cyclic creep (loading-unloading-reloading) is lacking for any direct comparison of the results. The various reports in the literature on cyclic creep generally refer to fatigue testing performed at low frequencies under trapezoidal waveform whereby peak loads are sustained just long enough (typically no more than a few minutes) to elicit creep response, i.e., enter secondary phase, however, such testing neither matches with current test design nor the results [43,52,61]. The current results are quite relevant, as they suggest that this material is highly sensitive to the unloading (relaxation) time, which may be true for most foam core sandwich composite systems. The fact that relaxation continues without reaching a threshold also suggests that more the material recovers (longer unloading periods), the more it is prone to damage upon reloading – which may be attributed to the time dependent localized cyclic densification and relaxation of the foam (Figure 17). Sandwich composites are composed of two completely dissimilar materials that are bonded together with a third material, creating a complex interface.

When the material is loaded, the compression develops at the top-side of the specimen while the bottom is dominated by tension, causing shear stresses to develop in opposite directions along the top and bottom facesheet-core interfaces. Upon unloading, the facesheet being stiffer would have the propensity to elastically recover much quicker than the viscoelastic foam; this mismatch is a major source of residual stresses that can lead to microcracking and rapid demise of the material. Furthermore, it is a common observation that higher the cyclic stress gradient (such as fully reversible tension-compression loading scenario), the more harm it inflicts on the material. The unloading periods being directly linked to the residual stresses would suggest that shorter unloading period will retain the material at a higher level of stress as compared with the material which is allowed to relax for a longer period. In other words, there is a greater disparity between the stresses at loaded and unloaded state for the material undergoing longer unloading periods; it is this disparity in the stress level which translates into greater damage to the material, as seen in Figures 14-16. The observations are quite relevant to any structure made of sandwich composites, in particular ship hulls that are designed to carry loads for an extended period of time followed by an unloaded phase.

3.6 CONCLUSIONS

Foam core sandwich composites were subjected to creep to failure and cyclic creep in seawater in order to mimic the ship hull service life scenario. In-spite of very limited water absorption, specimens creep tested till failure in seawater indicated a significant change in the secondary phase as well as reduction in overall life as opposed to testing in air. Furthermore, in comparison with creep to failure testing, lifetime was considerably reduced when specimens were subjected to cyclic loading whereby the loading periods were kept constant at 24 hours while the unloading periods varied as 6, 12, and 24 hours. Interestingly, longer unloading periods resulted into fewer cycles to failure and shorter overall life. Modes of failure were predominantly core compression and facesheet indentation.

CHAPTER IV: RESEARCH OUTCOME AND FUTURE RECOMMENDATIONS

4.1 RESEARCH OUTCOME

Advances in ship building technology is an ongoing process with a quest for ever lighter, stronger and corrosion resistant materials. The current stage of this pursuit resides with the laminated and sandwich composites - this class of material is resistant to both pounding waves as well as to the corrosive sea water. However, quantifying the extent of damage in sandwich composites is a difficult and delicate task as i) ship hull is simultaneously subject to a multitude of loading types each imparting its unique signature, ii) damage due to various sources does not follow a simple linear superposition, and iii) damage remains hidden and out of site for most of the service life of the ship manifesting on the surface only when nearing catastrophic dimensions – therefore, the problem is quite complex. With the main objective of understanding the damage mechanisms in foam core sandwich composite used in ship hulls, two of the most common and relevant loading scenarios were investigate, namely, repeated slamming and cyclic creep.

There is a consensus in the scientific community that slamming can impose detrimental consequences on the ship hulls, the results of this study confirm those claims. However, the unique outcome of this research is the striking shift in modes of failure and dramatic shift in the lifetime of the material as a function of the level of stress concentration. There is abundant reference and discussion regarding the shift in the modes of failure in the literature, however, a transition in the site of failure has never been reported – therefore, the results of this research offer a unique and relevant perspective.

In terms of cyclic creep, a ship is designed to carry passenger and cargo that must be loaded and unloaded at established time periods, thus inducing repeated hogging stresses on the ship hull structure. This part of the research was carried out by maintaining the loaded period at 24 hours but varying the unloaded times at 24, 12 and 6 hours. The results of this highly relevant loading scenario indicate, contrary to expected behavior, that longer unloaded periods lead to overall shorter life, which is a very significant outcome of this research. Therefore, minimizing the unloaded periods is an optimum condition for the service life of the ship hull.

The research also made some effort in understanding the effect of water ingress on the damage to the foam core sandwich composite. The results indicate, i) that water absorption was very limited in this closed cell foam laminated by carbon fiber/epoxy facesheets, ii) the presence of seawater had deleterious effect on the creep life of the material as indicated by a drastic reduction in the creep life as compared to tests performed in air. The deterioration in cell walls was attributed to synergistic effect of water pressure (being incompressible) and electrochemical reaction with the polymeric foam.

4.2 FUTURE RECOMMENDATIONS

In terms of repeated slamming, the current research suggests a detailed analysis of the shift in the mode and site of failure by testing a much broader range of foam densities and facesheet properties. In addition, a scaled model testing can provide a more realistic assessment of damage in ship hulls.

In terms of cyclic creep, various steps can be taken to advance the state of knowledge, for example, i) a fully reversible creep test would provide a clearer profile of the viscoelastic behavior, ii) testing can be performed for foams and facesheets of various densities and thicknesses as creep phenomena is size dependent, iii) creep testing must be performed in seawater, deionized water and air in order to correlate with the electrochemical analysis, iv) tests should be performed on foams and foam core sandwich composites separately, as the secondary viscoelastic effects are traditionally attributed to foam cores.

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