DOI 10.1515/jmbm-2013-0012 — J Mech Behav Mater 2013; 22(1-2): 73–80

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Shift in failure modes in foam core sandwich composites subject to repeated slamming on water

Abstract: A test program designed and carried out to mimic the repeated impact of the bow section of fast-moving small boats on the ocean surface provided some unique observations in terms of failure mode transition. 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. 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. Type 1 specimens (softer core/stronger facesheet) consistently failed by interface and through-the-thickness core shear, independent of the flaw size. In contrast, a gradual decrease in flaw size 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. The lifetime of Type 2 specimens was more than two orders of magnitude greater than that of Type 1 specimens.

Keywords: damage; modes of failure; repeated slamming; sandwich composites.

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1 Introduction

High-speed lightweight marine craft operating in rough seas undergo complex loading conditions principally as a result of the repeated slamming of the ship hull on the ocean surface. The term "slamming" is generally used when the forward bottom of the hull emerges out of the water due to large pitch and heave motions and slams the water upon re-entry – this type of impact represents a violent impulsive event with peak pressures occurring at high re-entry velocities, causing an acceleration rise time as high as 10 g and duration in the order of milliseconds that can induce serious damage to the ship hull structure [1–7]. Whereas, the term "flare slamming" refers to the occurrence of a frontal impact between the bow flare and the oncoming wave. Even though the analysis techniques are somewhat similar, a bow flare slamming event is not as severe as bottom slamming; however, bottom slamming is not nearly as common as the highly cyclic bow flare slamming.

Despite the 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. The pioneering work of Wagner [12] and Karman [13] resulting in the determination of peak pressures has essentially formed the basis of much of ship hull design and analysis; a typical analytical outcome of their work simulating bottom slamming is depicted in Figure 1. Since then, many other researchers have made significant contributions to the subject of pressure distribution under slamming. The problem of analytical fluid structure interaction is generally made difficult by continuously moving boundaries between the hull and the water surface, and the coupling of hydroelasticity and structural response [5, 6, 13–16]. The analytical problem is generally 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 important, by assuming that the loads can be applied quasi-statically, i.e., no hydroelastic interaction occurs and the hydrodynamic loads and structural response can be treated separately [5, 16–20].

On the experimental front, much of wave slamming has basically sought to corroborate the analytical work whereby flat panels instrumented with piezoelectric pressure sensors, strain gauges, and accelerometers are mounted on wedge-shaped rigid supports and dropped in a free or controlled manner from predetermined heights

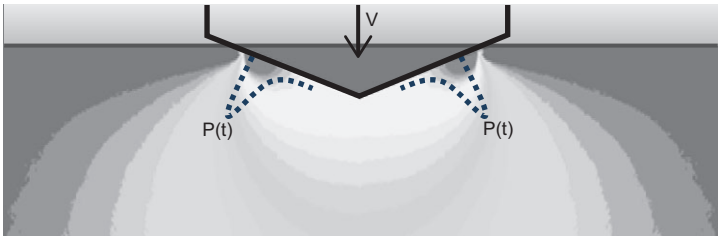

Figure 1 Wave slamming induced pressure pulse propagation along a typical wedge simulating a bow flare.

onto a body of calm water with the aim of discrete pressure measurement (Figure 2), which has been shown to increase with increasing bow flare [1–9, 17, 20, 21]. Granted that the pressure distribution is a key design parameter, it nevertheless does not offer any direct damage or service-relevant information [1, 3, 7–9]. Furthermore, in light of the discrete nature observed experimentally and the various simplifying assumptions imposed on the analytical solutions, the deterministic treatment of pressure distribution has given rise to large factors of safety in design in order to compensate for the lack of reliability [1, 3, 7, 11].

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 owing 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. Loading, environment, and type of material (core and facesheet shape, density, and composition) have significant effects 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, but 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.

The literature provides ample information about the modes of failure and shift thereof in foam core sandwich

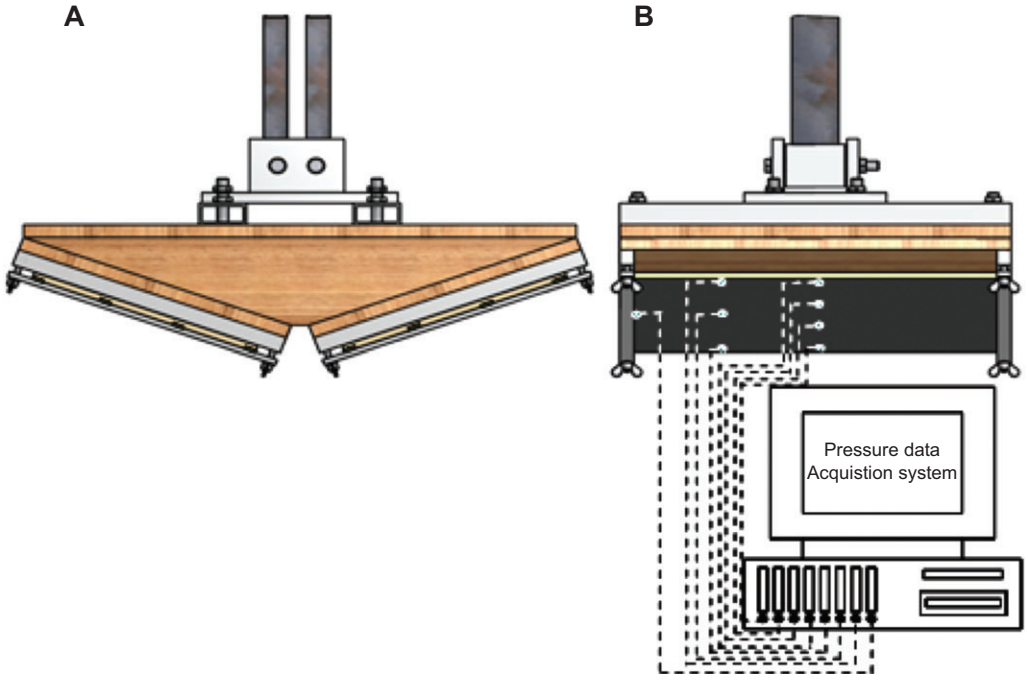

Figure 2 Wave slamming setup commonly used under drop testing with flat panels symmetrically mounted on each side.

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 occurs 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, the 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 the ratio of the 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 finite element analysis (FEA) is generally implemented, which requires that a failure criterion be established, the strain rate dependency of the material be checked, and the strain to failure data be available, which are not readily the case [33].

Damage detection in sandwich composites under water slamming is a highly elusive process owing mainly to the lack of viable instrumentation [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; and (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 through residual strength or lifetime testing proves unreliable owing primarily to the inherently large scatter in the data that obscures any slamming-induced damage [21, 23, 24].

There is little disagreement that repeated slamming can seriously compromise the integrity of the sandwich composite ship hull; however, the literature is extremely scarce on 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 Materials and experimental setup

Two type of specimens were fabricated, Type 1 and Type 2 with a 1:4 ratio of polyurethane foam density (64 and 260 kg/m^3) but similar $[0°/90°]_1$ glass fiber facesheet average elastic modulus and ultimate tensile stress. The flat rectangular specimen had a constant core thickness of 6.35 mm, whereas the facesheet thickness varied as 1.84 mm and 1.02 mm, making the overall dimensions of 38 cm×5 cm×8.2 mm and 38 cm×5 cm×7.37 mm for Type 1 and Type 2 specimens, respectively. The quasi-static flexural test results found the average load to failure and stiffness of the sandwich composite to be 587–649 N and 246.1 kN/m for Type 1 specimens and 551–810 N and 187.4 kN/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 600 cps 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 the vacuum-assisted resin transfer molding process.

Specimens were slam tested into a 152-cm-diameter and 122-cm-deep water tank. The impact velocity was

measured using a Kistler accelerometer (Amherst, NY, USA) (100 mV/g with a 25 ks/s sampling rate) that was mounted on the back face of the model specimen. Flexiforce pressure transducers (Tekscan, Inc., South Boston, MA, USA) of 5.7 kHz sampling rate installed on the impact faces of model specimens at critical locations exhibited a nearly linear distribution from the fixed to the free end with very little evidence of the hydroelastic effect. The 120-ohm strain gages capable of 25 ks/s sampling rate mounted on the back faces (tensile side) of the specimen in configuration shown in Figure 3 resulted in a highly erratic response. Damage was primarily monitored optically. In some cases, florescent dyes were injected at the core/facesheet interface at various stages of damage propagation to facilitate damage tracking.

Testing was conducted at a slamming velocity (at the free end) of 20 m/s at a frequency of 1 Hz 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° representing a vertical position and 90° the striking position (i.e., the surface of the water). Therefore, the velocity of impact varied from "0" at the fixed end to 20 m/s along the free end. At impact, the specimen was designed to penetrate the water to an additional 5° rotation with respect the water surface. The setup is more realistic than the 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.

Specimens were designed 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 3). At each flaw size, slamming cycles to

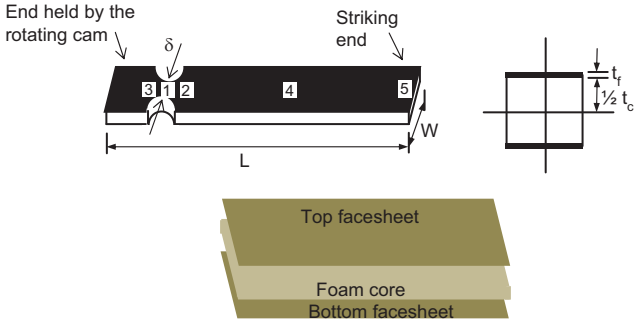

Figure 3 Specimen configuration: [1]–[5] represent the locations of the strain gauges, whereas pressure transducers were placed at locations [3]–[5] on model specimens.

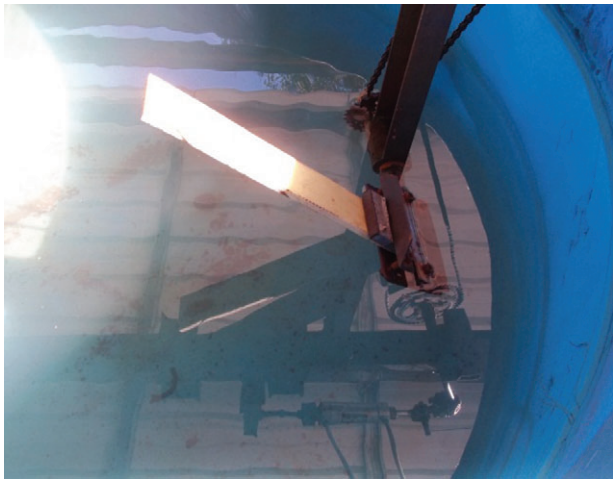

Figure 4 Slam testing apparatus.

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.

3 Results and discussion

3.1 Type 1 specimens (softer core/stronger facesheet)

Type 1 specimens consistently failed owing to the interface shear typically initiated at the free end independent of the flaw size, as seen in Figure 5. Facesheets, being significantly stronger, quickly lost contact with the 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-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 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

Figure 5 Typical interface and through-the-thickness shear failure in Type 1 specimens.

behavior. Overall, the scatter in the data was minimal at δ/w <0.5 and was observed to increase a little with decreasing flaw size.

3.2 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. This counterintuitive shift in the lifetime

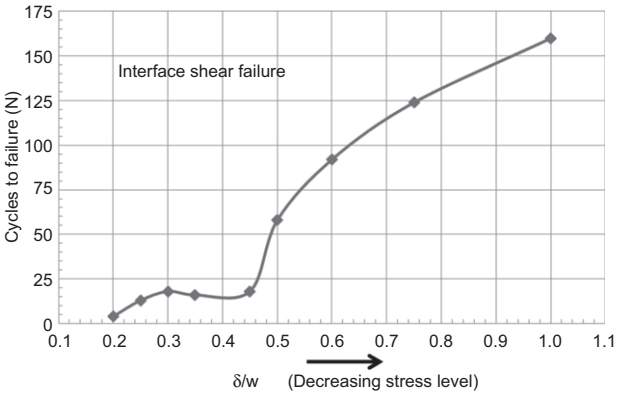

Figure 6 Average number of cycles to failure as a function of flaw size for Type 1 specimens. No shift in modes of failure.

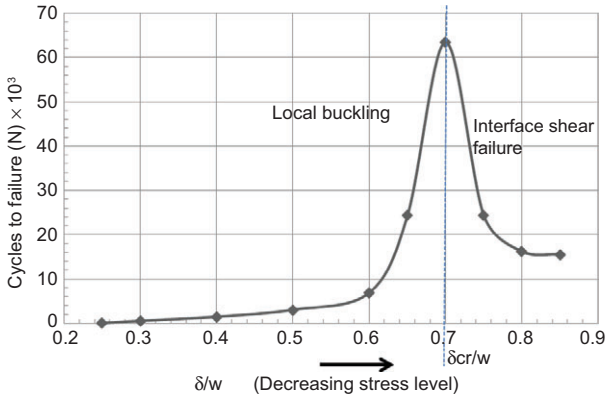

Figure 7 Average number of cycles to failure as a function of flaw size for Type 2 specimens. Shift in mode and site of failure at the transition point δ_{cr}/w.

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 before δ_{cr} to the 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 about the dramatic drop in lifetime observed beyond δ_{cr}.

The specimen failure due to local buckling provided some 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 the 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 occur when the 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 [30,

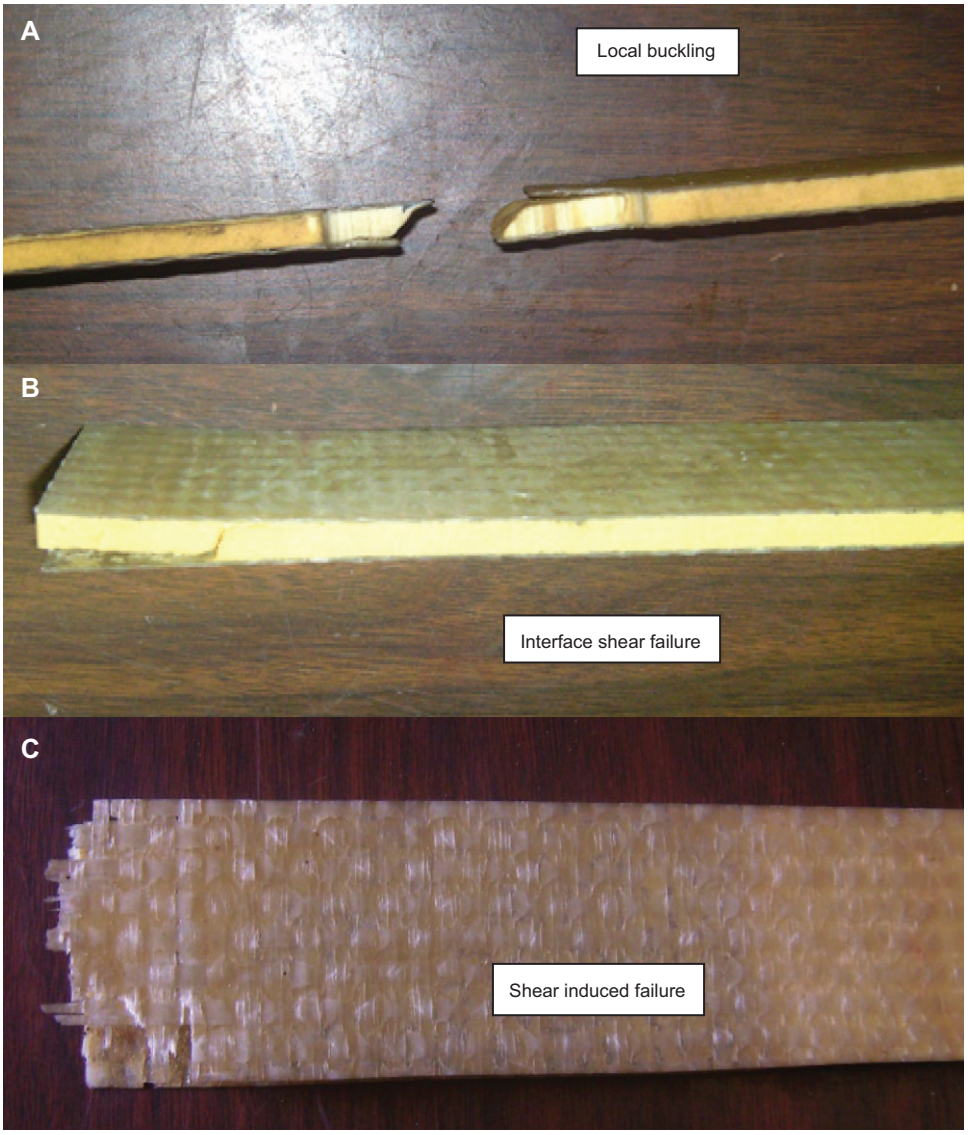

Figure 8 Typical (A) local buckling at the flaw site and (B, C) shear failure along the free end in Type 2 specimens.

31]; 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.

It is a common observation that damage accumulation and subsequent failure under cyclic loading in typical engineering materials reaches an 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 a significant drop in the lifetime beyond δ_{cr}. Mode transitions 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, the literature on slamming is largely devoted to discrete pressure measurements on wedge-shaped specimens, which offers little help in deciphering 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 the 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 local buckling – thus, the flaw site absorbs the bulk of the impact energy. However, 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. In contrast, 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 at a maximum. Therefore, in the absence of any flexure at the free end, the interface shear failure must be initiated/propagated owing 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 about 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, the shape of the projectile, and the material properties, which are 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, classic 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, but 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.

4 Conclusion

Two types of sandwich composite specimens were tested under repeated slamming. Type 1 specimens (weaker foam and stronger facesheet) failed exclusively owing to interface and through-the-thickness foam shear independent of the flaw size. Whereas, Type 2 specimens (higher core density and lower facesheet strength) revealed 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. Despite the comparable flexural strength and stiffness of the sandwich composites, Type 2 specimens lasted more than two orders of magnitude longer as compared with Type 1 specimens. The longevity of the specimens under slamming therefore appears to be related to designing composite structures to fail by local buckling. The results offer a unique perspective on the damage assessment of sandwich composite ship hulls.

Acknowledgments: The authors acknowledge the support and guidance of Dr. Yapa Rajapakse, the ONR program manager. The research was conducted under ONR grant no. N000141110101. The authors would also like to extend their gratitude to Drs. Fredrick Just and David Serrano for facilitating the experimental work.

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