SPECTRUM SLAM FATIGUE LOADING OF SANDWICH MATERIALS FOR MARINE STRUCTURES

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Keywords: Fatigue, Sandwich, Slamming, Spectrum loading, Real-time history

Abstract Sandwich materials are more frequently used in high speed craft and ferries. The motivation is reduced weight and associated operational cost. The hull structure in these vessels is subjected to repeated (fatigue) slamming loads (high strain rate loading). Scantling societies treat sandwich materials differently in their design rules. In common reduction or safety factors on the static strength of sandwich materials are used calculating the design stress. In most rules there is no explicit consideration of fatigue performance nor of the altered material properties related to high strain rate loading. In this work actual response measurements on a high speed vessel are used to formulate a tentative slam fatigue loading spectrum for sandwich core materials. This spectrum is then used in the testing of one type of core material common in hulls panels, Divinycell H200. The slam spectrum fatigue results are then compared to fatigue test results based on constant amplitude loading based on a method of equivalent stress. Earlier studies indicate that slamming fatigue do not affect the life compared to constant amplitude loading. However there are also studies that indicate that both a static overload (post the yield point) prior to fatigue loading, and block sequence fatigue loadings with initial high amplitudes followed by low amplitude have a detrimental effect of the fatigue life. In the current study both various amplitudes and high strain rates are included in the fatigue loading sequence. The spectrum fatigue results match the fatigue life from the constant amplitude loading. However, the number of samples is limited and the different effects of fatigue at high strain rates and fatigue block sequence are not fully clarified. It is possible that those effects may counteract each other in the current work. Further studies on sandwich foam core material properties and improvement of methods for material characterization is concluded to be of interest and will follow.

INTRODUCTION

Lightweight ship designs using composite and sandwich materials have a high commercial interest with the possibility of reduced operational cost (fuel consumption and maintenance) and environmental impact. Most classification societies issue scantling rules for ships built using composite and sandwich materials. However, the design stress for sandwich materials as used in marine vessels differ between these societies. Only one of six addresses the fatigue and slamming performance for this class of material. Based on polymers the mechanical response of sandwich core (and face) material often shows a viscous elastic response and associate strain rate dependence. A design stress solely based on the static strength and a factor of safety may lead to a conservative design (increased weight and performance) or even worse, an non-conservative design with possible failure.

Several studies have investigated the fatigue performance of sandwich foam core materials. Even when data is readily available there are still many aspects of the fatigue characteristic and failure mechanisms not addressed or understood. Composite materials have been shown to be load sequence dependent and hence a linear cumulative damage hypothesis according to Palmgren-Miner would not be valid. An early study indicates that foam core materials may behave similarly.

Several authors have reported on load rate dependence for foam core materials with increase strength for high strain rates. Fatigue testing using a slam type sequence has however not indicated changes in the fatigue life in comparison to the standard constant amplitude sinusoidal loading.

The onset for this study is the uncertainties associated with the design stress and the characterization methods for sandwich material in slam loaded hull bottom panels of marine vessels as stated by the classification societies.
BACKGROUND

Design shear stress for sandwich core materials in marine applications

There are several different regulations, design codes, for high speed light craft, ABS, DNV, GL, ISO and RINA are some examples [1-5]. These regulations prescribe different methods to determine the design shear strength of a core material as used in sandwich panels and some use different reduction factors depending on the core strain to failure. Only one address slamming and fatigue aspects of sandwich core materials in their design code. In the following some general remarks on these rules are discussed but for details of each regulation the reader is referred to the original documents when these are subject to constant changes.

DVN [2] is the only regulation that attributes the fact that foam core material will have a different response when subjected to high strain rates. Many commonly used foam core materials show an increase in both stiffness and strength under high strain rate loading [6-8]. (The same authors also proved the opposite relation for some materials.) In the high-speed material characterisation test defined by DNV the loading rate is specified to 65MPa/s [9]. A dynamic correction factor, \( D_f = \text{dynamic strength} / \text{static strength} \) is used together with a general core reduction factor equal 0.4 to calculate the allowable design shear stress.

In addition, DNV includes an optional fatigue testing requirement, stating that the material should display a residual strength of 80% (minimum) after fatigue cycling at a stress level of 50% for 100,000 cycles. The loading rate of the slam fatigue pulse should be 65MPa/s and the maximum time between peaks should be 0.1 s.

The design shear stress stipulated by ISO [4] differ for high and low elongation core materials, i.e. whether if the strain at failure is higher or smaller than 35%. In addition the ultimate shear strength must be higher than 0.40 MPa for panels in the hull bottom. Furthermore, ISO require that tested strength values shall be taken as 85 % of the mean value or this mean value minus two standard deviations, whichever is lesser.

RINA [5] consider two load cases in their scantling rules, still water and dynamic loads. Depending on the panel location or type of structural member RINA tabulate different allowable stresses in the sandwich composite face laminate. The allowable shear stress in the core of a sandwich is specified as to be no greater than 50% of the shear strength (Pt B, Ch 4, Sec 1, Table 1) independent of the loading condition.

Germanisher Lloyd [3] simply specifies that in case of sandwich construction the Factor of Safety (FoS) against core shear failure must be at least 2.0.

The ABS [1] rules consider two types of foam core materials, high and low elongation (break point is 40% strain at failure). The corresponding allowable shear strengths are 55% and 40% of the minimum static strength measured.

Table 1 summarises these classification society rules formulate the allowable design shear stress, \( \tau_{\text{Design}} \), in relation to the ultimate static strength, \( \tau_{\text{ULT}} \). Different societies use different terminology, e.g ultimate stress, maximum stress etc. However, they all refer to the two common block shear test standards ISO1922 [10] and ASTM C273 [11] where the strength is defined as maximum applied load during the test. Some societies specify that the minimum value issued by the manufacturer or from the material qualification test should be used. DNV [2] use the definition Mean Specified Minimum Value (MSMV) and Mean Specified Value (MSV), and this nomenclature is used herein. As an example of the consequences of the different rule formulations on the allowable core shear stress, a commonly used core material for sandwich hull structures is analysed, Divinycell H200. The specification for this material is given in DIAB [12]. The shear strain at failure is given as \( \gamma = 40\% \). (Note that the stress values in Table 1 should not be used for design purposes but merely work as an illustration of the differences between class rules. For correct calculations of the allowable stresses for an individual ship design the reader is referred to the respective classification society rules). As seen there is a vast difference in the design stress for this material using different scantling rules, 1.28-1.93MPa.
Table 1 Allowable design shear stresses for foam core material as given by different scantling societies. The difference in design stress is exemplified by the material used in the current study, H200.

Core shear testing procedure

The specified testing standards for shear strength evaluation in the above mentioned design rules are the ASTM C273 [11] and/or ISO 1922 [12]. Both standards can be used to determine shear strength and shear modulus. The shear strain is normally calculated from the relative displacement of the two loading plates measured by an extensometer. In both the ISO and the ASTM standard the maximum applied load during the test is used for the shear strength calculation. Battley and Burman [13] showed that post the yield point the stress changes from pure shear to a compression dominated stress state. Hence the definition of shear strength based on maximum load is questionable. There is no detailed instruction in any of the standards on at which point the maximum shear strain should be taken, and hence the strain at ultimate failure is commonly used.

Core fatigue testing

Common practise within the sandwich community, and also specified by DNV [9], is to use test rigs and procedures based on ASTM 393 [14] for fatigue testing of sandwich core materials. This has also been used herein and the test rig is shown in Figure 1 and details about this is found in [15]. There is a long list of studies [15-19] where this method been used. Zenkert and Burman [20] showed that the results from core fatigue testing may be plotted in a standard double logarithmic stress-life using a Basquin’s law type relation

\[ \Delta \tau = B(N)^{-m} \] (1)

where \( \Delta \tau \) is the stress range, \( N \) is the number of cycles to failure, and \( B \) and \( m \) are fitting constants where \( m \) is the curve slope.

Figure 1: Four point bending rig used for fatigue testing.
Slam fatigue testing of sandwich materials

There is only a few published studies that investigates fatigue performance of foam core materials with high strain rate loading sequences, e.g. [6] and [21]. Buene et al. [6] tested three different foam core materials in a four point bend rig for static strength, dynamic strength (2.5/s strain rate), sinusoidal fatigue and slam fatigue (1/s strain rate). A 50% strength increase for the H200 material was observed when loaded at 2.5/s in relation to the static strength. Buene et al. presents S/N curves showing results up to one million load cycles both for the sinusoidal and the slam type fatigue tests using peak loadings with 1/s strain rate. The conclusion from this study was that fatigue life for the H200 is independent on the fatigue loading type, constant amplitude and slamming.

Fatigue block sequence

A simple and linear empirical rule for fatigue life-time predictions under variable loading sequences is the well established Palmgren Miner (PM) rule

$$D = \sum \frac{n_i}{N_i}$$

Here $N_i$ is the lifetime (cycles to failure) for a constant amplitude loading at a given stress level $\sigma_i$ and $n_i$ is the number of cycles applied at that stress for the given block sequence. Common practice state that when, $D$, the sum of the fractional lifetime, is 1, failure will occur. In the case of composite laminates, Gamstedt et al. [22] showed that sequence effects have to be taken into account, since the degradation after each load cycle depends on the loading characteristics of the current cycle as well as on the loading history previously experienced by the material. PM cannot account for load sequence effects that are encountered in practice [22-23]. In [22] it was concluded that a block sequence with initial high amplitudes followed by low amplitudes (high-low) were more detrimental than a low-high order. A physical explanation was offered including initiatory and progressive failure mechanisms associated with the different stress levels. Whether any such sequence effects can be observed for polymeric foam materials have not been investigated.

In [6], the authors touched upon the effect of fatigue block sequence for sandwich core materials. In a separate study, [16] the authors performed fatigue sequence loading at two different load levels (for each specimen) on two PVC foam materials, H100 and H200. The fatigue life at three different stress levels were established through testing under constant sinusoidal loading. Then a second test series was carried out were all samples were fatigue at two different levels. The first fatigue sequence was interrupted at 50% of the expected lifetime for that load level applied. Then, in the second sequence the fatigue load changed to one of the other two levels and the specimen was then run until failure. Comparison was then made between the reference series and the samples subjected to the block sequence loading. The results showed no difference in life compared to the reference for the low-high block sequence order. However, in the opposite case, high-low, a reduction in fatigue life was noticed. The scatter was quite significant and the number of samples limited, but the findings are interesting enough for a deeper investigation into the effects of load block sequence order and is hence a topic for coming investigations.

In the same study specimens were also subjected to one static overload (past the yield point) and then tested under constant amplitude fatigue loading. It was clear that the fatigue life, especially in the high cycle regime, was affected with a reduced life as a consequence. Again, only a limited number of samples were tested and the conclusions are hence weak but as for the effects of block sequence this is a topic for coming work.

SEA TRIALS

The relevance in constant amplitude fatigue testing with relatively low loading rates can hence be questioned for slamming loaded marine sandwich panels. The real loading situation for the core in hull bottom sandwich panels in a high-speed craft will here be examined and based on this a spectrum slamming loading will be formulated as input to the fatigue testing. The craft studied is the Visby class corvette which is a sandwich construction with foam core and carbon fibre reinforced laminates. The core shear recordings referred to are from full-scale trials performed in rough seas in the Baltic Sea. A schematic picture of the craft and the craft main particulars are given in Figure 2. More information about the full-scale trials is found in Rosén el al [23] and other information about the craft is for example found in Lönnö [24], Hellbratt & Vallbo [25], and Milchert et al [26].
An example of shear strain recordings in the sandwich core of a hull bottom panel is given in Figure 3. The material in this panel is Divinycell H250 [12]. The recordings shows the typical characteristics for this kind of loading situation, where some wave encounters results in large transient responses due to slamming (i.e. hydrodynamic impact loads) while many wave encounters results in more harmonic loading and responses on significantly lower levels. The sequence in Figure 3b for example comprises around seven wave encounters out of which two have resulted in slamming. The response signals can be seen as two superimposed stochastic processes: one corresponding to the linear wave loading with a period corresponding to the period of wave encounter (here is around 2-5 s), and the other process corresponding to the nonlinear transient slamming loads which has a duration of around 0.1-0.3 s and occurring every third or so wave encounter.

Examples of strain rates in the Visby hull bottom panel cores are given in Figure 4. Each mark represents the maximum strain rate recorded with one particular shear gauge during one particular slamming event. This particular data set includes recordings in two different locations in the hull bottom from all 276 slamming events experienced during seven different 15-minute test runs, at different speeds, headings (head and bow seas), and sea states where the seas where rough but not extreme. As seen the highest recorded strain during this set of runs was 0.8 %. This can be compared with the (maximum allowable) design strain for the Divinycell H250 which was set to 2 %. The highest recorded strain rate during this set of runs was as seen 57/s, which corresponds to 59 MPa/s with a static shear modulus of 104 MPa for the H250 [12]. A clear trend is seen with increasing response rates for increasing response levels. This can be used to at least approximately extrapolate the strain rates to the maximum allowable strain level. If this is done linearly the strain rate would be 116/s, i.e. 120 MPa/s, for a strain level of 2%. A quadratic extrapolation to the same level gives 244/s, i.e. 254 MPa/s. There are of course large uncertainties in these extrapolations, still a significantly larger stress rate than the by DNV [2,9] stipulated 65 MPa/s is indicated. Similarly the times for a response from 0 to 2 % can be approximated to 0.017 s with a linear extrapolation and to 0.008 s with a quadratic extrapolation.
Figure 4: Examples of strain rates in the Visby hull bottom panel cores where each mark represents the maximum strain rate recorded with one particular gauge during one particular slamming event. The data is from two gauges and 276 slamming events (PAN1-S3 and PAN2-S1; runs 6, 8-9, 11-17, 19-20).

Figure 5: a) Signal for input to the fatigue testing based on synthetisation of the strain recordings Figure 3. b) Part of the synthesized signal where the second and third peak corresponds to the two slamming events in Figure 3 b.

A response signal, representative for a slamming load spectrum for hull bottom panel cores, and feasible for phenomenological fatigue testing, is synthesized from the strain recordings in Figure 3 in the following manner. First all slamming events resulting in strains between 0.07 and 0.20 % are identified. For every event the peak value and 0.15 seconds of the recording proceeding and following the peak are extracted. These 0.3 second sequences are, based on ocular judgment, considered to cover the principal part of the slamming events. The extracted slamming sequences are then merged through linear interpolation over 0.1 seconds from the last sample in one sequence to the first sample in the succeeding sequence. Hereby a signal with a primary frequency of 2.5 Hz is created, which is considered to be low enough to avoid material property affecting temperature increase and high enough to make the fatigue testing duration feasible. To enable smooth looping of the signal linear interpolation over 0.1 seconds is also made between the last sample in the last sequence and the first sample in the first sequence. Based on the above observed correlation between response rate and response level the synthesized signal is finally normalized with respect to the highest peak value, and then linearly scaled to represent different load levels in the fatigue testing as described in the following. The resulting synthesized signal is shown in Figure 5 which is 15.6 seconds long and contain 39 load reversals.
FATIGUE TESTING - CONSTANT AMPLITUDE AND SPECTRUM SLAMMING

The test rig set-up for the constant amplitude and spectrum slam fatigue tests is shown in Figure 1. The Schenk servo hydraulic test machine used has a 40kN load cell, a Moog valve with 63 l/min and 50 mm diameter cylinder. This machine configuration just manage the max peak loads at the highest strain rates, the difference between the machine command and response signal for this extreme is less than 10%. For coming studies a faster hydraulic machine is recommended. Two different fatigue test series were performed, one with constant amplitude loading ($R=0.1$, $f=0.4-3$ Hz depending on load level avoiding heat problems) and the other with spectrum slam loading derived from the full-scale recordings on a high-speed craft as described above, where each 15.6 second (39 load reversals) are continuously repeated. Two spectrum fatigue levels were chosen for this study corresponding to a core shear stress of 2.25 MPa and 2.50 MPa respectively. This was achieved by a linearly scaling of the signal in Figure 5 (only the load signal and not the time was scaled).

In order to compare the spectrum slam fatigue results with those from the constant amplitude testing a method of equivalent stress was used. For this the amplitude in the synthesised signal of each load reversal is required. In Figure 6 the number of reversals per amplitude (in steps of 0.05) are given for one sweep.

![Figure 6](image)

**Figure 6** Number of reversals per (normalised) load amplitude for one sweep of the applied fatigue slam spectrum.

The equivalent stress of the load spectrum applied is calculated using,

$$
\Delta \tau_{eq} = \left( \frac{\sum_{i=1}^{1} n_i (\Delta \tau_i)^m}{N_d} \right)^{1/m}
$$

where $n_i$ is the number of load reversals at a specific stress range $\Delta \tau_i$, $N_d$ is the total number load reversal, and $m$ is the slope of the S/N curve, in this case 16. The equivalent stress for the spectrum sweep with a max shear stress 2.25MPa is 1.50 MPa, and the series with max 2.50 MPa have an equivalent stress 1.70 MPa.

MATERIAL

In the present study a sandwich core material commonly used in slamming exposed hull bottom panels of marine vessels is used, Divinycell H200. Selected data for the material as given by the manufacturer [12] is found in Table 2. Sandwich beams were cut from a panel manufactured using vacuum infusion. Each face had 8 layers of glass fibre non-crimp fabrics (DBL 800g/m²) impregnated with Vinylester resin (DION 9500). From this panel beams were cut to the geometry given in Table 2.

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<th>Unit</th>
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<td>Inner support span</td>
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Table 2: Selected material data as given by the manufacturer [12] and test specimen geometry used

**FATIGUE TEST RESULTS**

The results of the constant amplitude fatigue testing are given Figure 7 as a standard double logarithmic stress-life relation with a curve fit according to Eq 1, where the slope of the curve is $m=16$ for H200. The data taken from Buene et al (1992) are included in Figure 7 and show good agreement with the current data.

The test results from the spectrum slam fatigue are also plotted in Figure 7 with the equivalent stress calculated using Eq. 2. As observed, the fatigue life for the slam fatigued samples match the prediction curve derived from the constant amplitude tests. This then indicate that there is no effect on the fatigue life due to load cycles with variable amplitude at high strain rates. Only two stress levels have been used in the study and the findings should be treated cautiously.

![Figure 7 Test results presented in a log-log diagram](image)

**CONCLUSIONS**

In the current study a response signal, representative for a slamming load spectrum for sandwich hull bottom panels and feasible for phenomenological fatigue testing has been formulated. The signal is synthesized from the strain recordings during full-scale sea-trial with the Visby class corvette. Visby is a sandwich construction with foam core and carbon fibre reinforced laminates. From the sea-trials measurements, a clear relation between the response rate and the peak response level for slam events is seen. Using this correlation to approximately extrapolate the strain rates to the design strain level indicates significantly higher strain rate levels than what is stipulated for material testing in the DNV scantling rules.

Fatigue test on a sandwich core material commonly used in slam and fatigue exposed hull panels have been performed. Two series were carried out, constant amplitude fatigue tests and slam spectrum fatigue. The load spectrum is based on the synthesized signal from the sea-trials and for result presentation the signal was analyzed using a method of equivalent stress. The results are plotted in a standard double logarithmic stress-life diagram and a
good match between the two series was found. This indicates that the fatigue life of this material is unaffected by high strain rates and block sequence. This experimental finding is somewhat unexpected. Literature references indicate reduced fatigue life for variable amplitude fatigue loadings. However, the number of test data is limited and the continued research efforts will focus on trying to clarify the effect of block sequence and high strain rate fatigue separately.

ACKNOWLEDGEMENT

The financial support for this investigation has been provided by The Office of Naval Research (ONR) through programme officer Dr. Yapa D.S. Rajapakse (Grant No. N00014-07-1-0344) and The Swedish Defence Materiel Administration (FMV) through Anders Lönnö and John Timerdal (Grant No. 328668-LB758165). DIAB AB are acknowledged for supplying the materials. Special thanks to Anders Bäckman and Bo Magnusson for help with the manufacturing of the test specimens and the fatigue testing.

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