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Damage Tolerance Assessment of Composite Sandwich Panels with Localised Damage

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Abstract

The work described herein is part of a larger context in which the effect of damage in sandwich composite structures for marine applications has been investigated. The overall aim of this effort has been twofold: to develop and verify existing damage assessment models to be used to assess the effect of damage on marine sandwich structures, and to develop a damage assessment scheme to be used by shipyards, ship owners and navies.

More specifically, this paper presents a sub-set of this overall effort looking at impact and indentation damage and its effect on the load carrying capacity of state-of-the-art carbon composite sandwich panels for marine applications. Damage types are modelled based on physical observations from tests. Testing is then performed on different scales in order to validate the models. The overall aim is to use such models to produce information that can be used for decision-making at two levels. The first is to evaluate the damage tolerance of ship structural components and thus to calculate the size and extent of damage that a component can have without risk of growth or failure at ultimate local or global loads on the entire ship. The second is to have information at hand to decide if, and when, a structural part needs to be repaired if damage has been detected. A scheme developed for this purpose is presented herein. Finally the paper will briefly describe a common framework for damage assessment in composite sandwich structures. Herein, models are used in conjunction with the design specifics and functional requirements to create a scheme for repair decisions.

Keywords

A: Carbon fibre, B: Impact behaviour, Strength, C: Damage tolerance, Sandwich

1 Introduction

Composite sandwich structures have in recent years found widespread acceptance in advanced structural applications ranging from aerospace to civil engineering. In aerospace structures, sandwich panels are used in control surfaces, interior flooring etc., but have yet to see major use in primary load carrying parts. Sandwich panels are used in civil engineering applications but so far not fully utilised as self-supporting structures. In other transportation applications, composites and sandwich panels are being introduced but have so far not seen a general widespread acceptance. In ships, on the other hand, composite sandwich structures are used to a full extent. Complete ship hulls have been built in glass and carbon composite sandwich structures for almost 25 years. Acceptance of and confidence in the concept have led to larger

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and larger all-composite sandwich structures being built with the 72 m Visby class corvette being the largest one so far [1,2].

The main driver for using composite sandwich structures in ship hulls is low structural weight. However, ships are often built in short or very short series, implying that using composites can be cost effective too. Other important features are the non-corrosive material that leads to much lower maintenance costs in the lifetime of the structure. Maintenance costs in the order of 15% of those of a similar steel ship have been reported. In naval applications, a non-magnetic hull material is very advantageous and sometimes necessary. Other important features of composite sandwich hulls are low acoustic and thermal signatures. By using carbon composite face sheet, electromagnetic shielding can also be obtained. Through the development of various naval sandwich ships, one has also found that sandwich panels are inherently blast resistant compared to steel or single skin structures.

Historically, sandwich structures were first used in mine counter measure vessels, mainly designed for underwater blast protection. Having relatively low speed, these vessels became very much over-designed for normal sea loads and thus very damage tolerant under normal usage. However, ships with other mission objectives, be it high speed ferries or naval craft, where speed and agility are the main priority, low weight becomes the most important design driver. Optimisation methods are then often used to minimise the structural weight. A minimum weight design is then sought after, while fulfilling constraints on stiffness, strength, natural frequencies, etc. The materials are then utilised highly even in normal usage. This implies that hull structure will be designed for sea loads rather than extreme load cases such as underwater explosion and are thus designed towards more narrow limits. Another complicating factor appears in the design of more advanced composite sandwich hull structures using carbon composite face sheets. Carbon fibre laminates are much stiffer than their glass counterparts, while only giving limited increases in strength, if any. Thus, many structures for which stiffness was the governing design criterion in glass composite have strength as the governing criterion when built in carbon composite. Localised damage generally affects the global stiffness very little whereas the strength can be reduced significantly. Thus, strength driven components in ship hulls will be much more affected by any kind of damage, in-service damage or manufacturing defects.

This paper will present some results from a multi-national effort in the project SaNDI [3], in which several navies jointly developed methods for inspection and damage assessment of composite sandwich hull structures. The part described herein refers mainly to work within the Swedish project and is performed on materials of a similar type to that used in the Visby class corvette, see Fig.1, covering only the work addressing local in-service damage types.

Figure 1 Side view of the all composite/sandwich Visby class corvette (Photo courtesy of Peter Nilsson/Kockums AB).

From a damage tolerance perspective there are several important aspects to consider. One cannot guarantee that damage or defects can be detected, both since NDI of sandwich structures is difficult due to their multi-material constitution and that ship structures are indeed very large. From a practical point of view one must therefore consider only damages that are barely visible or clearly visible. The question often asked is – “Does all damage have to be repaired?” and “Is this damage critical for the integrity of the structure?”. Decisions must be taken on corrective measures relatively quickly once damage has been found. Large damages will obviously be found and often requires immediate repair, either for structural reasons or for functional reasons (water tightness, etc.). The problem addressed herein concerns barely visible impact damage (BVID) and visible impact damage (VID) with the aim of finding how much such damage will affect the load carrying capacity of a panel or component in the ship. Large damage is thus addressed but the focus is on damage that may exist without being detected, or damage that is small enough not requiring repair for functional reasons. Such damage may, or may not, require repair depending on its size, its type and the type of loading at its location.

More specifically, the damage types covered in this presentation are limited to ones caused by localised quasi-static loads or local impact. Furthermore, residual strength testing and assessment was limited to compressive loading. This may appear limiting, but is due to the fact that carbon composites usually exhibit a considerably lower compressive than tensile strength. Thus, the parts of the ship that are designed for strength, are most often designed for compressive strength.

2 Materials and damage types studied

The materials used in the sandwich specimens are similar to the materials used in the Visby corvette and consist of carbon/vinylester face sheets and a PVC foam core material. The carbon fibre (CFRP) face sheets were manufactured from quadrilateral (0/90/45/-45) non-crimp fabrics (NCF) of Toray T700 fibres. The PVC foams used were Divinycell H80 and H200 with nominal densities of 80 and 200 kg/m³, respectively. Data for nominal material properties can be found in [4]. The test panels were manufactured by vacuum infusion of the resin into a stack of core material and NCF-reinforcements. The infusion was performed at room temperature with at zero bar pressure. The vinylester resin was set to have a 1 hour gel time and the panels were post-cured at 60°C for 12 hours. Two material configurations were studied: one denoted “thin” and one denoted “thick”, as described in Table 1, where the wording thin and thick refers to the thickness of the face sheet.

Panel type	Core material	Core thickness [mm]	Face sheet lay-up	Face sheet thickness [mm]
Thin	Divinycell H80	60 mm	[0/90/45/-45] _s	1.8
Thick	Divinycell H200	50 mm	[0/90/45/-45] _{s3}	5.4

Table 1 Definition of materials in test panels

The materials were chosen as quasi-isotropic, though actual ship hull structures utilises various types of lay-ups. The reason for this choice was rather that the thin type panel is chosen to resemble materials and dimensions of superstructure parts with relatively low

loading, whereas the thick panel type more resembles highly loaded areas. The unidirectional lamina data for the face sheet material were taken as; $E_1 = 114$ GPa, $E_2 = 9.0$ GPa, $G_{12} = 3.0$ GPa, $\nu = 0.25$ with a compressive strength in the fibre direction $\sigma_{1c} = 844$ MPa. This gives a homogenised elastic modulus of the quasi-isotropic face sheet of 43.4 GPa, a Poisson's ratio of 0.32 and a compressive strength of 325 MPa (corresponding to a failure strain of approximately -0.0075 , which is a conservative value).

3 Blunt and sharp impact damage

Two types of impact damages were used; denoted blunt and sharp impact. The blunt impact damage was created using a spherical head impactor with a diameter of 25 mm. The sharp impact damage was created using a pyramid shaped impactor [5]. The impact tests were performed using a free-fall weight of 15.29 kg at different drop heights. The energy levels were chosen so that one level created a barely visible damage (BVID) and a second higher level gave clearly visible damage (VID). For the thin panel configuration the energy levels were taken as 30 and 50 J, respectively, and for the thick panels, 100 and 250J. The panels were laid flat on a rigid foundation during the impact event without any further boundary restrictions.

Figure 2 Damage types occurring from (a) blunt object impact and (b) sharp object impact.

The blunt impact damage consisted of a very small dent, 0.8 and 0.4 mm deep for the thin and thick panels with BVID damage, respectively, with some minor surface fibre breakage in the VID case. The underlying core showed a small zone of crushing, but apart from that there was no other visible damage indicated. A cross-section of the impact zone is shown in Fig.2(a). However, ultrasonic C-scan investigations revealed significant overlapping delaminations with a diameter $2R = 15$ -20 mm for the thin panels and $2R = 20$ -30 mm in the thick panels [6]. The sharp type impact created a slit in the face sheet, as shown in Fig.2(b). The projected length of this slit was in the order of $2a = 15$ to 25 mm, with the higher value for the higher impact energy.

3.1 Compression after impact testing

The test panels (dimension 300 by 300 mm) were inflicted with one impact damage at the centre on one side. In order to achieve symmetric loading and to avoid premature failure at the

load introductions, the two loaded edges were milled plane and parallel and the thin panels were also equipped with tabs in order to increase the contact area. The panels were mounted in a 2 MN displacement controlled compression testing machine. The milled edges were placed horizontally while the vertical edges were free and unloaded. Testing was performed under a 1 mm/minute displacement control until failure.

In some of the tests, digital speckle photography equipment (DSP – Aramis by GOM) was used to measure and monitor surface strains. The surface strain mapping revealed clear indications of stable microbuckling growth before final failure. For some panels, the compression loading was interrupted just before complete failure and the panel was sectioned, and the surfaces polished and inspected in a microscope. Microbuckling was seen in this fractographic investigation with lengths up to 20 mm [6]. These lengths corresponded very well with the lengths of localised strain growing from the damage as observed by DSP measurements. Two such DSP strain map plots are shown in Fig.3 for a thin panel with a BVID (30J) blunt impact damage. The first (Fig.3a) shows the axial strain at 120 kN load, which corresponds to approximately half the failure load. The second strain map (Fig.3b) shows the axial strain just prior to failure (at 216 kN, or approximately 200 MPa nominal stress). The localised strain (dark area) corresponds to an axial strain of 1%. As seen, strains localise near the damage and damage progresses in a stable manner during the loading of the panel. No visible damage progression could be seen on the surface of the panel until complete fracture.

Figure 3 DSP plot showing axial strain (vertical = load direction) (a) at 120 kN load and (b) just before failure (at 216 kN) for a thin panel with a blunt impact damage. The dark area corresponds to compressive strains of 1%. The horizontal length of the plots corresponds to approximately 100 mm (not the complete panel width).

3.2 Prediction model applied

The model developed by Soutis *et al.* [7,8] was used for the prediction of the compressive strength of notched composite laminates. The model assumes closing cracks to develop from a notch and uses a linear stress-displacement cohesive law for the crack flanks. The model was used for laminates containing both holes and cracks showing good agreement with experiments [8]. From fractographic investigations of the blunt impact damages described above, clear evidence of progressive microbuckling failure was observed [6]. A similar approach to that of Soutis and Curtis [9] was taken herein; assuming an equivalent hole the

size of the overlapping delamination area found from C-scanning. To do the predictions, the code *Composite Compressive Strength Modeller – CCSM* [10], which implements this progressive microbuckling analysis, was used for the blunt impact cases by assuming an equivalent hole representing the damage. The same code was again used for the sharp impact tests, but then an equivalent crack model was used, since a clear crack was produced by the impact. The crack length used in the model was the projected length of the slit, perpendicular to the load direction.

In order to find the necessary input data for the CCSM model, un-notched compression tests were performed on the laminates using the Wyoming modified IITRI test set-up. To find the fracture energy, small panel specimens (150 by 150 mm) were manufactured with central holes cut. These were tested in compression from which the fracture energy can be deducted by the use of CCSM [5] and it was calculated to $47 \text{ MPa}\sqrt{\text{m}}$.

3.3 Results

The failure load as measured from the testing machine was converted to nominal stress and strain and compared with the output from the CCSM analysis. The results from this analysis are given in Table 2.

Panel type	Damage	Damage size	$\epsilon_{exp.} [\%]$	$\epsilon_{pred.} [\%]$
Thick/Thin	None	-	-0.75	-
Thin	Blunt, 30J	$2R = 15 \text{ mm}$	-0.488	-0.495
Thin	Blunt, 50J	$2R = 20 \text{ mm}$	-0.472	-0.459
Thick	Blunt, 100J	$2R = 20 \text{ mm}$	-0.433	-0.459
Thick	Blunt, 250J	$2R = 30 \text{ mm}$	-0.406	-0.410
Thin	Sharp, 30J	$2a = 20 \text{ mm}$	-0.433	-0.477
Thin	Sharp, 50J	$2a = 25 \text{ mm}$	-0.426	-0.419
Thick	Sharp, 100J	$2a = 15 \text{ mm}$	-0.421	-0.484
Thick	Sharp, 250J	$2a = 22 \text{ mm}$	-0.398	-0.435

Table 2 Results from compression after impact tests and predictions using CCSM [10] for thin and thick panels with BVID and VID, blunt and sharp impact damage. Damage size $2R$ corresponds to measured projected diameter of delaminations for blunt impacts, and length $2a$ corresponds to measured projected length of slit from sharp impacts.

The results indicate that using equivalent hole and crack models in CCSM produces good predictions of the post-impact strength for the sandwich panels studied herein. For other laminate lay-up sequences, the fracture energy will have to be obtained experimentally. From a practical point of view, one can now produce simple graphs of strength reduction versus damage size for blunt and sharp impact damages to be used in the assessment of damage criticality and to find a critical damage size. Such graphs, produced using the panel types used herein, are shown in Fig.4. Recall that as long as the lay-up sequence is the same, the thickness has no effect on the prediction model used.

Figure 4 Strength reduction curves for blunt (equivalent hole model) and sharp (equivalent crack model) impact damages. Experimental data for blunt and sharp impact damages indicated as stars and squares.

From a practical point of view it is useful to provide relations between damage size and reduction in strength like those shown in Fig.4. The first aspect is that such information can be used to quickly assess the criticality of damage. If the damage is larger than the allowable size it may grow at the specified design load. This may imply that restrictions in the operational profile can or must be imposed. A graph of the type presented in Fig.4 merely provides information on the strength reduction versus damage size for the failure mode assuming face sheet compression failure. The reduced strength must also be compared with the actual load level at the position of the found damage, taking account of the assumed failure mode for the component and the used safety factors. This information is readily available from the design specification of the structure. By combining this information, the true reduction in load carrying capacity of the structure, if any, can be obtained. The second important issue is that critical damage sizes can be mapped onto the entire structure and used for inspection purposes and input data for non-destructive evaluation (NDE). In practice, it is important to know what size damage it is relevant to look for at different parts of the structure. If the critical damage size is large, visual inspection may be sufficient, but if it is small, more elaborate methods may be required in certain areas.

4 Validation experiments

4.1 Scaled-down component compression tests

In order to validate the tests and predictions for flat sandwich panels, a set of larger panels were manufactured and tested. Two sets of panels were made for this purpose. The first type was a scaled down ship panel resembling a typical wet deck plating – a flat plate with two longitudinal stiffeners as shown in Fig.5. The panels were manufactured the same way as above, using the same materials, having “thin” faces (see Table 1). The stiffeners were made of H80 core and attached using core bonding adhesive, then covered with the dry carbon fabrics and infused with the resin according to the same principles as in a shipyard. Four panels with dimension 800 by 800 mm were manufactured and then impacted with a 100 J sharp or blunt impact, at the centre of the panel or near one corner, respectively. There is thus just one panel test per configuration in this test series. More details about this investigation can be found in [11].

Figure 5 Sandwich panel with two longitudinal stiffeners (prior to lamination of stiffeners to make the photograph more clear).

The reason for placing the impact damages at the centre of the panel and at one corner was to see if the position of the damage would make any difference, as it was not anticipated. The prediction for the blunt impact damages was done using the equivalent hole model in the CCSM and for the sharp impact damage, the equivalent crack model in CCSM was used. The experimental results and the predictions are given in Table 3.

Damage	Position	Damage size	$\epsilon_{exp.} [\%]$	$\epsilon_{pred.} [\%]$
Blunt, 100J	Centre	$2R = 26 \text{ mm}$	-0.43	-0.42
Blunt, 100J	Corner	$2a = 36 \text{ mm}$	-0.37	-0.37
Sharp, 100J	Centre	$2R = 39 \text{ mm}$	-0.42	-0.42
Sharp, 100J	Corner	$2a = 26 \text{ mm}$	-0.40	-0.42

Table 3 Residual strength measurements and predictions for validation panels subjected to an in-plane compression load given in strains at failure.

4.2 Panels subjected to hydrostatic pressure loading

In a second stage, sandwich panels with impact damages were subjected to hydrostatic pressure loading. Herein, panels were subjected to a uniform pressure loading by means of a water-filled rubber bag. The panels were placed simply supported on a frame measuring 980 by 625 mm and within this area the water-bladder was used to distribute the pressure on the impacted side of the panel. The panels were made from the same type of materials as described previously, but in the lay-up sequence [0/45/-45] with an approximate thickness of 0.7 mm and a 25 mm H160 core (density 160 kg/m³). The panels were subjected to impact damage using a sharp impactor with a relatively high impact energy of 270 J using a mass of 49.6 kg free falling from 555 mm height. This was done at two different impact locations; at the centre of the panel and one near the corner of the panel. The interesting point here is that the remote loading is different at these positions. Since the lay-up is different than in the previous cases, a new set of tests had to be performed to obtain the fracture energy. This was again done by performing compression tests of specimens with a central hole.

There are two ways of performing predictions using the CCSM in this case. The first is to estimate the local strain (or stress) at the location of the damage by simply computing the entire strain vector $\boldsymbol{\varepsilon} = (\varepsilon_x, \varepsilon_y, \gamma_{xy})^t$ in global co-ordinates and inserting this into the CCSM model, which takes account of not only uniaxial compressive strain but also transverse stress and shear stress. The other option is to transform the global remote strain at the position of the damage, $\boldsymbol{\varepsilon}$, to layer-wise local strain and use the fibre compressive strain (or stress) for micro-buckling analysis. For damage at the centre of the panel, the maximum compressive strain (or stress) occurs along the short span direction and the prediction for micro-buckling failure will then be in the 0-degree layer only. For a damage located at a corner, on the other hand, the global strain is mainly from shear and thus a 45-degree layer will experience the highest compressive strain. The two approaches gave similar results for the core damage residual strength prediction [11], as given in Table 4.

Damage	Position	Damage size	$\varepsilon_{exp.} [\%]$	$\varepsilon_{pred.} [\%]$
Sharp	Centre	$2a = 73 \text{ mm}$	-0.29	-0.24
Sharp	Corner	$2a = 76 \text{ mm}$	-0.24	-0.24

Table 4 Residual strength measurements and predictions for validation panels subjected to uniform pressure load given in strains at failure.

As seen in Table 4, the predictions agree quite well with the experimental results. The reduction in strength is quite large however, but the damages in this case are quite large too. The location of the damage does not appear to have a large influence simply by looking at the results, but this is merely coincidental in this case. The far-field stress at the position of the damage changes significantly over a plate subjected to pressure loading, and the position of the damage will thus be important. There is one further aspect to consider in this case. The undamaged panel will be designed for several failure modes, e.g. face sheet compression failure, core shear failure, etc. The strength reduction due to localised damage will strongly depend on how the panel is designed. To exemplify this we can use the following argumentation. Assume we have a composite sandwich panel subjected to a uniform pressure loading and that the maximum load this panel can carry is governed by core shear failure. At this load, the face sheet strain (or stress) is only half of its strength. A localised damage that

reduces the allowable face sheet strain with less than 50% will have no effect on the panel's load carrying capacity – it will still fail by core shear fracture. We can in this case allow rather large damages in the face sheet without any reduction in global strength. If the panel, on the other hand, is designed for face sheet compression failure, even a small damage at the location of maximum face sheet stress will reduce the panel's load carrying capacity. At other locations, the far-field stress is lower, and damage can be accepted without affecting the load carrying capacity. Sandwich panels are thus, due to multiple failure modes, somewhat more complicated to analyse than single-skin laminates from a damage assessment point of view. The conclusion from this investigation is that the effect of localised impact damage, blunt or sharp, can be predicted using existing tools with relatively good accuracy. The important outcome is that large parts of a ship structure can then be mapped for this damage threat in terms of critical damage sizes. The other outcome is that once damage is found, one can quickly, and accurately enough, decide on appropriate actions.

5 Indentation damage

Localised transverse loads may create indentation damage, which differs somewhat from impact damage. A local static overloading will usually not result in any face sheet damage, but the underlying core will crush causing a residual dent in the face sheet, as illustrated in Fig.6. Though the face sheet may be undamaged, it has a perturbed geometry and the crushed core underneath will provide a less stiff support, which may lead to a decreased load bearing capacity under compression loading.

5.1 Indentation testing

Panels with thin faces, as described in Table 1, were subjected to quasi-static localised loading to different indentation depths using a hemispherical steel indenter with a diameter of 150 mm. The panels were placed on a flat rigid foundation for preventing overall bending deformation. The tests were conducted using a displacement-controlled standard testing machine. Upon removal of the indenter, the elastically bent face sheet deflected back leaving a remaining dent due to the crushed core underneath the indentation point [12]. However, the core still remains attached to the face sheet.

A profile of the residual dent in the face sheet was measured by means of a dial gauge in two perpendicular directions across the dent area. The residual dent diameter, D_{dent} , was similar along both directions indicating that the residual dent is almost circular in the x - y plane. The residual dent depth, δ_{dent} , was typically greater by as much as 25-30%, if measured directly after indentation testing, owing to significant creep and relaxation effects in the crushed foam core [12]. In this study the measurements of residual dent parameters were conducted 10 minutes after the testing to ensure that the dent was in a quasi-stationary state. Both the depth of the residual dent in the centre, δ_{dent} , and the diameter, D_{dent} , were increasing with the indentation depth.

Destructive sectioning of some panels was performed to determine the diameter, D_{core} , and the depth, d_{core} , of the crushed core damage. The geometrical parameters of the damage, as defined in Fig.6, were subsequently used in the finite element modelling. It is interesting to note that the residual dent diameter, D_{dent} , was only marginally greater than the crushed core diameter, D_{core} , in all sectioned panels. The results are given in Table 5.

(a)

(b)

Figure 6 (a) Schematic of indentation damage and (b) a photograph of a cross-section with indentation damage.

In the panels considered in this study, there was no obvious evidence of large scale delaminations, debonding or fibre breakage in the face sheet.

Indentation depth [mm]	D_{dent} [mm]	δ_{dent} [mm]	D_{core} [mm]	d_{core} [mm]
5.5	60±1.2	0.85±0.03	60±1.0	7±1.0
7.0	92±1.5	0.91±0.03	90±1.5	11±1.2
10.0	121±1.4	1.54±0.04	120±2.0	16±1.9
15.0	158±2.3	2.65±0.06	155±2.0	23±2.1

Table 5 Geometrical parameters as measured on test panels and used in FE-modelling for panels with indentation damage.

5.2 Compression after indentation testing

Displacement-controlled CAI tests of sandwich panels were conducted in a hydraulic testing machine at the cross-head rate of 1 mm/min. The panels were instrumented with a dial gauge for measuring the out-plane displacements in the centre of the residual dent. All panels failed by compressive fracture of the face sheet containing the residual dent. There was no global deformation (Euler type buckling) of the panels during the tests. The compression failure was preceded by a distinct abrupt growth of the residual dent inwards, toward the mid-plane of the panel. The onset of residual dent growth was associated with a drastic loss of stiffness and

load bearing capacity in the panels. The ultimate failure loads decreased with increasing residual dent size. A typical load-displacement response from the CAI tests is shown in Fig.7.

(a)

(b)

Figure 7 Experimental results from edge-wise compression tests of H80/CFRP panels; a) load versus displacement response and b) compressive load versus out-of-plane displacement. Legend refers to thin panel with 10 mm and 15 mm initial indentation, respectively.

Visual observations during the CAI testing suggested that compressive failure was initiated in the middle of the residual dent and then propagated across the panel, perpendicular to the loading direction. For investigating the failure mechanisms in more detail, a digital speckle photography (DSP) analysis was used to measure displacements and, consequently, strains in the face sheet containing the residual dent. A typical z -displacement field (out-plane displacement) at different load levels for the panel after 10 mm indentation is shown in Fig.8. A negative displacement magnitude corresponds to an inward displacement. For this panel, the DSP analysis showed that growth of the residual dent was triggered at a load of about 220 kN, see Fig. 8b. At lower loads, no indication of dent growth could be observed. After the onset of dent growth, the dent rapidly develops inwards at almost constant load, see Figs.8b,c, followed by a compressive failure in the face sheet, see Fig. 8d. The growth of the residual dent and its profiles in two perpendicular directions were also measured by means of the DSP analysis and presented in Fig.9.

Figure 8 Out-plane displacements around the residual dent obtained by the DSP analysis. The loading direction is in the vertical direction in the plots. The horizontal length of the plots corresponds to approximately 200 mm (not the complete panel width).

(a)

(b)

Figure 9 The dent profile and its growth in x- and y-directions at different load levels. The y-direction is the loading direction.

Figure 10 shows the measured out-of-plane displacements and in-plane compressive strains in the centre of the residual dent compared with far-field values. It can be seen that the residual dent remains almost stationary until a certain load. After the onset of dent growth, it develops very quickly inwards. The strains in the centre of the residual dent and far-field strains are similar until the residual dent growth is triggered. After the onset of dent growth, the bending strains caused by the residual dent growth are superimposed on the in-plane compressive strain state resulting in very high local compressive strains which exceed the ultimate strain of the face laminate. It is interesting to observe that the far-field strain in the face laminate at failure is clearly lower than the ultimate strain.

(a)

(b)

Figure 10 Compressive strain and out-plane displacement in the centre of the dent. For comparison, far-field strain and displacement are also plotted.

5.3 FE-model and prediction approach

A three-dimensional (3D) finite element (FE) model of the sandwich panel was developed using the FE-package ABAQUS [13], see Fig.11. The faces and the core were explicitly modelled using geometry and properties as given previously. The model was parametrised with respect to the damage parameters given in Table 5 so that each test could be analysed specifically. The residual dent was modelled using a third degree polynomial and the crushed core zone profile with a second degree polynomial. Due to symmetry, only one half of the panel was modelled. The properties of crushed core differ from those of pristine core material, having much lower stiffness. The properties of crushed core material were measured using the same approach as outlined by Shipsha *et al* [14] and used in the FE model for the crushed core zone. A cartesian coordinate system was used with the origin in the centre of the damage. The y-axis corresponds to the direction of the CAI loading. Symmetry boundary conditions were imposed in the model. The compression load was applied as a prescribed displacement at the edge.

Figure 11 FE-model of a sandwich panel with indentation damage.

FE analyses of sandwich panels with residual dents of different geometry (see Table 5) were performed in order to predict the onset of dent growth and corresponding failure loads. The analyses included material non-linearity in the crushed core as well as geometrical non-linearity. The maximum compressive strain of the face laminate was used as a fracture criterion. A comparison of strains from the DSP test and FE analysis as a function of the in-plane displacement is shown in Fig. 12. The strains in the centre of the dent and far-field strains are presented. It can be seen that the FE model provides a good agreement with experimental results.

Figure 12 Comparison of the results from FE analysis and experiments; (a) predicted and experimentally obtained residual dent growth inwards the panel and (b) predicted and experimentally measured strains.

Numerically predicted failure loads (ultimate far field strains) are compared with experimentally obtained results in Table 6. In general, the FE-model slightly underestimates the failure onset, so the predictions are conservative. This approach demonstrates that the finite element analysis has a potential to provide accurate simulation of the behaviour of damaged panels in compression provided that the damage parameters and damage configuration can be characterised (NDI, destructive sectioning, etc).

Indentation depth [mm]	Far-field strain at failure (test), [%]	Far-field strain at failure (FE), [%]
5.5	-0.72	-0.67
7.0	-0.69	-0.65
10.0	-0.64	-0.58
15.0	-0.58	-0.54

Table 6 Comparison experimentally measured and predicted far-field strains at failure

6 Damage assessment scheme

In this paper, three typical types of damage to carbon composite sandwich panels in ships are investigated: local impact damage by sharp and blunt objects and indentation damage, as illustrated in Figs.2 and 6. From a practical viewpoint all possible threats and damage types

must be included in order to provide a comprehensive damage assessment system. To do this one needs not only the information on the localised strength reduction due to damage for individual panels but a more elaborate scheme for evaluating the influence of the damage on the structural performance and functionality of the ship as a whole. In the SaNDI project such a scheme was developed that is fairly generic in terms of damage types and ship structures, although the designs and design requirements may vary significantly. The damage assessment procedure for cases where strength is the main consideration is basically as follows [15,16]:

- Estimate the strength reduction caused by the damage or defect.
- Determine the allowable strength reduction based on the original design assumptions, operational envelope, etc.
- Compare these. If the residual strength is smaller than the allowable value, consider the possibilities for restricting the operational envelope and/or accepting a lower safety factor until repair can be effected.
- If this is not sufficient, carry out an emergency repair or take other emergency measures as necessary.

To do this, one may need to consider the damage in the local, panel and global (ship) contexts, as illustrated in Fig.13. The scheme as a whole is shown schematically in Fig. 14.

Figure 13 Damage illustrated in local, panel and global (ship) contexts.

Figure 14 Residual strength approach for local panel strength and global ship strength.

For damage confined to a single panel, we first consider the influence of the damage on the affected panel or component by estimating a strength reduction factor for the panel, R_p . This is then compared with the allowable strength reduction for the panel, R_{pa} . If the panel suffers from a reduced load bearing capacity, we need further to consider any implications of this at the global (ship) level and estimate any reductions in the global ship strength. For this purpose it is possible to calculate a ship strength reduction factor R_s , which again must be compared with some allowable global strength reduction factor, R_{sa} .

A division is made considering the level of damage, ranging from small local damage confined to a small part of one panel (level 1) to extensive damage affecting larger areas of two or more panels (level 4) [15,16]. For level 1 damage, which applies to the damage cases considered herein, the size of the damage is small compared to the panel size so that the stress distribution within the panel is unaffected by the presence of the damage (no stiffness changes). The assessment is then performed as follows:

1. Determination of the local strength reduction factor R_l that quantifies the reduction in far-field stress or strain at failure. The value of R_l should preferably already been calculated a priori, and recorded in tables or graphs, such as in Fig. 4.
2. Determination of a sensitivity factor S_p that accounts for the location of the damage in relation to the stress field in the panel for the real loading case.
3. Combination of these factors to give the panel strength reduction factor $R_p = R_l S_p$ or 1.0, whichever is smaller.

The sensitivity factor S_p , which is more correctly referred to as the local location and load case factor, also provides a means of seeing immediately what are most likely to be the critical locations of damage on a panel. It is defined as follows:

$$S_p = \frac{P_{ali}}{P_{api}} \quad (1)$$

where P_{ali} is the value of load that causes the critical stress or strain component at the damage location to reach its maximum allowable value ignoring the damage, and P_{api} is the maximum allowable value of load on the intact panel. For face sheet damage, the critical stress or strain component is usually assumed to be the in-plane compressive stress or strain at the point in question. S_p can never be smaller than unity.

As an example, suppose a panel under uniform, lateral pressure is designed so that it reaches the allowable limit for core shear stresses before the allowable stresses for face laminate failure. (This will often be the case for panels designed to classification rules, for example, if the minimum thickness requirements result in an increase of laminate thickness relative to the basic strength requirements.) Then P_{api} is the pressure load at which the allowable core shear stress is reached. Suppose that there is a local impact damage that has reduced the local in-plane compressive strength of the face laminate so this has to be checked at the damage location. Then P_{ali} is the pressure applied to the panel at which the allowable compressive stress (or strain) in the face laminate at that location reaches its maximum allowable value, also calculated for the intact panel. Note that all these quantities are calculated for the intact panel. This means that maps of S_p values can readily be drawn for panels with given dimensions and lay-ups for simple load configurations like uniform lateral pressure.

There is normally no need to consider an allowable strength reduction if $R_p = 1$. If $R_p < 1$ the possibility of accepting a reduction of panel strength must be considered unless the damage can be fully repaired immediately. If $R_p < 1$, the global strength reduction R_s must also be evaluated. For Level 1 damage, and also for some cases of slightly larger damage to a single panel defined as Level 2 damage, it is possible to neglect redistribution of stresses between panels (and other elements) in the structure when estimating the influence of the damage on the global strength. This enables R_s to be found from R_p by a procedure analogous to that for deriving R_p from R_l . For larger damage cases (Level 3 or 4), alternative procedures must be used as discussed in [15,16].

In some cases it is not possible to accept any reduction in the global or local strength of the structure. However, not all parts of the structure of a ship are highly stressed. In many cases a given panel may be exposed to a maximum loading that is lower than the allowable value because the design gave more than the minimum required reserve of strength, i.e. there is a lower utilisation of the panel than the maximum that is allowed. This is often due to the fact that a limited number of standard sandwich lay-ups are generally used in any given vessel. In such cases it will normally be acceptable to reduce the panel strength by an amount that reflects this extra reserve of strength in the intact structure. The same may apply at the global ship level if the ship has been generally over-designed against the global loads (e.g. because the local load requirements were more severe). These aspects are dealt with here by using the utilisation factors U_p and U_s . The panel utilisation factor is defined as the ratio

$$U_p = \frac{\text{maximum load applied to the damaged panel under extreme design load}}{\text{maximum allowable value of that load for the undamaged panel}}$$

The global (ship) utilisation factor is defined as the ratio

$$U_s = \frac{\text{maximum global load applied to the structure under extreme design load}}{\text{maximum allowable value of that load for the undamaged structure}}$$

Normally the allowable strength reductions for panel and global strength will be set equal to the respective utilisation factors:

$$R_{pa} = U_p \text{ and } R_{sa} = U_s$$

There are two main additional considerations that may make a strength reduction acceptable:

- Reducing the loads (relative to original design) by restricting the operation in some way.
- Accepting a reduced factor of safety in the interim period until a repair is effected.

The first of these leads in effect to a lowering of the utilisation level in that the extreme *design loads* are now *decreased*. The second leads to a lowering of the utilisation level in that the *allowable loads* are *increased*.

Note that the procedure described so far deals only with strength considerations. Considerations of functionality (which may include that of stiffness as embodied in deflection criteria) must be made separately. Functionality requirements, such as

- watertightness
- weathertightness
- smoke-tightness
- fire division effectiveness
- equipment functioning (machinery, instrumentation)
- signatures and shielding
- other functionality

may override any repair decisions based on load carrying capacity. Thus, although a damage does not require repair from a structural point of view, functionality may still require repair.

Finally, decisions about corrective measures have to be made on the basis of comparing the strength reductions R_p and R_s with their allowables R_{pa} and R_{sa} . Fig.15 shows an example of a flow-chart for such a decision-making process, taking account of only the strength reduction aspects.

Figure 15 Schematic illustration of assessment process.

7 Summary and Conclusions

Three localised damage cases on CFRP sandwich panels have been studied herein. For the test panels investigated it was found that impact damages, be it blunt or sharp impact damage, reduce the compressive load carrying capacity of the composite face sheet and that this reduction can be significant. Localised overloading (indentation) appears, at least for the material combinations studied herein, to affect the strength much less. The damage assessment will have to utilise such analyses and test results performed on smaller scale specimens. Clearly, damage will reduce the load bearing capacity of composite sandwich panels in general but in the context of ship design and usage, this is not necessarily all that critical. There are two reasons for this. Many components in ship structures are not utilised fully and can thus allow for damage to be present without affecting the overall load carrying capacity. Secondly, a damage may influence a failure mode that was not critical in the design of the panel, leaving a safety margin. Still, there will be panels and components that will suffer from reduced load carrying capacity due to damage. However, by means of a comprehensive damage assessment scheme, such areas and components can be mapped out and inspection schemes set up to ensure the integrity of the structure. If damage occurs in operation, the information gathered from the damage assessment scheme can be used for decision-making. It may be possible to reduce loads by restrictions in the operational profile, ensuring a safe structure, until a repair can be made.

The combined information can and shall also be used to set up inspection schemes and information on what types of NDI-techniques to be used. In large sections of a ship visual inspection may be more than sufficient, while in localised areas, advanced methods may be required. Since ships are large, such schemes do not only increase the probability of actually finding critical defects and damages, but increase safety and save costs of NDI.

Another important aspect of an elaborate damage assessment is that crew and maintenance personnel can have access to information on what types of damages must be found and repaired, according to their type, size and location. Other damages may be left in the structures if they are small enough or in places of low loading, thus focusing repair efforts and saving costs.

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