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DAMAGE ASSESSMENT SCHEMES FOR NAVAL SANDWICH STRUCTURES WITH FACE-CORE DEBONDS CONSIDERING RESIDUAL STRENGTH AND FATIGUE LIFE

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1. INTRODUCTION

Face-core debonds in sandwich structures of naval vessels may occur in production or result from unfavourable events or environmental conditions during service. A debond may be large enough to cause failure of a loaded sandwich component, while an initially harmless debond may grow under fatigue loading until it becomes critical. Thus, for cyclic loading, it is important to understand the way that debonds grow, the extent to which the component strength is reduced, and the remaining fatigue life at any given stage. It is also important to be able to include these in a damage assessment scheme for practical application when decisions have to be made, sometimes urgently, on corrective measures. Extensive studies have been performed at the Technical University of Denmark (DTU) into the behaviour of sandwich structures with face-core debonds. Fracture properties of the interface have been determined for several material combinations relevant to wind turbine blades and ship and aircraft structures. For hull and deck panels of naval vessels the dependence of residual strength on the debond size has been determined, and subsequently used in a damage assessment scheme [1-3]. DTU's research is now focusing especially on fracture and crack growth under cyclic loading.

Material and interface fracture properties are generally obtained from tests on small-scale specimens, often simple sandwich beams. Real sandwich ship structures consist of assemblies of panels. While extensive physical testing and numerical modelling have been performed on sandwich panels and joints with debonds for static loadings, much fewer studies have been performed for cyclic loading. In principle, once the interface fracture properties have been obtained, a structure can be modelled and its fatigue life estimated. However, in practice this can be demanding and time-consuming, so that ways of reducing the computational effort are needed [4-6]. The work reported here considers practical ways of assessing the consequences of defects and damage, as a basis for determining appropriate corrective measures. Procedures developed earlier for static or quasi-static loading [1] have been refined, and ways of adapting and extending them to damage growth and residual life under cyclic loading are explored.

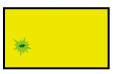
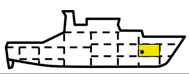
2. THE "SANDI" APPROACH TO DAMAGE ASSESSMENT BASED ON RESIDUAL STRENGTH

The SaNDI Project, *Inspection and Repair of Sandwich Structures in Naval Ships*, was performed in 2001-4 with participants in Norway, Sweden, Denmark, Finland and the United Kingdom. Methodologies for production control and in-service damage inspection were developed, and acceptance criteria established for defects and damage [4,5]. Several types of defects and damage were considered, including face-core debonds as well as various types of impact damage and production defects such as face sheet wrinkles. Damage assessment procedures developed for residual strength in the SaNDI Project use almost exclusively pre-calculated information that can be made readily available in decision support tools and/or manuals on board a ship and at its onshore support facilities.

In the SaNDI damage assessment procedure [1,2], four levels of damage severity are defined: level 1 (small local damage, covering a small part of a panel so that its influence on the panel stiffness and the stresses at remote points on the panel can be neglected); level 2 (as level 1 but involving a larger part of a panel); level 3 (confined to one panel but affecting its stiffness); level 4 (affecting two or more panels and/or supporting structure). The procedure involves consideration of strength reduction factors at up to three scales as illustrated in Table 1. Figure 1 shows local strength reduction factors for debond damage on some sandwich layups with GFRP faces and three types of foam core, from a later study [3]. Debonds may be of level 1, level 2, or level 3 damage. When they are within level 1, the local factor R_l can be combined with a local location and load type sensitivity factor S_p to give the panel strength reduction factor R_p:

$$R_p = R_l S_p \text{ with a maximum value of } 1.0 \tag{1}$$

Table 1: Three scales to be considered when assessing damage in a naval sandwich structure

Schematic	Scale	Strength reduction factor
	Local (for level 1 only)	$R_l = \dfrac{\text{Nominal (far field) stress or strain to cause failure with damage}}{\text{Nominal (far field) stress or strain to cause failure without damage}}$
	Panel	$R_p = \dfrac{\text{Maximum allowable load on damaged panel}}{\text{Maximum allowable load on intact panel}}$
	Ship	$R_s = \dfrac{\text{Maximum allowable load on damaged ship}}{\text{Maximum allowable load on intact ship}}$

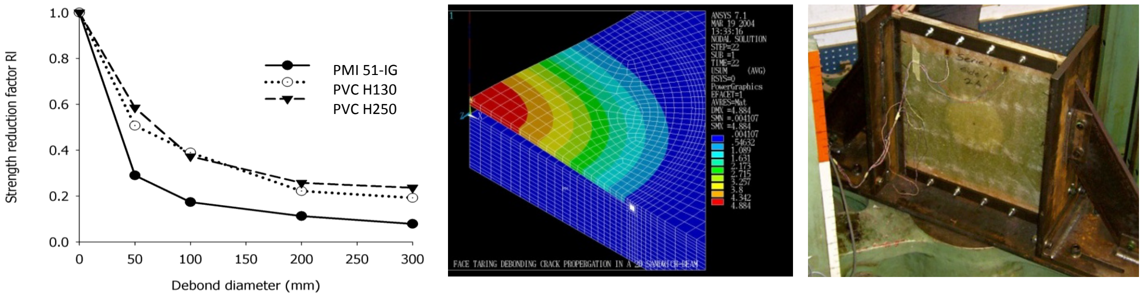


Fig. 1: Local strength reduction factors for face-core debond damage on sandwich layups with GFRP face sheets and three different foam core materials, with in-plane compressive loading [3]. FE analysis and physical testing.

The factor S_p is defined as the ratio of the value of the load on the panel that would cause the critical stress or strain component *at the damage location* to reach its maximum allowable value, *ignoring the damage*, to the maximum allowable value of load on the intact panel (i.e. the load that causes the critical stress or strain component to reach its maximum allowable value at the most highly stressed location). Even if parts of the panel are at their design strength limit under the maximum design loading, other, less severely stressed parts may be able to sustain damage without consequences for the panel as a whole. The variation of S_p over the panel depends on its boundary conditions and type of loading. It will always be on the conservative side to assume $S_p = 1.0$ since, by definition,

$$S_p \geq 1 \tag{2}$$

Any panel that experiences damage should be checked by comparing R_p with a minimum allowable value R_{pa}:

$$R_p \geq R_{pa} \text{ where } R_p = \min(R_l S_p \, , 1) \tag{3}$$

R_{pa} represents the minimum residual load-carrying capacity that can be allowed for the panel concerned in order to maintain its functionality. Such a limit can be defined for either local or global loading cases, or both.

If the damaged panel contributes to the global strength of the ship, the overall consequences for the ship must also be assessed. Then the ship strength reduction factor R_s is estimated for one or more global loading cases. For level 1 and 2 damage types, this can be done using a panel location and load type factor S_s that is analogous to the factor S_p so that

$$R_s = R_p S_s \text{ with a maximum value of 1.0.} \tag{4}$$

S_s represents the reserve of strength at the panel in which the damage occurs, calculated for the intact condition. Analysis of the intact ship can provide a map showing the reserve of strength and the S_s value for each panel. For level 3 damage, an approximate method has been proposed [1] for estimating R_s. For level 4 damage, a direct assessment of the damaged ship must be performed. Finally the ship strength reduction R_s has to be compared with an allowable value R_{sa} based on evaluation of the required margin of safety for the design of the ship as a whole:

$$R_s \geq R_{sa} \text{ where } R_s = \min(R_p S_s \, , 1) \tag{5}$$

Apart from establishment of the strength reduction at the lowest level, all the factors required can be obtained from prior analysis of the intact ship and its components, considering the relevant loading conditions on the ship in service, as part of the design calculations. Once the above checks have been performed, a decision can be made on further actions.

Subsequent studies have shown that it may be preferable to transform the global strength criterion to either the panel or the local level, so that R_{sa} is used to establish an allowable panel strength reduction factor R_{paG} and, where appropriate, an allowable local strength reduction factor R_{laG}, for global loads. From Eqs. 1-5 it can be shown that

$$R_{paG} = \max\left(\frac{R_{sa}}{S_s}, \frac{1}{S_s}\right) \quad \text{and} \quad R_{laG} = \max\left(\frac{R_{sa}}{S_p S_s}, \frac{1}{S_p}\right) \tag{6}$$

Then the condition $R_s \geq R_{sa}$ can be applied at either the panel or the local level:

$$R_p \geq R_{paG} = \max\left(\frac{R_{sa}}{S_s}, \frac{1}{S_s}\right) \quad \text{or} \quad R_l \geq R_{laG} = \max\left(\frac{R_{sa}}{S_p S_s}, \frac{1}{S_p S_s}\right) \tag{7}$$

Since normally $R_{sa} \leq 1$ these criteria normally reduce to

$$R_p \geq R_{paG} = \frac{1}{S_s} \quad \text{or} \quad R_l \geq R_{laG} = \frac{1}{S_p S_s} \tag{8}$$

Application at the panel level is often most convenient. However, the formulation at the local level is relevant for the extension to damage growth under cyclic loading (see Section 3). The allowable strength reduction factors for local load cases are designated R_{paL} and R_{laL}, and those for global load cases R_{paG} and R_{laG}. By similar arguments to the above,

$$R_{laL} = \max\left(\frac{R_{paL}}{S_p}, \frac{1}{S_p}\right) \tag{9}$$

3. APPLICATION TO CYCLIC LOADING

With cyclic loading on level 1 damage, the local strength reduction curve should in principle be replaced by a *residual life reduction curve*. This would have to be drawn for a given load level (as amplitude of load or stress cycles) and a given minimum/maximum load or stress ratio, most appropriately that for the far-field stress. Figure 2(a) shows schematically a set of such curves. These intersect with the horizontal axis at the points where the applied maximum load is equal to the residual strength of the component in its *initial damaged* state. For a given observed damage size and load amplitude, this shows the expected residual life. This can be compared with the minimum acceptable residual life considering the situation in which the vessel is operating. If the relevant load level is not known, it is still possible to use R_{laG} given by Eq.6, or the value of R_{laL} given by Eq. 9, to give a maximum allowable load value. This is given by multiplying the intact static strength by R_{laG} or R_{laL}. As load values above this would violate the static strength acceptance criterion, this must give a conservative estimate for the residual fatigue life.

Although the initial damage may be level 1, growth under cyclic loading might possibly increase the size beyond this level. However, if the same type of damage has been considered under static loading and found to give failure while the size is within level 1, this is unlikely to be a problem, though change of shape of the damage during growth might invalidate this assumption. Such situations will, however, become clear during the analysis or testing at the local scale.

Another approach is to use the same data as presented in Fig. 2(a) but plot the load level (amplitude) against the initial size of damage, for a series of values of residual life. The load level can be made dimensionless by dividing it by the intact strength, as shown schematically in Fig. 2(b). This is the inverse of what is normally calculated, because the residual life would be calculated based on a given load amplitude. The inversion process would require interpolation between actual calculated cases. This approach allows the SaNDI damage assessment procedure to be applied directly, with use of the load type and location factors as for static loading. We now have a series of local strength reduction curves for given desired values of residual life. For level 2 damage types, similar curves can be drawn at the panel level.

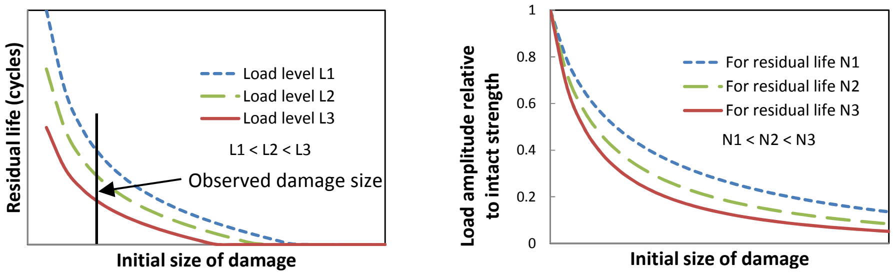


Fig. 2: (a) Residual life reduction curves; (b) Strength reduction curves for different values of residual life.

4. CONCLUSION

Previously developed schemes for assessing damage experienced by sandwich structures in naval ships and their influence on residual structural strength have been described and discussed. Possibilities for devising similar procedures for assessing residual fatigue life following a damage event have been explored. It is important to bear these schemes in mind when performing research into the effects of damage (under both static and cyclic loading) on structural performance, in order to ensure that the results can be used by navies in the operation of their ships. In particular there is a need for research into the way that damage grows in realistic, three-dimensional sandwich structures; knowledge and experience of such processes is essential if approaches to damage assessment are to be tried and tested.

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