

The Influence of Defects and Damage on the Strength of FRP Sandwich Panels for Naval Ships

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Abstract

The paper describes a methodology for determining the influence of both production defects and in-service damage on the performance of composite sandwich panels in ship structures, and for deciding whether, when and where replacement or repair is needed. The approach is based on quantitative modelling of the respective defect and damage types.

Keywords

Composite; sandwich; ships; defects; damage; repair.

Introduction

Sandwich construction, with fibre-reinforced polymer (FRP) skins separated by a lightweight core, has been used extensively in hulls and superstructures of high speed and naval craft. Currently the inspection and repair procedures for such structures are not generally based on a quantitative description of the growth of defects and damage. Without such an approach it is difficult to establish limits for acceptable defect and damage sizes. Sometimes in-service damage is repaired unnecessarily, and in some cases the repair may even reduce the structural performance more than the original damage.

Studies performed in the UK to establish the damage tolerance of stiffened, single-skin GRP ship structures are reported by Sumpter *et al.* (1997) and by Elliott and Trask (2001). These have enabled repair criteria to be established for the Royal Navy's *Hunt* Class vessels. The aim of the current work has been to develop a similar approach for sandwich structures in naval ships. The work has been performed within a European collaborative project (SaNDI).

The paper begins with a review of the defects that are known to arise during production of FRP sandwich panels for naval and other ships. A similar review is made of the various types of damage that may occur in

such structures while in service. Also reviewed are the options available for corrective action.

Attention is then turned to rational ways of assessing the influence of the defect or damage and deciding whether, when, where and how a repair should be effected. Attention is focused on retention of adequate local and global strength, though other functionality considerations can readily be built into the methodology. Some examples of defect and damage models are discussed, and strength reduction curves for some relevant defect and damage cases are presented.

The paper concludes with a brief discussion of the challenges being faced with regard to the detection of such defects and damage and the determination of their location and extent.

Defect and Damage Types

For single-skin laminates and skin laminates of sandwich structures, production defects include dry zones, voids, delaminations, wrinkles, misalignment of fibres, and poor curing (giving reduced physical properties). For sandwich structures, core/skin debonds must be considered in addition, and also voids and inclusions in the core, and lack of bond (edge-to-edge and face-to-face) between core sheets.

In-service damage may include various types of contact damage (quasi-static contact as well as impact), heat damage and numerous types of damage resulting from overloading, such as core fracture or crushing, skin/core debonds, laminate rupture, delamination either within a laminate or at a secondary lamination, and failure at equipment fastenings. Impact damage may be confined to the impacted face laminate (with or without penetration of the laminate), or may involve crushing and/or cracking of the core. In extreme cases, penetration of the entire sandwich may occur. More substantial damage cases include the removal of whole panels or assemblies by fire or collision. For naval vessels some types of damage may be caused by weapon effects, such as air blast, underwater explosions, and fragment or missile hits.

Corrective Measures

The purpose of defect/damage assessment is to decide on corrective actions. The main choices available are outlined below.

In-Service Damage

For damage detected in service, available corrective measures may involve some or all of the following:

- Perform immediate emergency repair (followed by a permanent repair later), possibly with stipulation of operational restrictions until a permanent repair is effected.
- Perform permanent repair at sea; this is not usually an option as conditions at sea are rarely conducive to such repair.
- Proceed to safe harbour or dry dock and perform repair (or make new assessment). Possible interim operational restriction.
- Proceed to dry dock and strengthen/modify structure. Possible interim operational restriction.
- Repair at next scheduled survey, possibly monitoring development in the interim.
- No repair, no further action.

It is extremely important to assess the cause of damage before deciding on corrective actions, and in particular to establish whether the damage is a result of inadequate design. The decision on corrective action may also depend on whether or not a monitoring system is installed. For naval vessels it may depend on whether the ship is in a war- or peace-time situation.

The repairs themselves may be broadly divided into the following categories:

- Emergency, temporary or simplified repair
- Cosmetic repair (repair localised surface defects and prevent moisture ingress)
- Permanent structural repair to original integrity, or to a specified percentage of the original strength
- Repair and modification to give better performance than the original structure.

Production Defects

For production defects, corrective measures may be:

- Rejection/replacement
- Repair
- No repair, no further action

Normally only permanent repairs (cosmetic or structural) are relevant for production defects.

Defect/Damage Assessment

If a defect or damage has been detected and its form, size and position determined, a decision on whether, when and how to repair should be based on a quantitative assessment of the influence of the defect or damage.

For structures or structural elements that are not subjected to repeated loading that might cause fatigue failure, the problem reduces to deciding whether the damaged structure has sufficient residual strength to withstand future static or dynamic loads with an adequate margin of safety. To assess this it is important to establish the strength of the structure with the appropriate type of defect or damage, for different sizes of the defect/damage. A defect or damage case may be considered critical when the reduction in residual strength is unacceptably large. To assess the residual strength, it may be necessary to use a fracture mechanics approach to model damage growth, but in some cases simpler strength modelling approaches are sufficient.

For structures that are subjected to many cycles of repeated loading, it may be necessary to consider the additional damage that is induced in successive cycles of loading, and to estimate the residual life of the structure. A decision on whether and when to repair should then be based on the adequacy of the residual life.

The present study focuses on the residual strength approach.

In-Service Damage

To decide which of the corrective measures should be taken the following input parameters are needed for the case of in-service damage:

- Type of damage
- Size/extent of damage
- Location of damage in relation to the local structure (e.g. centre, edge or corner of a panel)
- Location of damage in relation to the global structure, i.e. where on the ship
- Expected load or stress state at the damage location, in particular the utilisation level under the design loads, and frequency of loading
- Consequences of failure (including risk of progressive collapse)

It is assumed that the type, extent and location of the damage have been established using inspection or monitoring techniques. (However, there will always be uncertainty arising from the limitations in sensitivity or reliability of these techniques.)

The assessment consists in establishing whether the stress levels expected at the damage location, taking account of appropriate safety factors, will be sufficient to cause failure of the damaged structure. If a criticality assessment is required for a specific ship or ship series, and extensive structural and load analysis models are available, the stress levels could in principle be determined and criticality assessed for the exact damage type, size and location. However, in practice the assessment must normally be based on a series of prior analyses.

Production Defects

The principles are essentially as for in-service damage, but there are fewer corrective measures to choose be-

tween. In general a higher proportion of defects will be repaired (or the components rejected) because the finished product is usually expected to meet the full specification; a reduced operational envelope or functionality will not normally be acceptable. Furthermore, repairs are generally easier to carry out during production.

Assessment procedure: Principles

The damage assessment procedure for cases where strength is the main consideration consists essentially of the following steps:

1. Estimate the strength reduction caused by the damage or defect.
2. Determine an allowable strength reduction based on the original design assumptions, operational envelope, etc.
3. Compare these. If the residual strength is smaller than the minimum allowable value, consider the possibilities for restricting the operational envelope and/or accepting an increased probability of failure until a repair can be conveniently effected.
4. If this does not help, carry out an emergency repair or take other emergency measures as necessary.

In practice there are several possible ways of implementing this. Also, the way of estimating the strength reduction varies according to the type and extent of damage. The subsequent sections describe a possible scheme that lends itself to either manual or computer-aided implementation. It recognises three potential contexts in which the damage may have to be considered in relation to the structure – the local, panel and global (ship) contexts, as illustrated in Fig. 1.

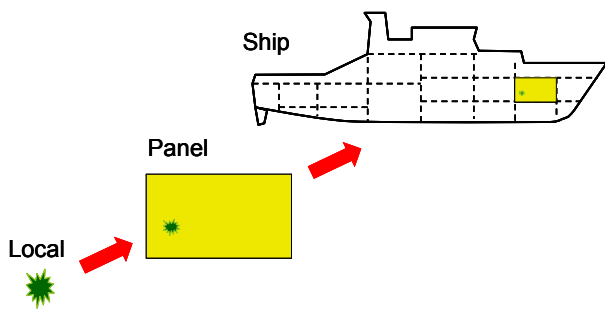


Fig. 1: Damage illustrated in local, panel and global (ship) contexts.

Damage levels

It is convenient to divide damage into the following classes or levels, which determine the procedure to be followed for damage assessment.

Level 1 damage: Small local damage

Level 1 damage covers a small part of an individual panel so that its influence on the panel stiffness and on stresses at points on the panel some way from the damage can be neglected.

In such cases, when considering uniform in-plane load-

ing (e.g. in-plane compression) it is possible to find a value of the far-field stress or strain at which failure occurs, whose value is dependent on the damage size but not on the width or length of the panel.

Examples are small impact damages. Small core/skin debonds may also lie in this category.

Assessment of the influence of Level 1 damage on panel strength can be performed in three steps:

1. Determination of a local strength reduction factor R_l that quantifies the reduction in the far-field stress or strain at failure (for a given in-plane loading).
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 $R_p = R_l S_p$.

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

For Level 1 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 global strength.

Level 2 damage: Medium local damage

Level 2 damage is confined to one panel but does not meet the requirements for Level 1 damage. However, the damage is not so severe that the stiffness of the panel is significantly influenced by the damage. This means that, as with Level 1 damage, redistribution of stresses in the global structure can be neglected in assessing the reduction of global ship strength.

Examples of medium local damage include moderately large impact damage, moderately large debonds, and moderate core shear cracking.

In such cases the influence of the damage on the panel strength has to be considered for the particular damage size, damage location and load case.

Level 3 damage: Large local damage

Level 3 damage is confined to one panel but does not meet the requirements for Level 1 or Level 2 damage. The damage is so severe that the stiffness of the panel is significantly influenced by the damage. This means that redistribution of stresses cannot be neglected in assessing the reduction of global ship strength.

Examples of large local damage include large impact damage, large debonds, and developed core shear cracking with debonding.

In such cases the influence of the damage on the panel strength has to be considered for the particular damage size, damage location and load case. In extreme cases it may be appropriate to assume that the panel's contributions to the global strength and stiffness have been completely destroyed. In this case the panel is removed from the global analysis model of the ship.

Level 4 damage: Extensive damage

Level 4 damage affects two or more panels and/or supporting structure. Each case must be considered individually. Generally this type of damage leads to redistribution of stresses in the remaining structure. It may or may not be relevant to consider the damaged panels as fully removed for the purpose of the analysis.

In cases of Level 3 and Level 4 damage it is important to consider carefully whether the damage has led to a change in the external loading on the structure. If the damage is modelled simply by removal of the damaged panel it may be important to retain in some way the external loadings that were applied to the removed panel, and also the masses of the removed elements.

Panel Strength Reduction: Local Impact Damage

For cases of in-plane compressive loading, local impact damage involving only the face sheet can be analysed using equivalent hole and equivalent crack models as described by Bull and Edgren (2003, 2004) and Edgren *et al.* (2004). These models are based on the Budiansky, Soutis and Fleck model developed by Soutis *et al.* (1991). For damage involving fibre fracture it may be appropriate to use either the equivalent crack or the equivalent hole model; Bull and Edgren (2003) provide guidance on how to determine the equivalent hole diameter or equivalent crack length.

For less severe cases where the damage does not involve fracture of the fibres, it may still be possible to apply the equivalent hole model, but if there is permanent damage to the underlying core it may be necessary to consider an alternative residual dent model, and also to check for delamination buckling.

Fig. 2 shows the far-field strain at failure predicted by Bull for panels of differing widths having holes of diameter 20, 40 and 60 mm. The laminates have quadraxial, quasi-isotropic, CFRP reinforcement in a vinyl-ester matrix. It is seen that the strain at failure is virtually independent of panel size provided the hole diameter is less than about 25% of the panel width. On this basis it

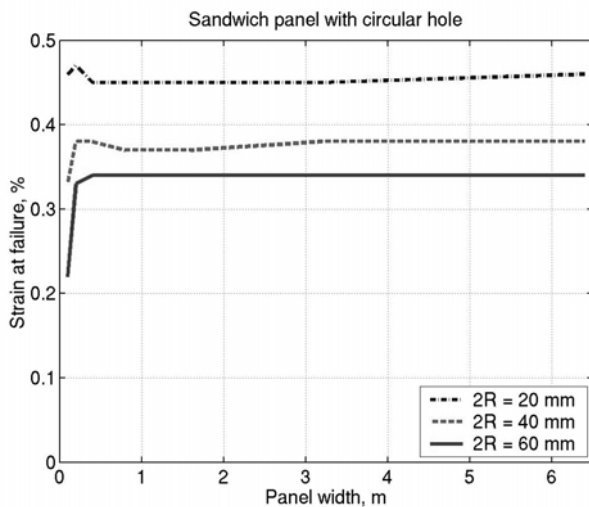


Fig. 2: Far-field strain at failure for panels of differing widths having holes of diameter 2R in the face laminate.

appears that impact damage to the face laminate can be taken as Level 1 damage provided the damage diameter is less than this size.

Local strength reduction factor, R_l

The local strength reduction factor for a Level 1 damage, R_l , is defined as follows:

$$R_l = \frac{\text{nominal stress or strain to cause failure with damage}}{\text{nominal stress or strain to cause failure without damage}}$$

For impact damage modelled with the equivalent hole model referred to above, the local strength reduction for quasi-isotropic CFRP laminates is shown in Fig. 3. Note that this applies for all face laminates of this lay-up provided the hole diameter is less than 25% of the panel width. A similar curve can be drawn for the equivalent crack model.

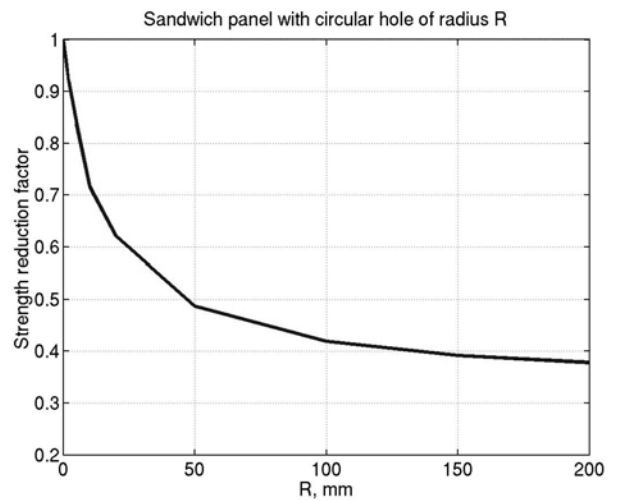


Fig. 3: Local strength reduction factor for face laminate impact damage, equivalent hole model

Estimation of local location factor relative to panel, S_p

The local location factor S_p indicates how large a margin exists for accommodating small local damage at a given location on the panel. It is a function of the following:

- the position of the damage on the panel
- the type and direction of loading on the panel, and the resulting stress distribution
- the governing failure mechanisms for the intact and damaged panel, and safety factors associated with these in the design.

Thus values have to be given for specific damage types and loading cases.

The local location factor S_p is defined as follows:

$$S_p = \frac{P_{ac}}{P_{ai}} \quad (1)$$

where P_{ac} 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_{ai} 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. The value of S_p should be taken as 1.0 unless a higher value can be demonstrated; 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_{ai} 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_{ac} 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 be drawn for panels with given dimensions and lay-ups for simple load configurations like uniform lateral pressure.

Such a map for the specific case of a simply supported 3 m x 2 m panel with 1.8 mm quasi-isotropic CFRP face laminates and 60 mm H80 core under uniform lateral pressure loading is shown in Fig. 4. The safety factors incorporated in the allowable stress levels are 3.33 for compressive failure of the face laminate and 2.5 for core shear failure.

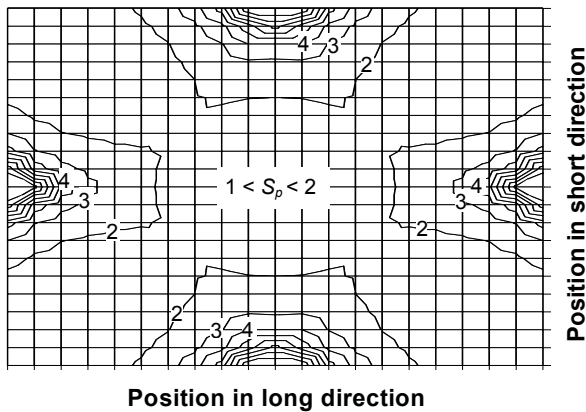


Fig. 4: Local location factor S_p for simply supported sandwich panel (contour plot)

Such figures can be developed for a panel with any lay-up and dimensions, for either local face sheet damage or local core damage. They are dependent only on the undamaged properties of the panel. In the case shown, the cross-shaped area within which $S_p < 2$ is the area most sensitive to face sheet damage. Plotting the same figure with finer resolution shows that the corner regions are in fact more sensitive (having lower S_p values) than the centre.

Estimation of panel strength reduction factor, R_p

The panel strength reduction factor R_p is a measure of

the extent to which the panel strength is reduced by the given damage at the given location on the panel.

For cases of Level 1 damage, the panel strength reduction factor is given by

$$R_p = R_l S_p \text{ or } R_p = 1.0 \quad (2)$$

whichever gives the lower value.

Note that $R_p = 1$ implies no reduction in panel strength caused by the damage. Note also that R_p calculated in accordance with the first equation above may be greater than 1.0.

If $R_p = 1$ the damage has no immediate consequences for the strength of the panel and immediate repair is not normally required unless either watertightness or other important serviceability characteristics are affected. However, the possibility of damage growth under repeated loading may also need to be evaluated.

Panel Strength Reduction: Face/core Debonds

As with face sheet damage, the reduction in in-plane compressive strength caused by face/core debonds is found to be insensitive to the panel size provided the debonds are below a certain size. Furthermore, their influence on panel stiffness is very small. This means that small face/core debonds can be treated as Level 1 defects.

The local strength reduction R_l may be established, for example, using the methods of Berggreen (2004) or established software such as DEBUGS (Nilsson *et al*, 1997, 1999). Fig. 5 shows an example established by Berggreen, including corresponding experimental results. This applies to a sandwich lay-up with quasi-isotropic GRP face laminates and H80 PVC foam core. For small debonds the local location factor S_p and panel strength reduction factor R_p can then be calculated by a similar method to that described above for local impact damage. However, for panels with lateral loading it is necessary to take account of the out-of-plane shear stress as well as in-plane compressive stress as this influences the possible kinking of the crack from the face/core interface into the core.

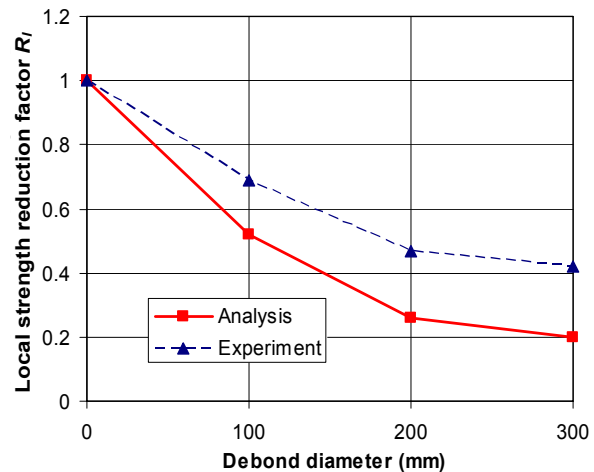


Fig. 5: Local strength reduction factors for face/core debonds

Larger debonds and cases with more complex loading have to be considered as Level 2 damage. In these cases the above-mentioned methods can be applied for estimating the strength reduction, but the analysis has to be applied directly to the panel with specified damage, and R_p is found directly.

Panel Strength Reduction: Wrinkle Defects

A wrinkle is a type of production defect that is caused by a slight excess of reinforcement in the skin laminate in relation to the surface area available or by unevenness arising from the production or transportation of the fabric. Thus one or more reinforcement layers is unable to lie completely flat and forms a small, outward buckle or wrinkle. The defect often affects only the topmost layer or layers of fabric. The region below the wrinkle is usually filled with resin, but the presence of a void cannot be ruled out.

Such wrinkles usually occur over a significant part of the panel width or length. They reduce the compressive strength of a laminate for in-plane loading applied perpendicularly to the line of the wrinkle, but the strength for loading applied parallel to the wrinkle is not believed to be significantly reduced.

Fig 6 shows the panel strength reduction factor R_p for sandwich CFRP face laminates with compressive loading perpendicular to the axis of the wrinkle, plotted as a function of the proportion of the plies involved in the wrinkle. The curve is based on the results of four-point bending tests performed on sandwich beams having wrinkles across the compressive face laminate in the mid-span region. The lay-ups were quadri-axial, quasi-isotropic CFRP in which the outermost plies were in the loading direction.

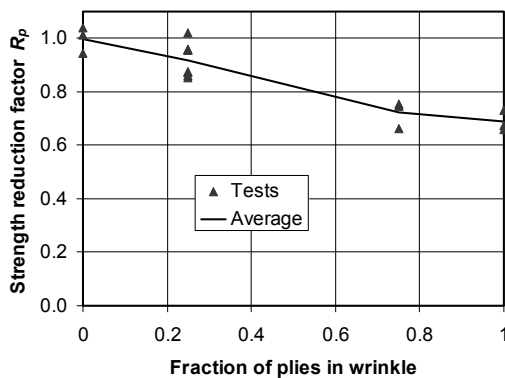


Fig. 6: Panel strength reduction factor for CFRP sandwich panels with wrinkle defects.

Note that the results presented in Fig. 6 are provisional and are to be verified by further testing and modelling studies now in progress. In particular, the face laminates of the panels used in these tests had somewhat low compressive strengths in the regions without wrinkles. For laminates with higher initial strength values, the reductions due to wrinkles may well be greater.

Wrinkle defects may be considered as Level 2 damage. They are not small in the sense of being confined to a small area over which the stresses can be considered

constant; however, they do not normally affect the panel stiffness significantly.

Panel Strength Reduction: Core Shear Cracks and Debonds

Core shear cracking is usually accompanied by debonding of the face from the core. This may be fairly localised, e.g. along one edge of the panel, or may cover a considerable part of the panel area. This type of damage affects the stiffness of the panel for some types of loading so it must be considered as Level 3 damage.

Models for strength and stiffness reduction for panels with core cracks and associated debonds are currently under development.

Global Strength Reduction

The ship strength reduction factor R_s is the proportion of the global strength that remains when the damage is taken into account. It can be defined in a way that is analogous to the panel strength reduction factor R_p . The method of estimating R_s depends on the type and size of damage, as described below.

Estimating R_s for Level 1 or Level 2 damage

For cases of small and medium local damage (Level 1 and Level 2 damage) the change in panel stiffness due to the damage can be neglected.

A global panel location and load case factor S_s , can be defined that is analogous to the local location factor S_l . The global load reduction factor R_s is then given by

$$R_s = R_p S_s \text{ or } R_s = 1.0 \quad (3)$$

whichever gives the lower value. Here R_p must be found for the loading condition on the panel that is involved in the global strength in question.

However, in some cases it may be relevant to consider in addition the maximum allowable global load on the ship when the damaged panel is *completely* removed, and calculate the corresponding strength reduction R_o . This may be used as an alternative to R_s in assessing the acceptability of the strength reduction. In some cases it may give a more favourable value than R_s .

Estimating R_s for Level 3 or Level 4 damage

For cases of large local damage and extensive damage (Level 3 and Level 4 damage) the change in panel stiffness due to the damage cannot be neglected.

In cases of Level 4 damage it is normally necessary to perform a fully detailed analysis of the ship with the damaged panels removed or having appropriately reduced stiffnesses. This is also the case for Level 3 damage, especially if the structure is a complex, three-dimensional one and the influence of the damage on global behaviour is unclear.

However, for many cases of Level 3 damage it is possible to estimate the residual strength using approaches based on pre-calculation of standard cases and simpli-

fied treatment of stress redistribution.

Allowable Strength Reduction

There is normally no need to consider an allowable strength reduction if the panel strength reduction factor $R_p = 1$. However, if $R_p < 1$ the possibility of accepting a reduction of panel strength must be considered unless the damage can be fully repaired immediately. The global strength reduction R_s must also be evaluated.

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. 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 can be dealt with by using the panel and global utilisation factors U_p and U_s defined as follows.

$$U_p = \frac{\text{max. load on damaged panel under extreme design load}}{\text{max. allowable value for the undamaged panel}}$$

$$U_s = \frac{\text{max. global load on structure under extreme design load}}{\text{max. allowable value for the undamaged structure}}$$

Normally the allowable strength reductions R_{pa} and R_{sa} for panel and global (ship) strength will be set equal to the respective utilisation factors.

There are two main additional considerations that may make a further strength reduction acceptable. The first of these is to reduce the loads (relative to the original design) by restricting the operational envelope. This leads to a lowering of the utilisation level in that the extreme design loads are now decreased. There are two distinct ways to restrict the operational envelope:

- Restriction in relation to season and geographical location, as defined in the International Load Line Convention and used for defining service restrictions in classification rules.
- Application of a more restricted speed-heading-wave height relationship than that within which the vessel was originally approved to operate. This type of restriction is easiest to implement if a system of load or response monitoring is installed.

Alternatively, or in addition, it may be possible to accept a reduced factor of safety in the interim period until a repair is effected, i.e. a higher probability of failure during that period. This leads to a lowering of the utilisation level in that the *allowable* loads are *increased*.

Adoption of reduced design loads may also be justified by recognising that the time of exposure to environmental loads in the interim period may be considerably shorter than the original design life.

Decision-making process

Decisions about corrective actions have to be made on the basis of comparing the strength reductions R_p and R_s with their allowable values R_{pa} and R_{sa} . Fig. 7 shows an example of a flow-chart for such a decision-making process.

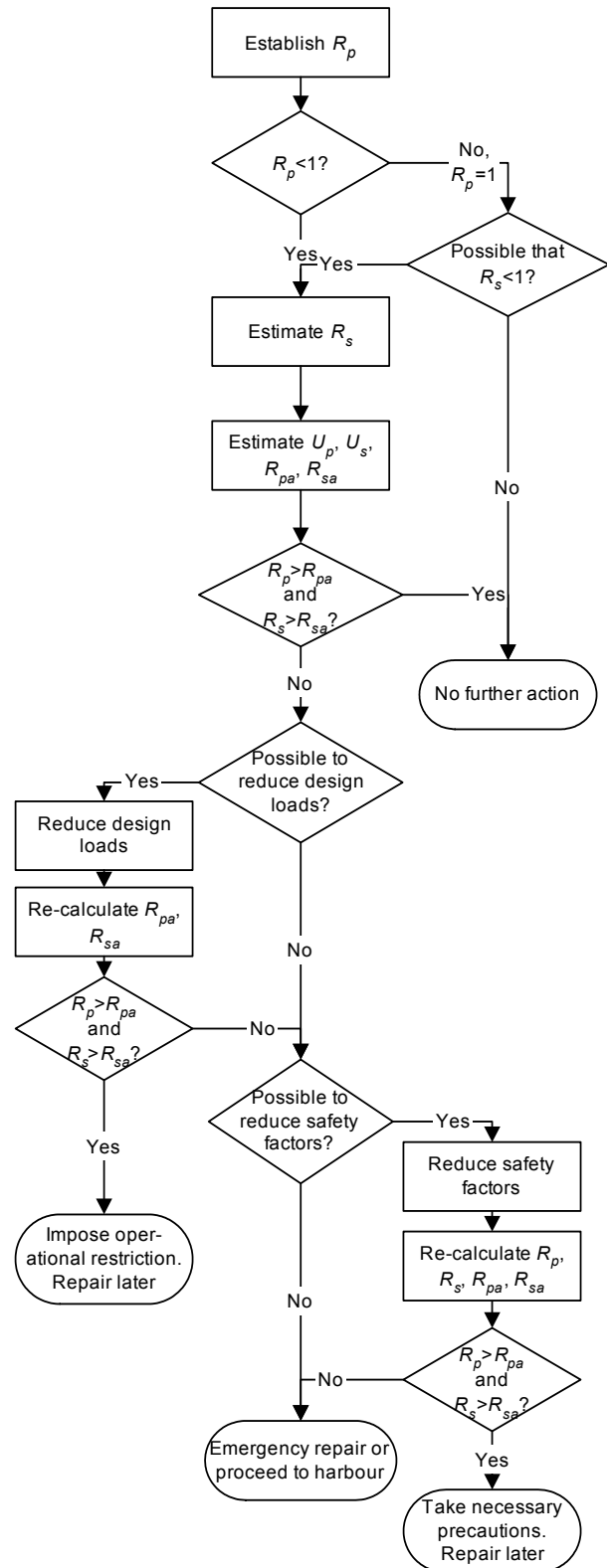


Fig. 7: Schematic illustration of assessment process.

Inspection Methods

Defects and damage can only be assessed if they have been detected and measured by some sort of inspection or monitoring. Many production defects can be found by visual inspection (though that is more limited with opaque CFRP laminates than with translucent GRP). Generally for deeper defects and for most kinds of in-service damage, other non-destructive inspection (NDI) methods are needed.

Comparative studies of NDI methods for marine composites have been performed previously. The study reported by Weitzenböck *et al.* (1998) considered ultrasound, thermographic, microwave and certain acoustic methods. In the SaNDI Project new studies have been performed to include both a wider range of sandwich materials and recently developed methods, such as those based on shearography and X-ray techniques. The results will be reported elsewhere, but it is relevant to mention here that some challenges remain if a fully integrated system for defect/damage inspection, assessment and repair is to be implemented in practice:

- The potential for detecting deep defects/damage in thick sandwich structures remains limited, especially for methods that can be used on board or around a ship.
- It is generally not possible to detect far-side defects with one-sided inspection methods.
- Thick coatings may have to be removed when vessels are inspected in service.
- There is a need for more rapid scanning methods for large areas.

Conclusions

A procedure for defect and damage assessment for FRP sandwich structures in ships has been developed that is based on defect/damage modelling, taking account of the influence on both local and global strength. It also provides a systematic approach to the process of deciding whether, when and how to perform a repair, and whether to take interim measures to mitigate the effect of damage. Together with a thorough evaluation of non-destructive inspection methods and repair techniques, the SaNDI Project has thereby provided the basis for a fully integrated defect/damage inspection, assessment and repair methodology that lends itself to both manual and computer-assisted implementation.

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