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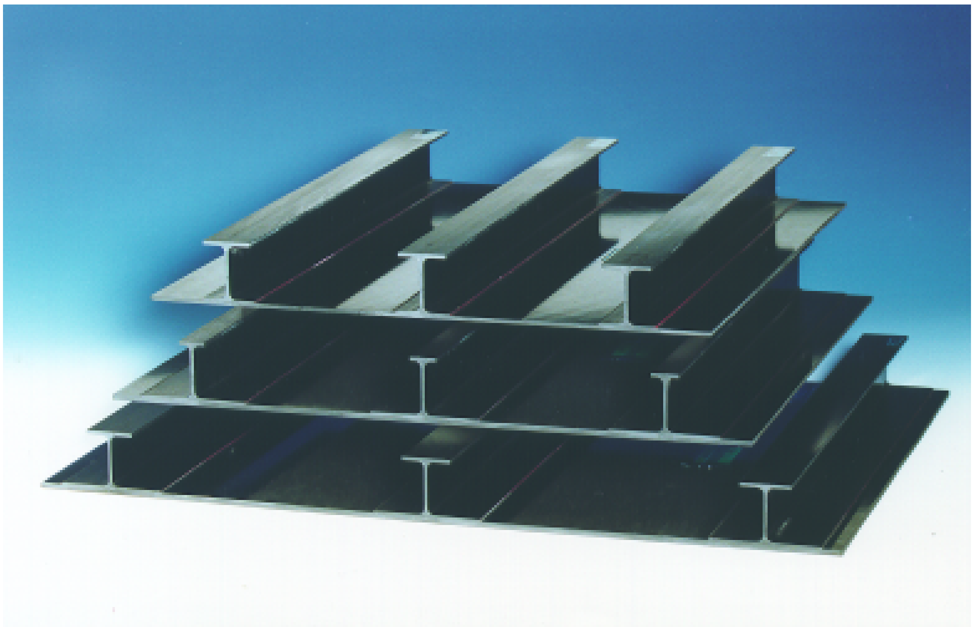

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DESIGN OPTIMIZATION OF STIFFENED COMPOSITE PANELS FOR DAMAGE RESISTANCE*

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An optimization code for the design of stiffened, composite panels was extended with the capability to optimize panels for "damage resistance". Hereto, a damage initation constraint was implemented. Three different panels were designed, fabricated and tested: one baseline configuration with previous design methodology, and two "damage resistant" configurations, according to the new design capability.

The new criterion was found to be accurate for impacts at stiffener edge locations, and conservative for impacts at locations midbay between stiffeners. Although the panels were not fully damage resistant for 35 J impacts as intended, the results were close, and clearly superior to the baseline configuration. The penalty for increased damage resistance is increased panel weight, while the advantages are savings of fabrication and maintenance costs.

INTRODUCTION

Although aircraft structures made of composite materials may have superior properties, compared to metal structures, when considering structural weight, corrosion resistance and fatigue behavior, they are more vulnerable to defects incurred during production or damage induced during service. This is due to the inability of the material to redistribute peak stresses by plastic deformation, the weak out-of-plane properties associated with its layered architecture, and the heterogeneous nature of the material, consisting of stiff fibers contained in a soft matrix.

Impact damage or defects, when present in composite structures, are known to reduce the strength considerably, in particular the compression strength, because the highly loaded fibers are no longer adequately supported by the matrix. Moreover, the presence of defects or the extent of impact damage are difficult to detect, and the residual strength of the flawed or damaged structure is difficult to predict. As structures with "barely visible impact damage" must still be able to carry the ultimate design load, these technological problems, which still have not been fully resolved, have led to conservative designs, time consuming inspection procedures and expensive repair techniques.

Considerable efforts have been undertaken to make composite structures more damage tolerant, i.e., to minimize the strength reduction caused by the presence of a specified defect, or resulting from a specified impact threat scenario. Meeting this objective has been pursued by improving materials systems and by optimizing geometric configurations, with modest success. Tougher matrix material systems may limit the damage extent resulting from impacts, and structural concepts based on alternating stiff stiffener zones and soft skin zones[1] may delay the damage from spreading across the structure. However, a higher level of damage tolerance often leads to increased production costs.

More recently, efforts have been aimed at the design of composite structures which are not just more damage tolerant, but also more damage resistant, given specified impact threat scenarios. This would lead to a saving of costs associated with inspection and repair, and possibly also of fabrication costs. However, a higher level of damage resistance often leads to increased structural weight.

Clearly, to obtain structural designs with improved damage resistance, while minimizing the corresponding weight increase, an optimization procedure is required. The present study describes the extension of an existing design optimization code for stiffened, composite wing panels with the capability to predict the occurrence of impact damage for a certain impact threat, in order to find minimum weight designs with a specified level of damage resistance. The validation of this capability, performed on the basis of an experimental programme, is also described. The development presented here is the partial result of a tri-national programme of the aerospace research establishments of the Netherlands (NLR), Sweden (FFA), and the U.K. (DERA).

DESIGN OPTIMIZATION

To achieve a minimum weight design, design optimization code PANOPT[2] finds optimum values for a range of selected design variables, while satisfying a range of specified constraints. Design variables used in the present study are ply thicknesses for given laminate stacking sequences, and geometric entities, such as stiffener dimensions and the stiffener pitch. Constraints that can be imposed are limits on buckling loads, overall panel stiffness, geometric dimensions, etc., as well as a newly developed "damage initiation constraint". At each optimization cycle, the constraints of the current design are evaluated to determine whether they are active, inactive or violated. This requires the performance of appropriate numerical analyses, such as the calculation of the buckling load, or the peak force during a simulated impact. Upon this evaluation, certain design variables are changed, until a minimum weight design has been achieved.

A previous study[3] carried out at NLR was aimed at the design of damage tolerant stiffened, composite panels by numerical optimization, for which a multi-model capability was developed, and incorporated in computer code PANOPT. This capability allows the design optimization process to consider several configurations simultaneously, configurations which represent the panel in an undamaged state, as well as in several representative damage states, each for different strength criteria, depending on the severity of the damage. This study indicated that the multi-model approach clearly results in different, lighter panel configurations than when such scenario's are considered one by one.

As already postulated in reference 3, the same multi-model capability for damage tolerance can also be used to design panels which are more "damage resistant". This means that the formation of damage is to be avoided entirely in case of a range of specified impacts at specified locations, or is allowed to occur only for very high impact levels. In order to facilitate the design of panels for damage resistance, optimization code PANOPT, which uses an efficient finite strip analysis routine[4] to compute buckling loads, as well as a corresponding finite element representation to compute deflections due to transverse loads, was extended with a new "damage constraint", based on an impact damage initiation criterion.

IMPACT DAMAGE INITIATION CRITERION

During an impact, the force exerted on the panel by the impactor builds up to a maximum, the peak force, and decreases again to zero. During this process, damage may or may not be induced. It turns out, that the peak force is the critical parameter governing the occurrence of damage initiation, rather than the impact energy[5]. If the peak force reached during the impact is higher than a critical value, damage has been induced. As the process of damage initiation is rather unstable, quite a large damage area may be generated when the peak force has just reached the critical value (Fig. 1[6]).

Based on this observation, a damage initiation criterion was formulated by the authors of reference 5 at the Imperial College in London. This criterion, which has now been implemented in design optimisation code PANOPT, is as follows:

$$Fcr = C \cdot t^{3/2},$$

with

Fcr (N) = the critical peak force at which damage is initiated.

C = $\dfrac{8\pi^2\ E\ t^3\ G_{IIc}}{9\,(1-\upsilon^2)}$, a specific material constant.

t (mm) = laminate thickness.

Knowing the properties C and t of a particular composite plate, the critical peak force can thus be computed at which the initiation of damage can be expected.

If it is assumed, that in case damage is not induced, the structural response during the impact is linear elastic, the force-deflection "curve" is a straight line, and the triangular area below the curve represents the impact energy, hence:

$$Energy = 0.5 \text{ x Force x displacement.}$$

Figure 2 shows this curve, which is extended to the point of damage initiation, when the critical force is reached.

If the impact threat is specified for which damage resistance must be "guaranteed", i.e., the highest amount of impact energy at which damage may not yet occur, the minimum displacement under the impactor that the structure should allow, which is a measure for the maximum stiffness that the structure should provide, can be computed:

$$d_{min} = 2\, E_{threat}/F_{cr} = 2\, E_{threat}/Ct^{3/2}.$$

A structure made of a more brittle material, i.e., a material with a smaller value C, needs to allow more displacement, i.e., must be more flexible, (see curve for C' in Fig. 2).

The damage initiation constraint implies, that for a selected impact location on the panel, a specified amount of impact energy for which damage should not occur, and assuming a linear elastic structural response, the peak force must not exceed the critical peak force, or else, certain design variables have to be changed to satisfy this constraint. The peak force is determined in PANOPT by computing the transverse displacement resulting from an applied unit force, and scaling up the force, and hence the displacement, until the work done by the force is equal to the specified impact energy. If the damage initiation constraint is violated, either the critical peak force must be increased by increasing the plate thickness, or the peak force must be decreased by decreasing the transverse panel stiffness, for instance, by enlarging the stiffener pitch.

Hence, the impact damage initiation prediction is based on static, linear analysis. It was shown before , that static indentation may give comparable damage as low velocity impacts, such as caused by tool drops, which are the threats considered here. The use of linear theory results in an overestimation of the deflection of only 10 percent for the configurations and impact energy considered in the present study, as determined by a more detailed, nonlinear finite element analysis.

THE EFFECT OF DAMAGE RESISTANCE CONSTRAINTS ON PANEL DESIGN

Although ply angles may be selected in PANOPT as design variables, typical design variables specified in a stiffened panel optimization process are ply thicknesses (rounded up in a second design cycle to integer ply numbers) and geometric entities, as ply angles and stacking sequences are usually selected a priori because of a wide range of constraints not considered by PANOPT.

For the optimization to find configurations which satisfy the newly developed impact damage constraints, in addition to the constraints which were already available in PANOPT, it can either decrease the impact peak force corresponding to the specified impact energy by increasing the transverse flexibility of the panel, or it can increase the critical peak impact force value by changing the material properties (in-plane stiffness, GII_c), or by increasing the local plate thickness. As changing the material properties by a change of ply thicknesses is not very effective, the impact damage criterion assumed the material properties, in terms of the value C, to be constant during the optimization.

Hence, for the optimization process to find designs with an increased impact resistance, it can either increase the transverse flexibility (by increasing the stiffener pitch, for instance), or increase the local laminate thickness by increasing one or more ply thicknesses. It is obvious that a damage resistant panel carries a weight penalty compared to designs derived without damage constraints, but the objective of the optimization is to keep the weight penalty to a minimum.

Three different I-stiffened panels were designed for a running load of 1500 N/mm (design ultimate load) and a length of 550 mm, with the following constraints:

Minimum Euler buckling load	1800 N/mm.
Minimum torsional buckling load	1800 N/mm.
Minimum local skin buckling loads	1800 N/mm
Maximum postbuckling strain ratio	1.25 at 1800 N/mm.
Minimum axial panel stiffness	ε « 0.006 at 1500 N/mm.

Minimum stiffener pitch, and minimum and maximum stiffener dimensions.

The buckling loads were given a safety factor of 1.2, to compensate for the possibility that different buckling modes might coincide. Based on previous experience, the postbuckling strain ratio (postbuckling strain range divided by prebuckling strain range) was limited to 1.25, to prevent postbuckling to occur significantly below design limit load (1000 N/mm). The panel stiffness was constrained by an empirical value (maximum strain of 0.006 at design ultimate load), to provide sufficient damage tolerance, and geometric constraints were based on practical considerations, related to fabrication issues. The laminate stacking sequence was defined a priori, based on design rules.

The first design was the baseline design (BL), which did not consider the newly developed damage initiation constraint. The second and third designs did, and were required to be damage resistant designs (DR1 and DR2). The third design was given a larger "minimum stiffener pitch" constraint than the second design, to further drive down the manufacturing costs. In this respect it is interesting to note that the stiffened fuselage panels of the V-22 Osprey changed from a configuration with many, closely spaced stiffeners in the Full Scale Development phase to a configuration with fewer, wider spaced stiffeners in the Engineering Manufacturing Development phase of the programme. This change must have resulted in lower production costs, and, according to the results of the present study, possibly also in increased damage resistance.

Stiffener pitches for the three optimized designs were 150 mm, 179 mm, and 250 mm, respectively. The impact scenario's considered for the second and third designs were an impact at a midbay location between stiffeners, and an impact at the stiffener edge location, both at 35 J. The latter impact location turned out to be a design driver for both designs. Considering the damage resistance criterion during the optimization resulted in weight penalties compared to the baseline configuration of 16 % and 28 % for the second and third designs, respectively. The resulting designs are shown in figure 3.

EVALUATION OF THE DAMAGE INITIATION CRITERION

Of all three configurations, three test panels were fabricated, using IM7/8552 prepreg material. One panel of each of the configurations was used to determine the actual impact damage threshold, in terms of impact energy. Using an instrumented drop weight impactor, impacts were applied at several midbay and stiffener edge locations (see Fig. 4) at different energy levels. The damage extent was determined by C-scan, and further post-failure analysis was carried out at FFA to support the development of their damage growth prediction capabilities.

The impact energy level corresponding to damage initiation was established at less than 15 J for the baseline configuration (BL), 25 J for panels DR1 and DR2 impacted on a stringer foot, 30 for panel DR1 when impacted in a midbay position, and more than 40 J for a midbay impact on panel DR2. Later, the remaining six panels were all impacted at 35 J, either at a midbay or at a stiffener edge location, to establish the damage tolerance of each of the three designs for equal impact threats. The panels were subsequently loaded to failure by DERA, to determine the damage tolerance of the designs.

The force-displacement curves recorded for a number of impacts on configurations BL, DR1 and DR2 are compared to the damage initiation criterion in figures 5-8, based on a material constant C of 680. This value, corresponding to prepreg material HTA/6376, had been used for the panel optimization, as the value of C for IM7/8552 was not known at the time. Later on, the value C for IM7/8552 was found to be equal to 538, as IM7/8552 is more brittle than HTA/6376.

Only a few test curves were obtained which are actually corresponding to impacts without damage, when the peak forces that occurred were equal or just smaller than the critical values. However, even for curves corresponding to impacts when substantial damage was induced, it can be assumed that the peak forces recorded during the tests were not much higher than the critical peak forces, due to the unstable nature of the damage initiation.

Comparing the peak forces which occurred during 35 J impacts at the mid-bay locations of all three panel configurations (Figs. 6a-8a), it can be concluded that these peak forces correspond well with the critical peak forces computed with the damage initiation criterion. In case of the 30 J impact on DR1 (Fig. 5a), at the damage threshold when almost no damage was induced, the peak force recorded during the test remained just below the predicted critical value.

Comparing the peak forces which occurred during 35 J impacts at the stiffener edge locations of all three panel configurations (Figs. 6b-8b), it can be concluded that the peak forces recorded for panels DR1 and DR2 correspond better with the peak forces computed with the damage initiation criterion when using the correct material constant C = 538, corresponding to the material actually used to build the panel. In case of the 25 J impact on DR1 (Fig. 5b), at the damage threshold when no damage was induced, this is also the case. Only in case of a 35 J impact on the stiffener edge of baseline panel BL (Fig. 26b), the peak force that occurred during the test corresponds better with the peak force predicted with the damage initation criterion for C = 680. However, in this case the damage was very large (1100 mm^2), and the peak force can be expected to be higher than the predicted critical value.

Summarizing, the damage initiation criterion based on the appropriate material constant C = 538 is accurate for impacts at the stiffener edge location, and somewhat conservative for impacts mid-bay between stiffeners, as illustrated in figure 9.

EVALUATION OF THE DESIGN OPTIMIZATION PROCESS

Figures 5-8 also indicate the estimations, computed by PANOPT, of the peak force-deflection states corresponding to the specified impact energies, at the specified locations, of each of the designs. Figures 5a, 7a and 8a show, that the maximum forces predicted by PANOPT due to midbay impacts on panels DR1 and DR2 remained below the values for the damage initiation criterion. This indicates that the damage initiation constraint was inactive. On the other hand, figures 5b, 7b and 8b show, that PANOPT predicted peak forces equal to the values for the damage initiation criterion. This indicates that the damage initation constraint was active, and the requirement for damage resistance was one of the design drivers. Finally, the panel forces predicted by PANOPT for the baseline panel (Fig. 6) were higher than the damage initation constraint, in particular for impacts at the stiffener edge. This indicates that the damage initiation constraint seems to be strongly violated in case of panel BL, but it should be kept in mind, that this constraint was not applied for the baseline configuration BL. However, the violation indicates that damage may certainly be expected in case of a stiffener edge impact on the BL-panels.

The damage initiation constraint used by PANOPT was based on a material constant C equal to 680, corresponding to the tougher HTA/6378 material, rather than on a value C of 538, corresponding to the more brittle material IM7/8552, used to make the panels, which is not conservative. The impact threat considered during the optimization was 28 J, rather than the 35 J energy as actually induced in the panels, which is also not conservative. Hence, it could be expected that damage would occur in the panels after all, even though the panels were designed to be "damage resistant" for 35 J impacts. However, the fact that configuration DR1, when impacted at 30 J mid-bay and at 25 J at the stiffener edge did not suffer damage (Fig. 5) is a very promising result. The same applies to panel DR2, which did not suffer any damage when impacted at 35 J mid-bay, and a small damage (< 100 mm^2) when impacted at the stiffener edge location with 30 J.
Thus, the failure criterion, even when based on the non-conservative value of material parameter C of 680, and the PANOPT approach to simplify the impact event as a linear quasi-static indentation, is accurate enough to enable the design of damage resistant stiffened panels.

CONCLUSIONS

An optimization code for the design of stiffened, composite panels was extended with the capability to optimize panels for "damage resistance". Hereto, a damage initation constraint was implemented, based on a critical peak force. The critical peak force is the discriminator between impacts which do or do not result in impact damage.

Three different composite stiffened panels were designed: one baseline configuration with previous design methodology, and two "damage resistant" configurations, according to the new design capability. Panels were fabricated and impacted, and the peak forces were measured to evaluate the damage initiation criterion. This criterion was found to be accurate for impacts at stiffener edge locations, and somewhat conservative for impacts at locations midbay between stiffeners.

The panel optimization was carried out in an early stage of the project, based on several non-conservative assumptions. Although the panels were not fully damage resistant for 35 J impacts as intended, the results were close, and clearly superior to the baseline configuration. Impacts at stiffener edge locations were driving the design, while impacts at midbay locations were not. This indicates, that attention should be paid to improvement of the skin-stiffener interface area, in order to reach a higher degree of damage resistance.

The penalty for increased damage resistance is increased panel weight (16-28 %), while the advantages are savings of fabrication and maintenance costs. In practice, the weight penalties will not be as large as for the present, fully optimized panels, due to the many other boundary conditions that are imposed during the integration of panels in a complete structure.

ACKNOWLEDGEMENT

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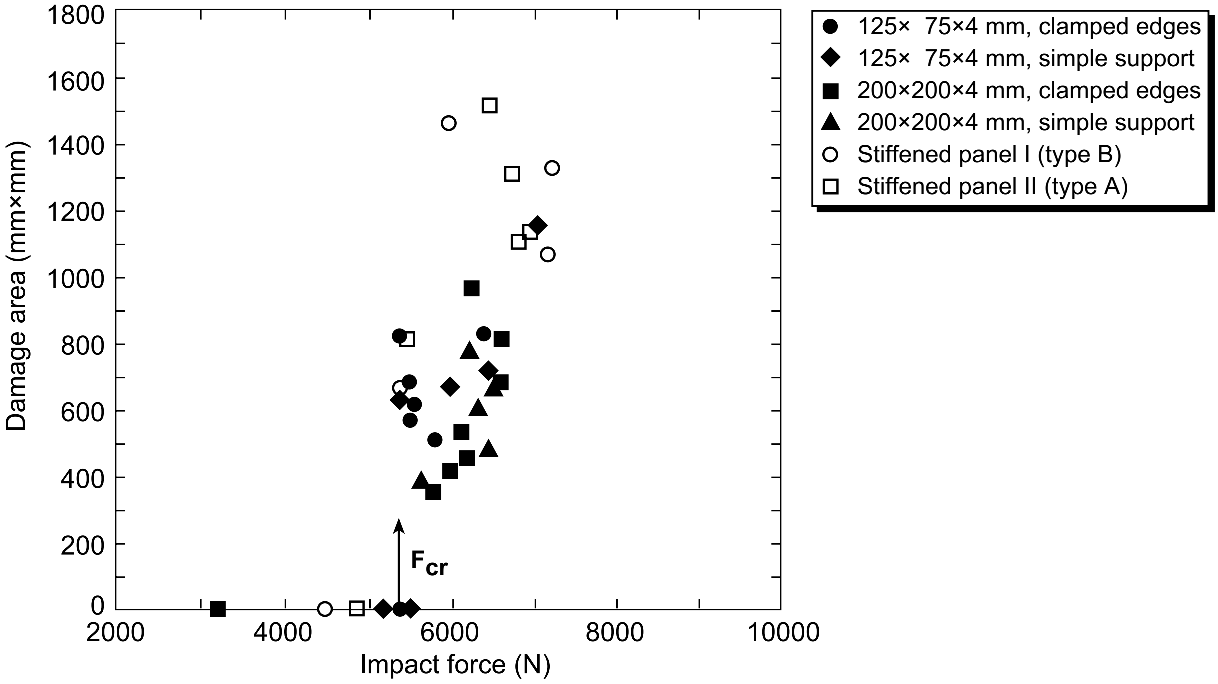


Fig. 1 Damage area versus peak force [Ref. 6]

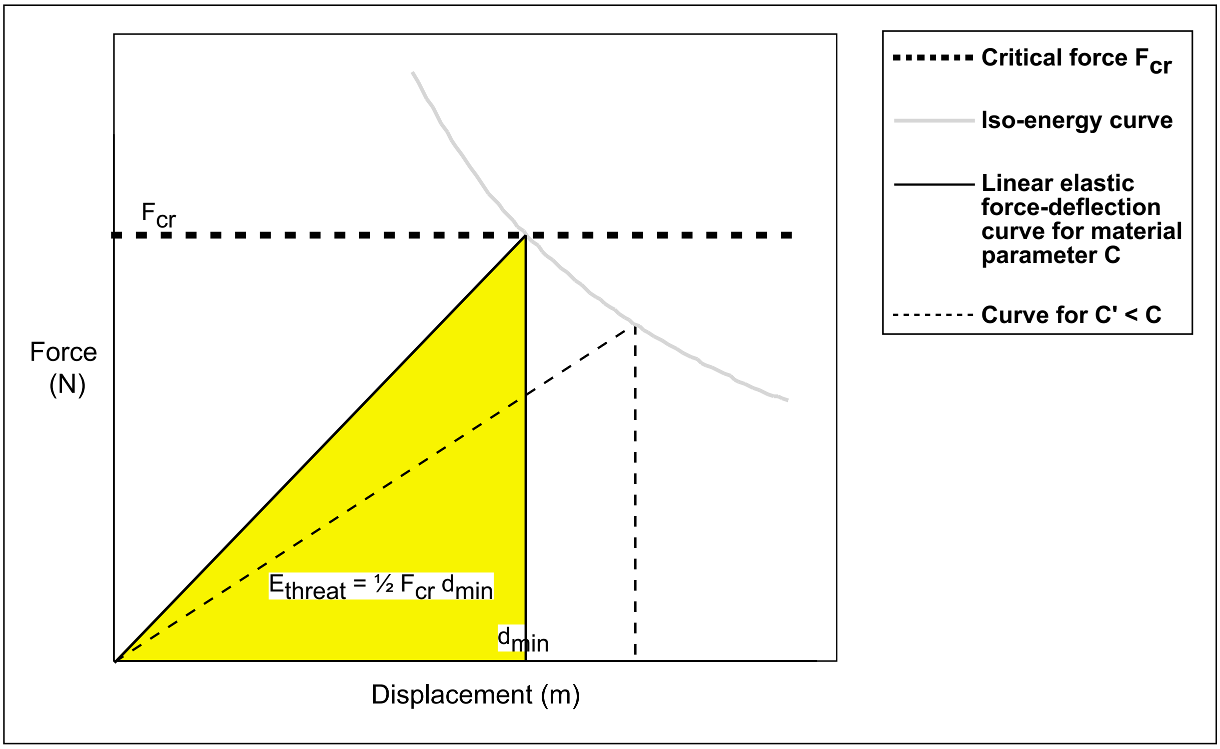
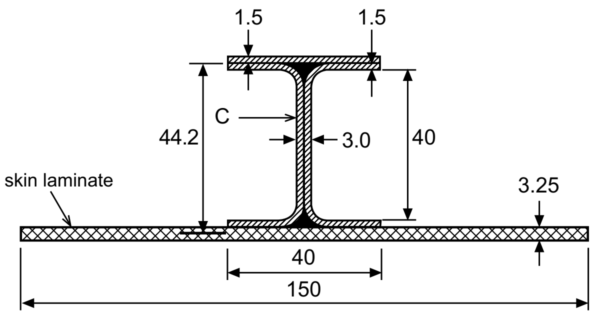
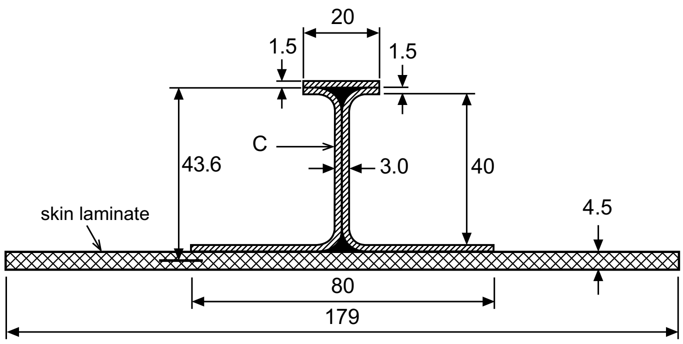


Fig. 2 Assumed linear elastic force-deflection response



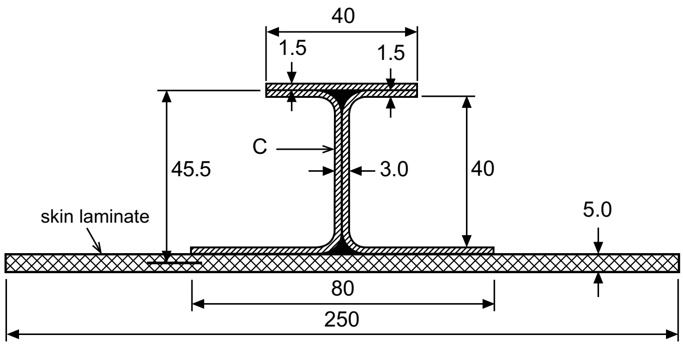
Skin laminate:	[8/16/2] fabricated	: $[45, 0, -45_2, 0, 45, 90, 45, 0, -45_2, 0, 45]_s$	t = 3.25 mm
C-laminate:	[6/4/2]	$[-45, 45, 0_2, 90, 0]_s$	t = 1.5 mm

a) PANOPT model Baseline BL



Skin laminate:	[12/20/4]	: $[45, 0, -45_2, 0, 45, 90, -45, 0, 45_2, 0, -45, 90, 45, 0, -45, 0]_s$	t = 4.5 mm
C-laminate:	[6/4/2]	: $[-45, 45, 0_2, 90, 0]_s$	t = 1.5 mm

b) PANOPT model DR1



Skin laminate:	[12/24/4]	: $[45, 0, -45_2, 0, 45, 90, -45, 0, 45]_{ss}$	t = 5.0 mm
C-laminate:	[6/4/2]	: $[-45, 45, 0_2, 90, 0]_s$	t = 1.5 mm

c) PANOPT model DR3

Fig. 3 PANOPT design for damage resistant panels

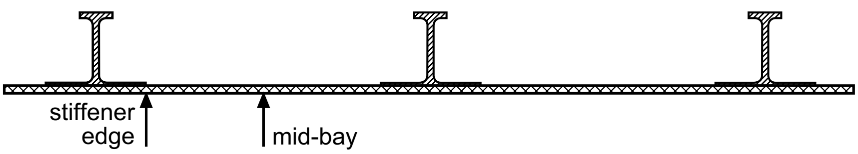
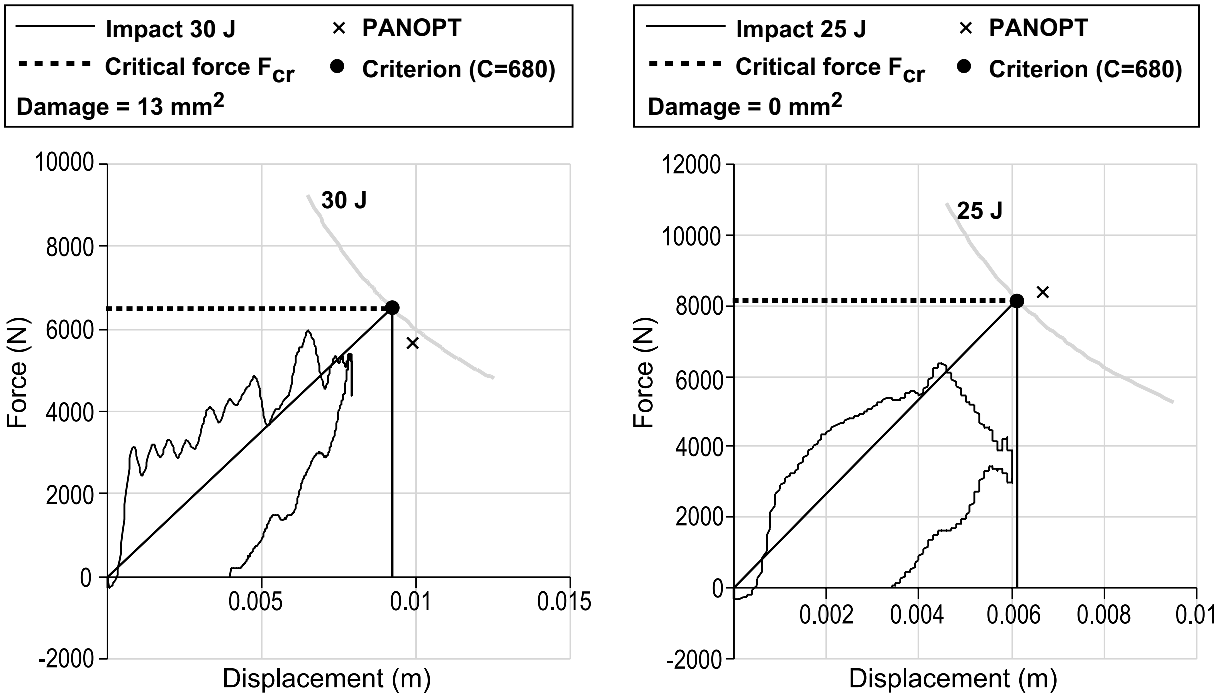


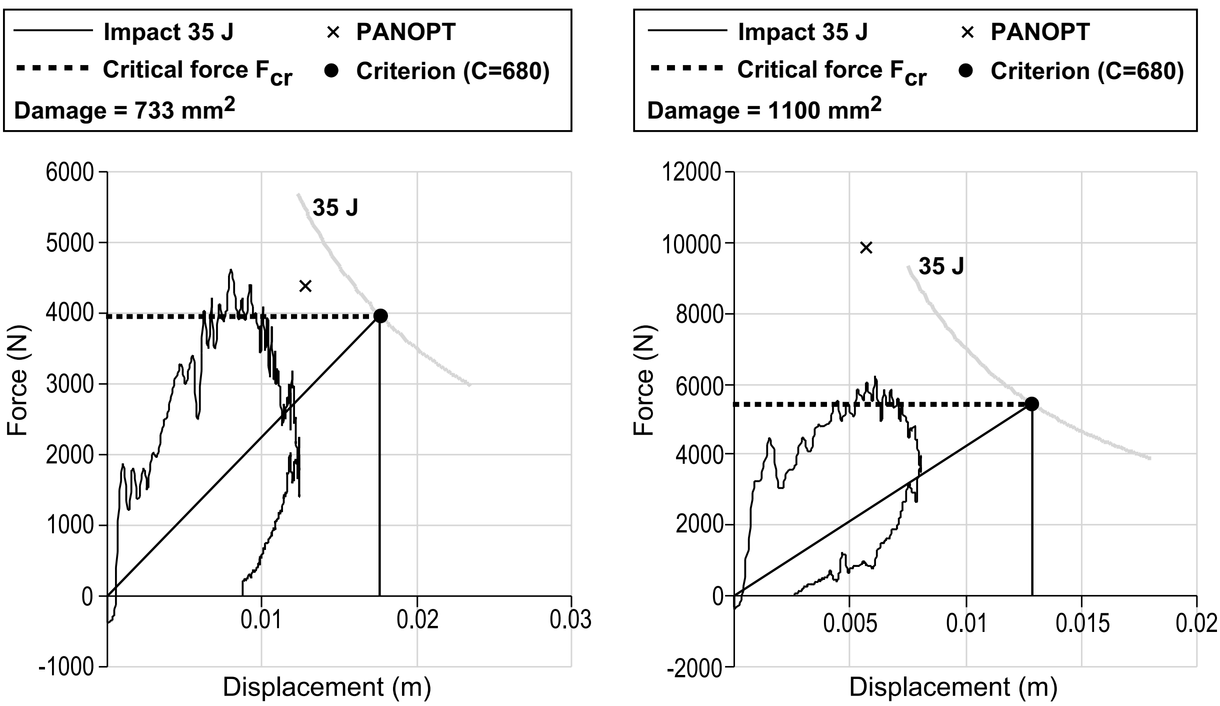
Fig. 4 Impact locations on stiffened panels



a) Mid-bay impact

b) Stiffener edge impact

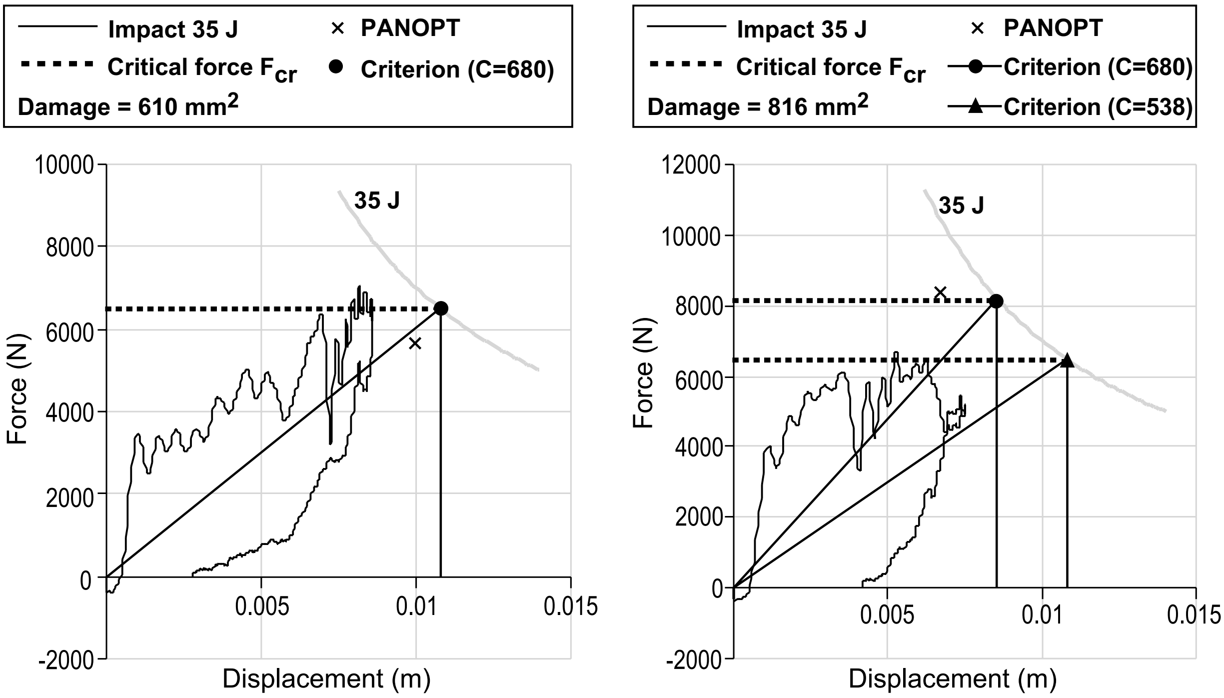
Fig. 5 Force-displacement curve, panel DR1



a) Mid-bay impact

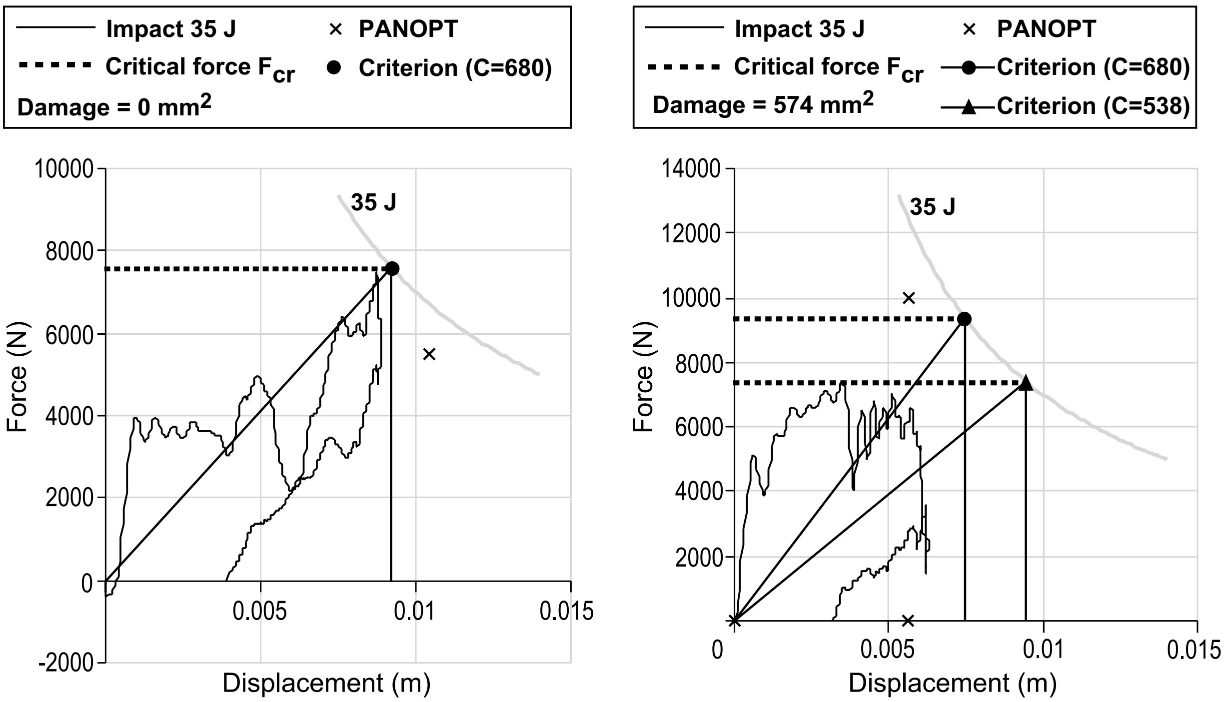
b) Stiffener edge impact

Fig. 6 Force-displacement curve, panel BL



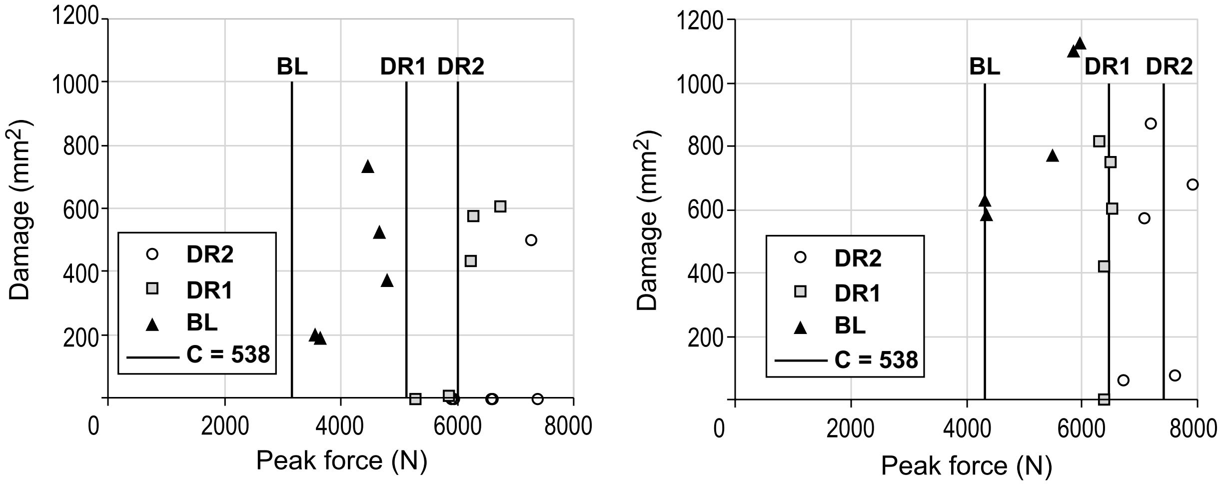
a) Mid-bay impact b) Stiffener edge impact

Fig. 7 Force-displacement curve, panel DR1



a) Mid-bay impact b) Stiffener edge impact

Fig. 8 Force-displacement curve, panel DR2



a) Impacts at mid-bay location

b) Impacts at stiffener edge location

Fig. 9 Damage initiation criterion compared with test results