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Impact energy absorbing surface layers for protection of composite aircraft structures

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Impact energy absorbing surface layers for protection of composite aircraft structures

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ABSTRACT
In the framework of a European Defence Research Programme the NLR investigated how the tolerance behaviour of carbon/epoxy composite aircraft structures can be improved by application of impact energy absorbing surface layers. A promising concept of protection layers consist of a layer of an adhesive filled with glass microballoons covered with one or more layers of aluminium gauze.
In an experimental test programme on unprotected and protected stiffened compression panels is was proved that surface layers may prevent impact damage in the composite panel for impact energies up to 60 Joule. As compared to an unprotected component the compression failure load was increased by approximately 40 T. This benefit has to be set off against a weight penalty of 26 %.

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Abstract

In the framework of a European Defence Research Programme the NLR investigated how the tolerance behaviour of carbon/epoxy composite aircraft structures can be improved by application of impact energy absorbing surface layers. A promising concept of protection layers consist of a layer of an adhesive filled with glass microballoons covered with one or more layers of aluminium gauze.
In an experimental test programme on unprotected and protected stiffened compression panels is was proved that surface layers may prevent impact damage in the composite panel for impact energies up to 60 Joule. As compared to an unprotected component the compression failure load was increased by approximately 40 %. This benefit has to be set off against a weight penalty of 26 %.

1. Introduction

The damage tolerance behaviour of aircraft structures made of composite materials is determined mainly by the compression strength in the presence of stress concentrations and impact damage. The inherently brittle behaviour of carbon fibres and the weak ply-interfaces in the laminated composite result in low design strain levels of composites with impact damage.
In the last decade there were great efforts to improve the resistance to impact damage by introducing tougher matrix systems and carbon fibres with a higher failure strain [1,2]. These attempts were of limited success. In a research programme carried out within the framework of EUCLID (EUropean Co-operation for the Long term In Deference), in particular Research Technology Programme RTP 3.1 "Impact and Damage Tolerance" it was investigated whether by mixing of different materials the resistance to impact damage could be improved. In this programme, the NLR focused on the evaluation of protection layers, added onto the surface of conventional carbon/epoxy laminates. After investigation of different types of protection layers on coupon specimens, the surface layer concept of an adhesive layer filled with glass microballoons, covered with aluminium gauze was selected for further evaluation on stiffened compression panels. The compression tests on impacted stiffened panels are discussed in this paper.

2. Impact energy absorbing surface layers

The concept of the surface is shown in figure 1. After grinding the surface, a 80 °C curing adhesive filled with glass microballoons is applied with a layer thickness of 2-3 mm. Three layers of aluminium gauze were applied on top and cocured with the adhesive. The layers have a dual function:

a) The ability to absorb energy, leaving less energy for formation of delamination damage in the underlying composite material. Energy absorption occurs due to crushing the glass microballoons at impact and by plastic deformation or fracture of the face sheet.
b) Decreasing the BVID[1] energy level by making impact in the surface layer visible in an earlier stage.

Figure 2 illustrates the effectiveness of the surface layer applied on a 4 mm thick quasi-isotropic carbon/epoxy laminate at an impact energy of 20 Joule. The performance of surface layers was determined in an earlier stage, i.c., at a lower impact energy level, by "Compression after Impact" tests on coupon specimens, figure 3 [3]. It is shown that without protection layer the compression strength drops from about 550 MPa to 200 MPa for an impact energy level higher than 15 Joule. A 3 mm thick protection layer can prevent impact damage in the substrate material in case of an impact of 25 Joule (no detectable damage by ultrasonic C-scanning). The latter type protection layer was selected for further evaluation on stiffened compression panels.

3. Stiffened panels for impact investigation

The panel concerned was designed with specific damage tolerance properties for a load level of 2000 N/mm [4]. The configuration consists of a "soft" skin (with a low axial stiffness), doublers (0-degree ply stades interleaved between the skin plies) and discrete stiffeners, see figure 4. The compression panels were manufactured from carbon/epoxy Fibredux HTA/6376 with a prepreg thickness of 0.181 mm (curing cycle 180 °C for 4 hours). The stiffeners were precured and bonded to the skin with adhesive FM300.

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1 Barely Visible Impact Damage.

For the experimental programme 4 panels of 500 x 292 mm (length x width) were prepared.

4. Experimental details

Based on preliminary drop weight impact tests on small stiffened specimens it was decided to apply impact energy levels in the range of 60 to 80 Joule on the compression panels. Instrumented impact tests were executed on midbay locations between stiffeners and at the transition of the stiffener to the skin. The impacter had a hemispherical nose of ∅ 16 mm in diameter. During impact the panel was supported in the centre of the stiffeners on welding wire ∅ 3 mm in diameter resulting in a line contact in panel length direction. At impact the contact force at damage initiation was recorded. The damage in the panel was determined by C-scanning and pit depth measurements. On each panel a midbay impact and an impact on the stiffener/skin was applied, figure 5. Two panels with surface layers and two panels without surface layers were prepared for compression testing. The surface layers were present only on the selected impact locations, layer dimensions 50 x 50 mm.

Compression tests were performed in a 900 kN Wolpert-Amsler servo hydraulic testing machine. The loaded panel ends and the panel edges were supported to prevent rotation of the stiffeners and premature buckling of the panel edges. Strain gauges were applied on the stiffeners and the skin while LVDT's were used to measure the panel shortening and the out-of-plane displacements at the impact locations during compression testing, see figure 5.

5. Results

Impact data for the compression panels are given in table 1. Without surface layers the C-scan damage area was about 30 cm^2. With protection the C-scan damage was about 20 cm^2 for 80 Joule impact and zero for 60 Joule impact. The contact force at impact increases with the presence of a surface layer. For one midbay location by error a too high impact energy of 100 Joule was applied resulting in penetration of the panel. The visible damages at the impact locations were all beyond the threshold for Barely Visible

Impact Damage (BVID) (pit depth larger than 1 mm).

The results of the compression tests are given in table 2. At the maximum load, the strain gauge and LVDT output are also indicated. In the last two columns the failure is given based on LVDT measurements and the strain gauge output on the stiffeners, respectively. For each panel the type of failure is mentioned. The following comments can be made:

Panel I : This panel failed at the midbay impact location. Although the C-scan areas at the edge of the stiffener and at midbay were almost similar, the stress concentration caused by penetration has promoted midbay failure, The failure strain for this severely damaged panel was still 0.46 - 0.50 %.

Panel II : This protected panel had a C-scan damage of about 20 cm^2 at midbay and edge/stiffener location. Failure initiated at the edge/stiffener location. However, the failure strain was about 40 % above the failure strain of the unprotected panel I, at 0.64 - 70 %.

Panel III (Fig. 7) : A 60 Joule impact on the unprotected panel resulted in a slightly smaller C-scan area as compared with that in panel I, see table 1. However, in this case the impact at the edge/stiffener was the most critical. Only small out-of-plane displacements were observed at the failure strain of about 0.5-0.55 %.

Panel IV (Fig. 7) : The 60 Joule impact did not result in damage in the composite panel. This panel is therefore also the reference panel for the behaviour of the undamaged compression panel. Failure occurred at the panel end by "brooming" at a failure strain of about 0.75 %, without any load drop in the load displacement curves.

This brooming results in a relatively large difference of the LVDT displacement between the left and right side of the panel, see LVDT 3 and 4 in table 2.

6. Discussion

The objective of this investigation was to establish the effectiveness of protecting surface layers on a primary composite structure representative for the aircraft structure. In a previous experimental programme different types of surface layers were evaluated and one specific layer was selected for the present investigation. The surface layer considered consistent of a layer of low density adhesive filled with glass microballoons covered with three layers of aluminium gauze. The application of aluminium gauze in the toplayer has the additional advantage of lightening protection. The total thickness of the surface layer was 3 mm and the weight 26 g/dm^2.

A stiffened compression panel with specific damage tolerance properties for a load level of 2000 N/mm was used. Impact energies in the range of 60 to 80 Joule were applied on unprotected and protected panels.

Figure 6 summarizes the compression test results in the shape of a load-strain diagram. It is shown that the panel strain determined from the measured shortening of the panel is about 10 % higher than the mean strain of the strain gauges mounted on the stiffeners. The failure load id about 40 % increased by the presence of a protecting surface layer. Accounting for the additional weight of the surface layer and the plain panel weight, a weight penalty of 26 % is obtained if the entire skin would be covered.

The advantage of surface layers on the stiffened panel configuration used for the present investigation is not so large because the panel was already designed for improved damage tolerance behaviour. A more effective use of the protective layer concept can be pursued if its inclusion is incorporated in the design phase.

The present investigation has demonstrated that the selected surface layer can prevent impact damage up to an energy of 60 Joule. This is a very high energy level and it is likely to assume that the occurence of lower impact energy values would be more realistic. In that case, thinner surface layers can be used giving less weight penalty. Surface layers can be applied selectively on certain areas of the outer surfaces which are particularly vulnerable for impact damage.

7. Conclusions

An experimental programme was performed on the effectiveness of protecting surface layers against impact damage. The following conclusions can be drawn.

1. The resistance to impact damage of a composite structure can be improved by application of a protecting surface layer.
2. A 3 mm thick surface layer consisting of a low density adhesive covered with 3 layers of thin aluminium gauze was capable to prevent impact damage in a stiffened composite panel for impact energies up to 60 Joule.
3. Compression tests were performed on stiffened compression panels with a midbay impact damage and an impact damage over the edge of the stiffener. The impact energy was in the range of 60-80 Joule.
   - Panels without protection showed a compression failure of about 0.5 %.
   - A 60 Joule impact on a protected panel did not result in impact damage and a failure strain of 0.7 % was obtained. In this case, failure was initiated by "brooming" at the panel end. An 80 J impact on a protected panel resulted in a compression failure strain of 0.65 %.
   - The weight penalty for a 40 % increase in failure load was 26 % for the panel configuration considered, if the skin would be entirely covered by a protective layer.

8. Acknowledgement

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Table 1 Impact data for compression panels

Specimen	Location		Surface layer	Impact energy (J)	F_{max} * (kN)	C-scan (cm^2)	Pit depth (mm)
	Edge stiffener	Midbay					
I	•		-	80	9.0	33.9	1.5
		•	-	100	10.0	34.1	1)
II	•		•	80	17.5	22.9	2.5
		•	•	80	10.1	20.5	2.0
III	•		-	60	10.3	32.7	1.0
		•	-	60	7.8	28.9	4.9 1)
IV	•		•	60	15.3	0	1.9
		•	•	60	8.9	0	1.5

* maximum force at (delamination) damage initiation
1) penetration

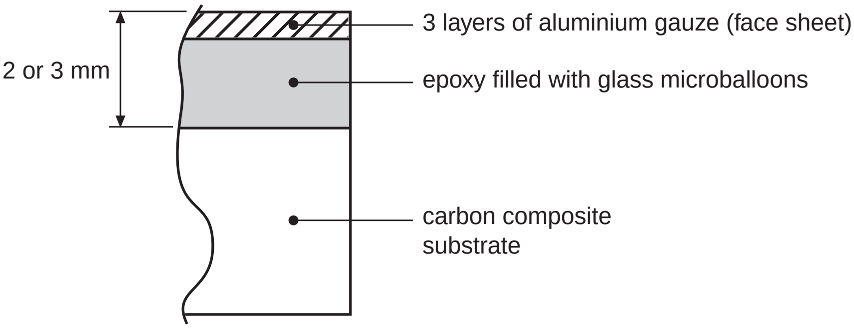
Table 2 Test results for the stiffened compression panels

Panel no.	Max. load [kN]	Impact (J) C-scan (cm^2)		LVDT [mm]				Straingauge output (μstrain)						Strain at failure	
		Stiff.	Midbay	1	2	3	4	1	2	3	4	5	6	A	B
I	506.2	80/33.9	100/34.1	3.78	-0.95	2.58	2.40	-4633	-4737	-3785	-3144	-4526	-4546	0.46	0.50
II*	678.3	80/22.9	80/20.5	1.35	3.48	3.55	3.41	-6204	-6684	-1164	-7110	-5978	-6542	0.64	0.70
III	548.2	60/32.7	60/28.9	0.95	0.60	2.75	2.72	-4712	-5229	-3491	-5127	-4849	-5183	0.50	0.55
IV*	759.7	60/0	60/0	0.45	3.48	4.13	3.73	-7288	-7527	-661	-7659	-6976	-7246	0.73	0.79

Failure locations

Panel I: midbay
Panel II: stiffener edge
Panel III: stiffener edge
Panel IV: brooming of panel end

A Strain based on LVDT measurements
B Main strain at stiffener location based on stain gauges 1/2 and 5/6, see figure 5
* With surface layers
See figure 5 for LVDT and straingauge code



layer thickness	weight g/dm^2
2 mm	22
3 mm	26

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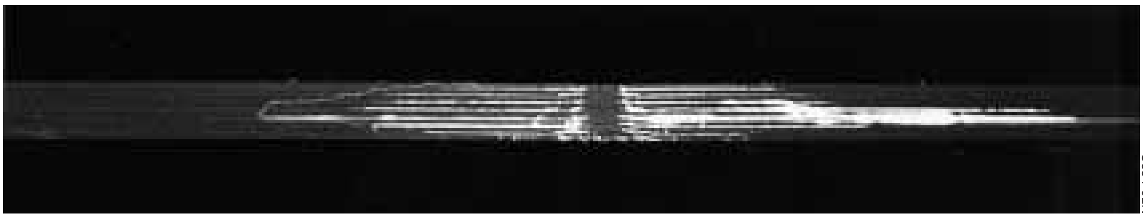
Fig. 1 Surface layer concept

20 Joule (Unprotected)



20 Joule (core + Al-gauze face sheet)

Fig. 2 Cross sections of impacted 4 mm thick carbon/epoxy specimens

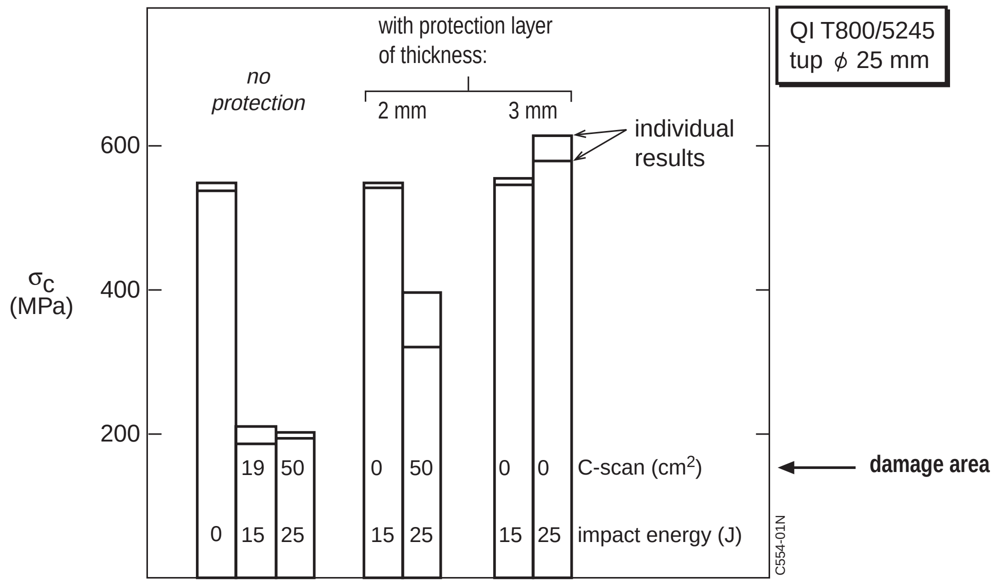


Fig. 3 Compression after impact strength of a 4 mm thick quasi-isotropic 110 mm wide coupon specimen tested in an anti-buckling guide

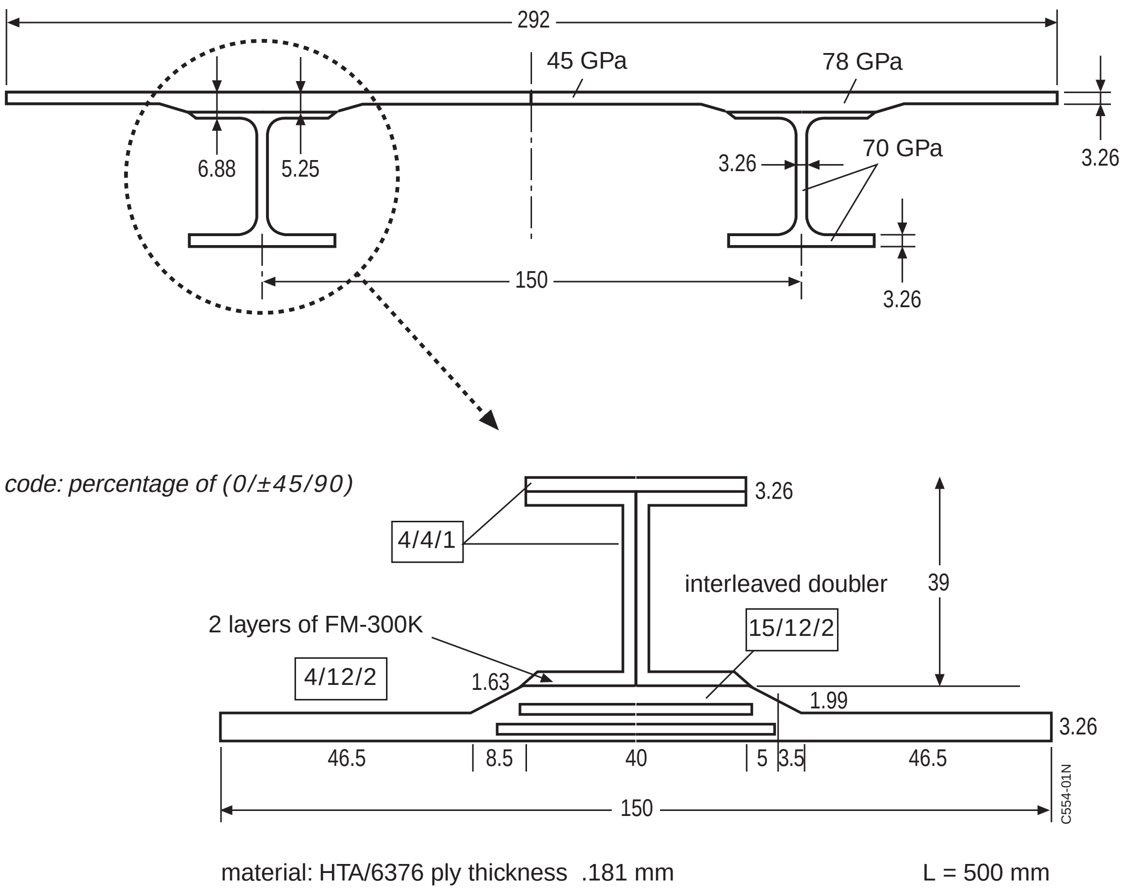


Fig. 4 Dimensions of compression test panel and lay-up details

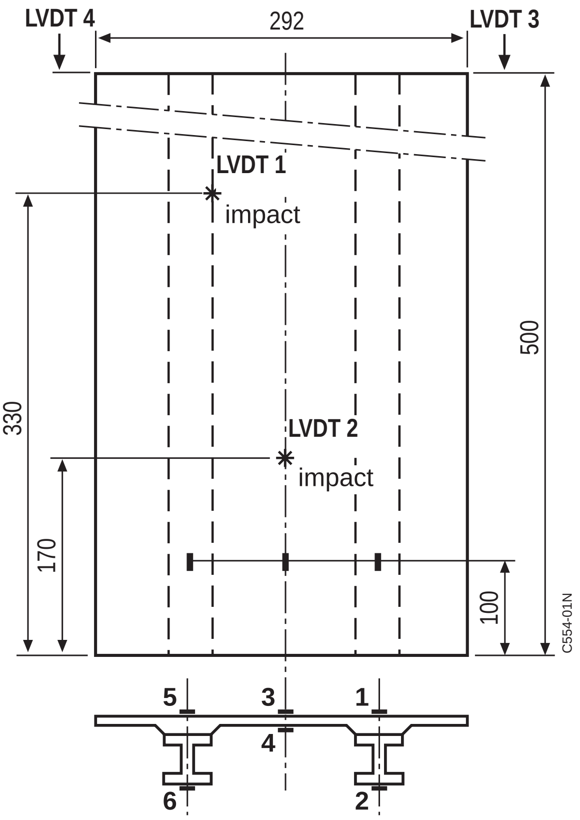


Fig. 5 Compression test panel with locations of impact, strain gauges and LVDT's

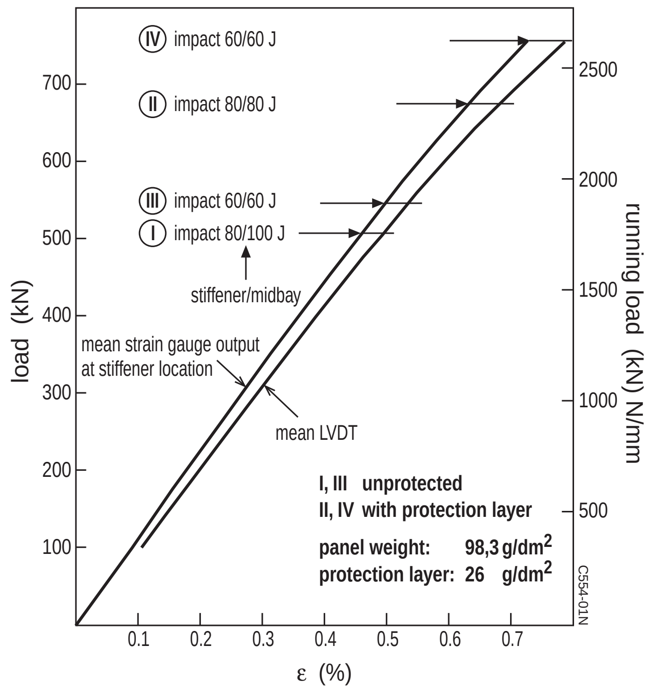
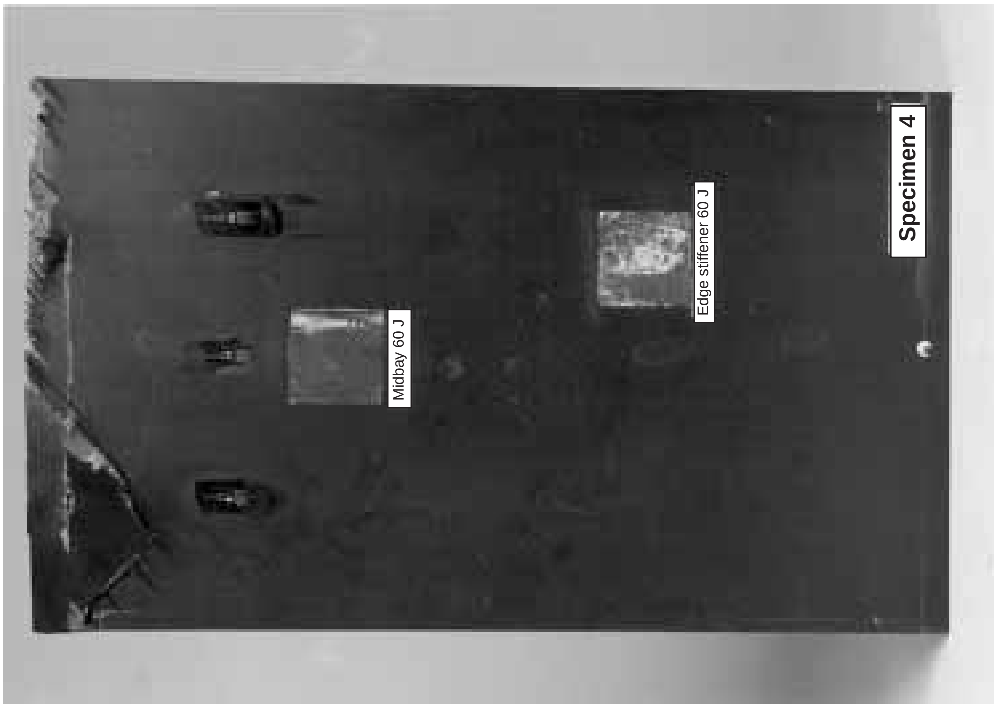


Fig. 6 Load - strain behaviour of tested compression panels and failure loads



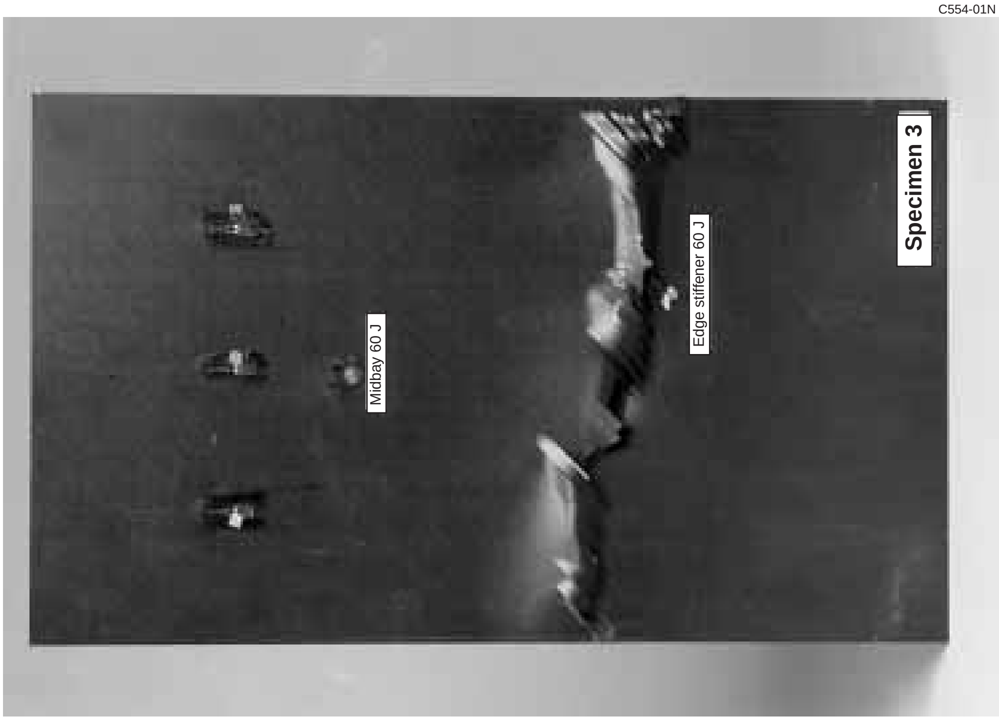


Fig. 17 Failed compression panels III and IV (surface layers removed for C-scan inspection)