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ABSTRACT

Different types of impact energy absorbing surface layers were evaluated for protection of 4 mm thick carbon/epoxy laminates. Instrumented drop weight tests were used to determine the impact energy levels for initiation of delamination damage. The effectiveness of the chosen protection layers was established by Compression After Impact (CAI) tests on coupon specimens of 250 x 110 mm. For specific layers it was possible to obtain protection up to an energy level of 30 Joule. At higher impact energies delamination occured at the substrate midplane. Nevertheless, the CAI strengths were superior to the CAI strengths of unprotected material impacted at the same energy levels. The potentially higher design stress levels amply counterbalance the weight penalty of surface layers.

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ABSTRACT

Different types of impact energy absorbing surface layers were evaluated for protection of 4 mm thick carbon/epoxy laminates. Instrumented drop weight tests were used to determine the impact energy levels for initiation of delamination damage. The effectiveness of the chosen protection layers was established by Compression After Impact (CAI) tests on coupon specimens of 250 x 110 mm. For specific layers it was possible to obtain protection up to an energy level of 30 Joule. At higher impact energies delamination occurred at the substrate midplane. Nevertheless, the CAI strengths were superior to the CAI strengths of unprotected material impacted at the same energy levels. The potentially higher design stress levels amply counterbalance the weight penalty of surface layers.

1 INTRODUCTION

The sensitivity of composites to impact damage limits the design stress level in current compression loaded composite structures to less than 30 % of the unnotched material strength. The dramatical reduction in compression strength after impact (CAI) is due to delamination and fibre damage, which result in early local buckling and premature composite failure.

In the last decade much effort has been spent on improvement of CAI strength for new material systems. These attempts were of limited success and did not result in potentially higher design allowables. Instead of modifying the base materials to improve CAI strength another approach is the application of impact energy absorbing surface layers.

This paper presents the results of an experimental program to evaluate the protecting capability of surface layers. The relation between impact damage susceptibility and designing in composite materials is first reviewed.

2 IMPACT DAMAGE AND DESIGN RULES

Primary composite structures for aircraft are designed according to the damage tolerance philosophy, wherein the effect of impact damage on the composite compression strength is a key element. Important aspects related to impact damage are the detectability of damage and the capability to sustain ultimate load after impact damage that cannot be detected by the usual inspection procedures. The threshold for detectability for impact damage is usually defined as Barely Visible Impact Damage (BVID) and may be set equal to a specific dent depth. When the geometry of an indentor is agreed the dent depth can be related to impact energy.

For civil/commercial aircraft the design stress level is usually based on the residual strength in the presence of a specific dent depth e.g. a BVID of 1 mm, or a maximum impact energy realistically expected from manufacturing and service circumstances. The U.S. Air Force has defined damage tolerance requirements for military aircraft based on ample upper bounds for impact energy and detectability (Ref. 1) Design stress levels are based upon the effect of a 135 J (100 ft.lbf) impact or a 2.5 mm (0.1 inch) dent depth, whichever is relevant. The latter depends on the material thickness.

An increase of design stress levels could be realized by developing materials with better residual strength properties or improving the visibility of impact damage.

3 IMPROVEMENT OF THE RESISTANCE TO IMPACT DAMAGE

Efforts to improve the resistance to impact damage in the last decade have concentrated on the introduction of fibres with a higher fracture strain and use of matrices with a higher toughness. This has resulted in some improvement of the compression strength after impact (CAI) if the same impact energy is applied as that for conventional older system. However, to create BVID a higher impact energy level often has to be applied. This implies that the internal laminate damage increases, resulting in a lower CAI. Thus higher design strain levels are not yet feasible.

Today, hybridization concepts are being considered for improving the CAI. This can involve:
1. 3 D reinforcement (stitching of preforms for Resin Transfer Moulding, RTM).
2. Application of additional Kevlar-/Glass-/Carbon fabrics (surface of interleaf).
3. Interleaf softening layers.

The main function of the hybridization should be to limit the interlaminar delamination at impact.

A different approach is the application of energy absorbing surface layers (Ref. 2). These layers have a dual function:
a The ability to absorb energy, leaving less energy for formation of delamination damage.
b Decreasing the BVID energy level by making a dent visible in an earlier stage.

The energy absorbing surface layer on a carbon composite component can consist of an intermediate layer of material that absorbs much energy upon deformation, and a strong cover layer that will fracture at a specific threshold energy. The concept for a protection layer utilizing a lightweight sandwich covered with aramid or glass fabric was previously investigated by Shuart (Ref. 3). The total layer thickness was about 7 mm. The present investigation concentrated on surface layers with a maximum thickness of 3 mm.

4 EXPERIMENTAL PROGRAM

Table 1 reviews the main aspects of the experimental program materials. The used base materials and the applied protecting surface layers are discussed in more detail below.

Materials

T800/5245 and T800/924 are 175 °C curing systems with high failure strain carbon fibres. The nominal prepreg thickness was 0.125 mm. After laminating and curing the quasi-isotropic laminates, the mean laminate thickness for T800/5245 and T800/924 was 4.1 and 4.3 mm, respectively.

Surface layers

The surface layers are shown in figure 1. After surface pre-treatment of the substrate by grinding, the 80 °C curing adhesive Scotch Weld A/B was used as a lightweight core and for bonding the face sheets. The precured aramid square fabric had a total thickness of 0.5 mm. Aluminium gauzes were impregnated with the core adhesive during application of the surface layers. The use of aluminium in the surface layer can also provide lightning protection for composite structures. The dimensions of the applied surface layers were 50 x 50 mm.

5 EVALUATION OF TEST RESULTS

The impact test results for the unprotected T800/5245 are plotted in figure 2 as C-scan area versus impact energy. There is no effect of tup diameter on C-scan area. For energies larger than 30 J the damage development is influenced by the limited dimensions of the impact fixture and this results in a sigmoidal C-scan curve. The C-scan areas for the protected substrate are shown in figure 3. It is seen that the occurrence of impact damage can be postponed to energy levels of 20 to 30 J, depending on the type of surface layer. However, once impact damage occurs the C-scan damage will be of the same magnitude as for the unprotected substrate.

Instrumented impact tests provide information on the occurrence of damage initiation. Figure 4 shows contact force-time curves for a 25 J impact on an unprotected and protected specimen that resulted in considerable C-scan damage. Without protection, delamination damage starts at a relatively low contact force F_i of 5 kN. Delamination damage and fibre damage continue subsequently up to the maximum contact force F_{max}. For the protected specimen damage initiation occurs at the maximum contact force (12.2 kN). The presence of protecting layers results in higher maximum contact forces and damage initiation coincides with this F_{max}.

Cross-sections of impacted laminates are shown in figure 5. The unprotected substrate shows the typical cone-shaped damage with delamination on 7 planes, figure 5a. If impact damage occurs in the substrate with a surface layer, delamination is restricted to two or three planes near the midplane and there will be no fibre damage, figure 5b. The use of aluminium gauzes in the surface layer effectively promotes a permanent dent after impact, see figure 5c. This is also demonstrated in figure 6, where the pit depth as a function of the impact energy is plotted. The aluminium-containing surface layers (S2) resulted in the largest permanent dents. For structural design the visibility of impact damage is important since the allowable strain (stress) is usually based on the strength reduction related to BVID. Improving the visibility of impact damage will decrease the impact energy required to obtain a specific dent depth. This could result in higher design allowables.

Compression after impact tests were performed on T800/5245 and T800/924 laminates provided with C1S2 and C2S2 surface layers. In figure 7 the test results are plotted in the shape of a bar diagram. Beside the CAI strength, the impact energies and C-scan areas are indicated. The CAI strength for unprotected specimens with 30 to 50 cm^2 C-scan damage is about 200 MPa, while the undamaged strength is about 600 MPa. CAI specimens with protection layers and a similar C-scan area of 50 cm^2 showed strength values between 350 MPa and 400 MPa.

6 DISCUSSION AND CONCLUSIONS

The objective of the performed investigation was to demonstrate the effectiveness of surface layers for protection of composite structures against impact damage.

The concept of a sandwich type surface layer consisting of a low density core with energy absorbing properties and a high strength face sheet proved to be successful. The occurrence of severe impact damage was postponed to high impact energy levels of 30 to 40 J. Instrumented impact tests showed that the contact force for damage initiation is significantly increased by the presence of surface layers. This is illustrated in figure 8, where the contact forces for damage initiation are indicated for unprotected and protected T800/5245 laminates. If impact damage occurs at high contact forces, the delamination damage tends to concentrate around the laminate midplane Despite similar C-scan areas for unprotected and protected laminates at high impact energies, a 75 % higher CAI strength was obtained for the protected laminate. If the limit for "visually detectable damage" is set to a dent depth of 1 mm, the associated impact energy is about 20 J for C1S2 and C2S2 layers, figure 6, and no strength reduction will occur at all. This means a residual strength improvement of 300 %.

The improvements of CAI strength have a weight penalty. The applied surface layers of 22 g/dm^2 and 26 g/dm^2 in weight result in a 33 % weight penalty for 4 mm thick carbon/epoxy laminates. This penalty has to be set off against a CAI strength increase of 75 to 300 %.

The use of surface layers on a certified base material will generally be more cost effective than the introduction of new hybrid materials with improved damage tolerance behaviour. New hybrid materials must be certified in expensive experimental programs, and improvement in DT behaviour is often accompanied by a reduction of other (hot/wet) mechanical properties. Therefore the application of surface layers could be attractive for incorporation in the design stage of new composite structures, and also for additional protection for impact-prone areas on existing structures.

7 ACKNOWLEDGEMENT

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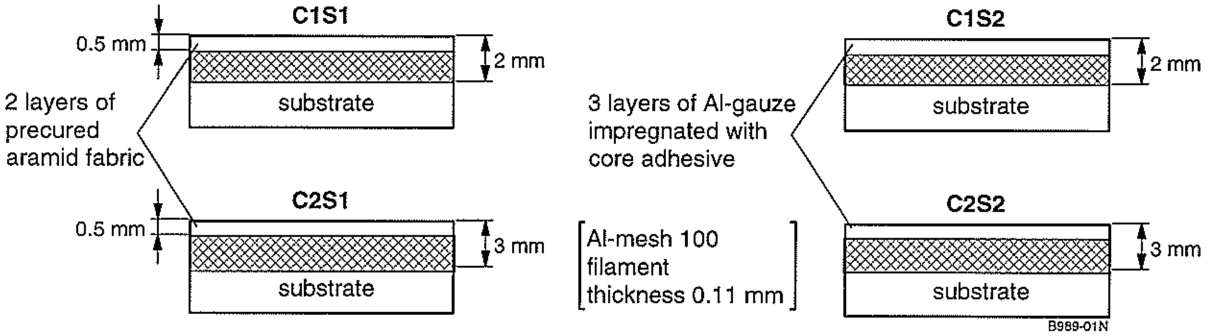
2. W.G.J. 't Hart and L.C. Ubels, Compressive strength after impact of T800/6376 laminates and HTA/6376 laminates with energy absorbing surface layers (NLR contribution to BREU-3159, task 1.2) NLR CR 92492, 1992.
3. M.J. Shuart, C.B. Prased and S.B. Biggers, A protection and detection surface (PADS) for damage tolerance. NASA Technical paper 3011, 1990.

Table I Experimental Program for Evaluation of Protecting Surface Layers

Material	T800/Basf 924 T800/Fibredux 924
Lay-up	$(+45, 0, -45, 90)_{4s}$, nominal thickness 4 mm
Surface layers	adhesive filled with glass microballoons, covered with precured aramid/epoxy fabric or three layers of aluminium gauze
Support condition at impact	75 x 125 mm
Impact energies	6 to 40 Joule Striker diameter ϕ 16 and ϕ 25 mm
Impact damage characterization	- Force-time response from instrumented drop weight tests - C-scan - pit depth
CAI testing	- specimen dimensions 110 x 250 mm - anti-buckling guide window 60 x 125 mm - protecting surface layers: C1S2 and C2S2



Weight C1S1 and C1S2	22 g/dm^2
Weight C2S1 and C2S2	26 g/dm^2
Weight substrate	65 g/dm^2

▨ Scotch Weld adhesive A/B

Fig. 1 Investigated surface layers

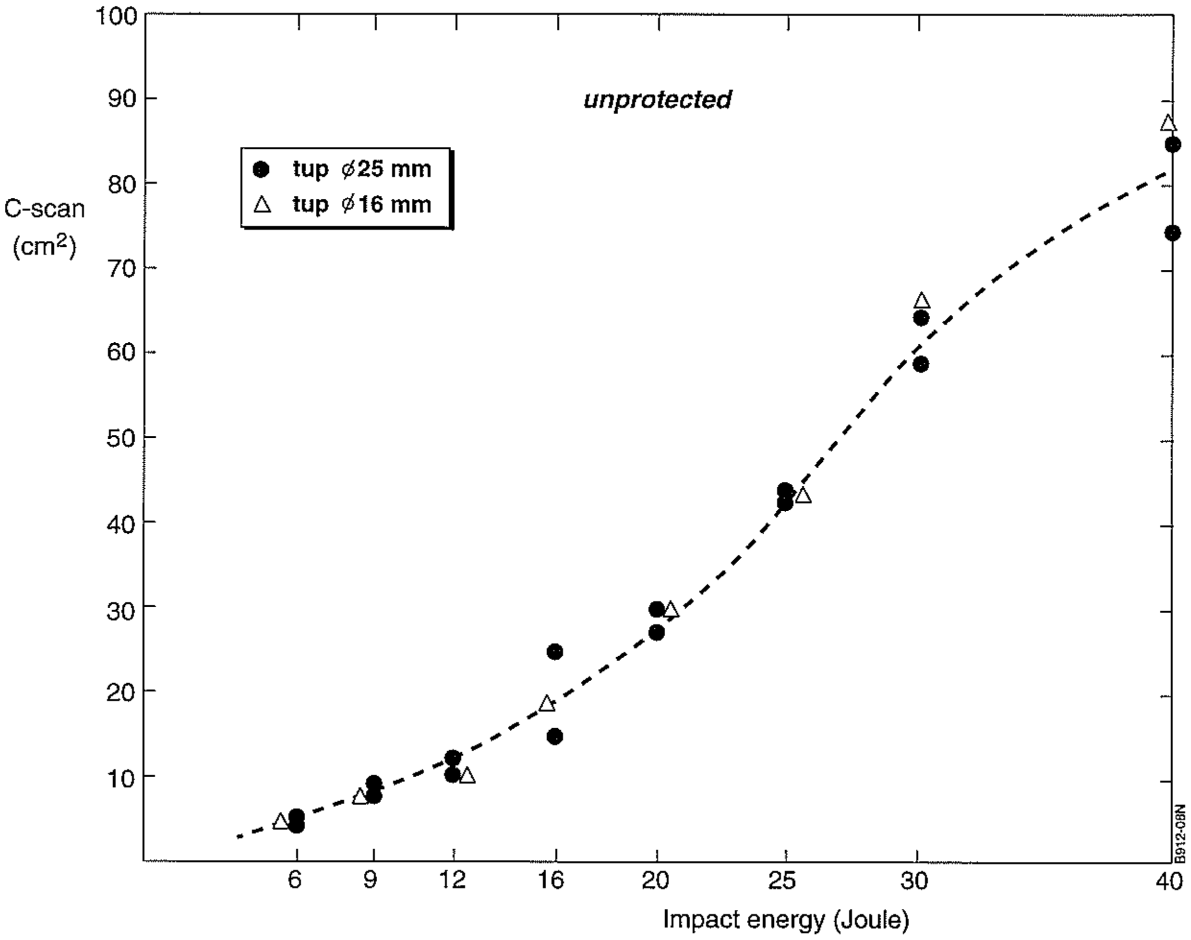
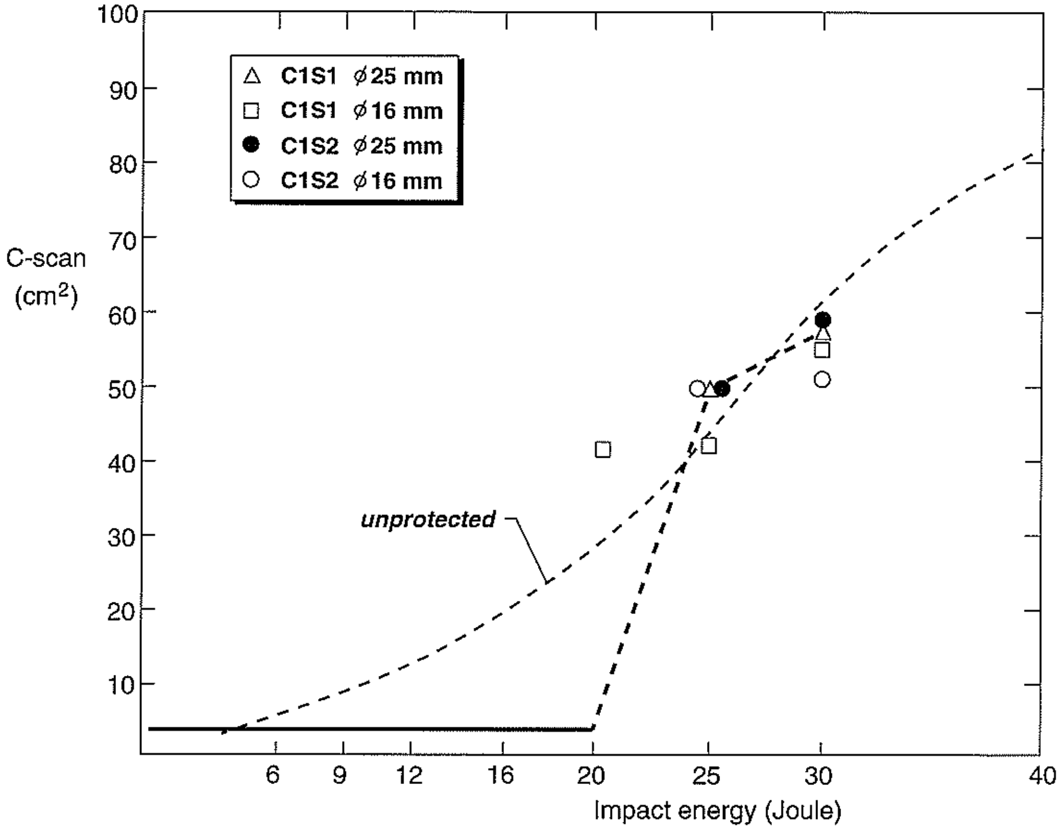


Fig. 2 C-scan area as a function of impact energy for the T800/5245 substrate



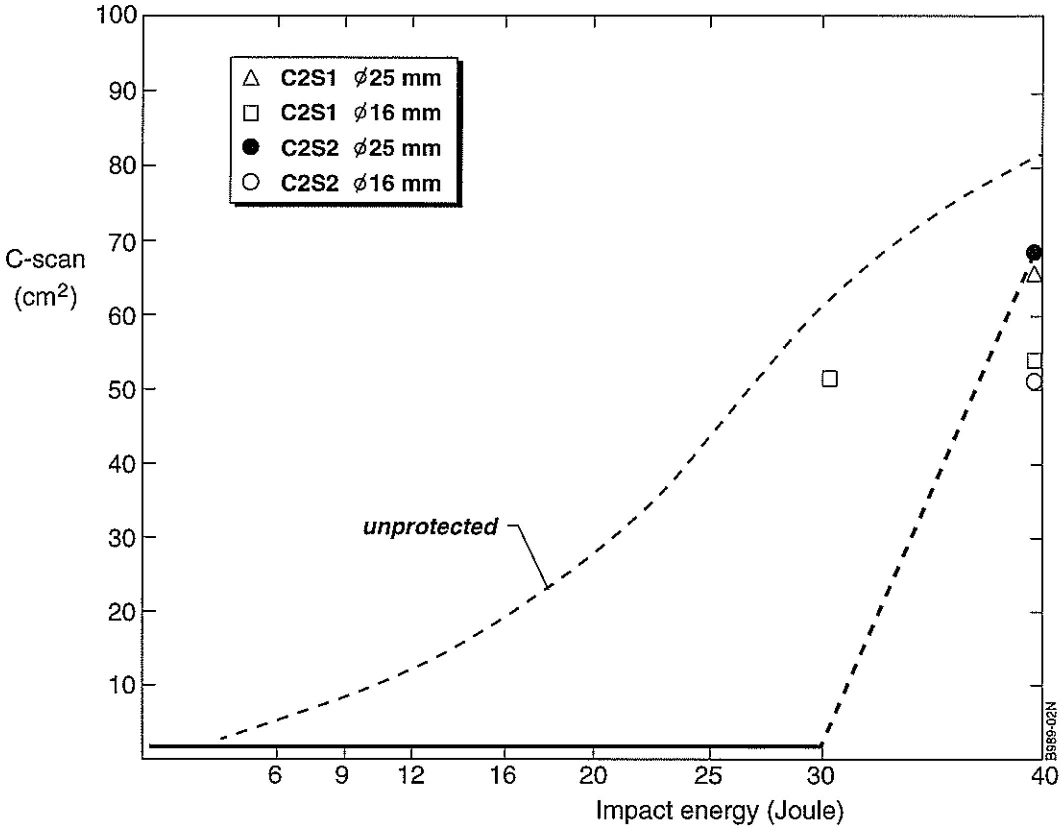


Fig. 3 Influence of protecting surface layers on C-scan damage development in T800/5245

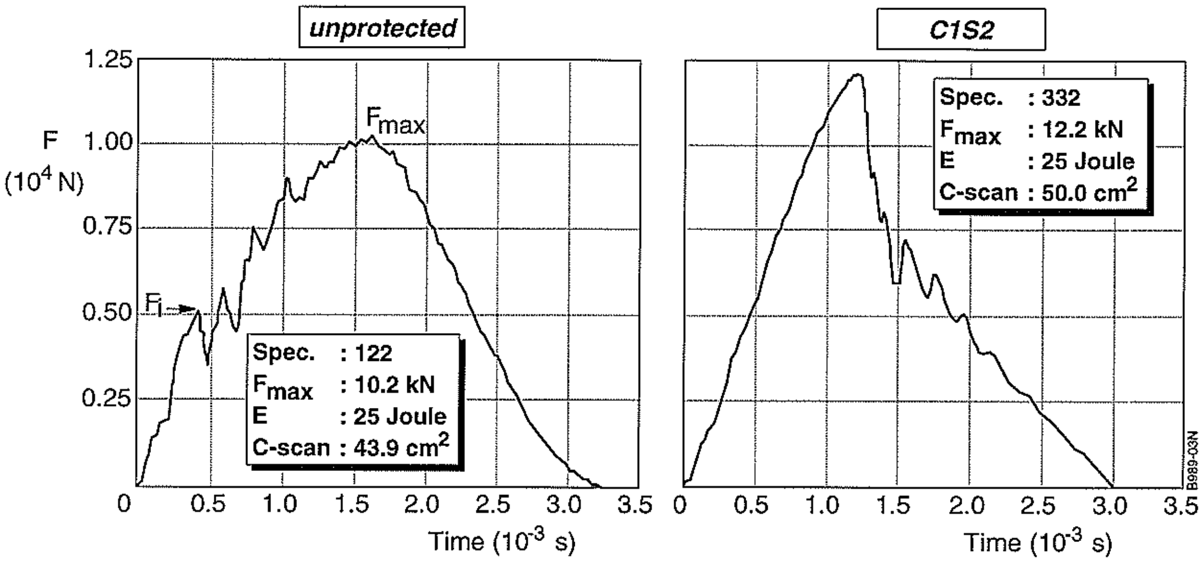
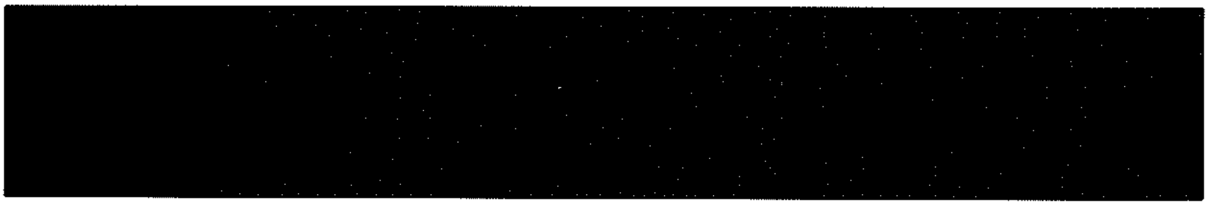
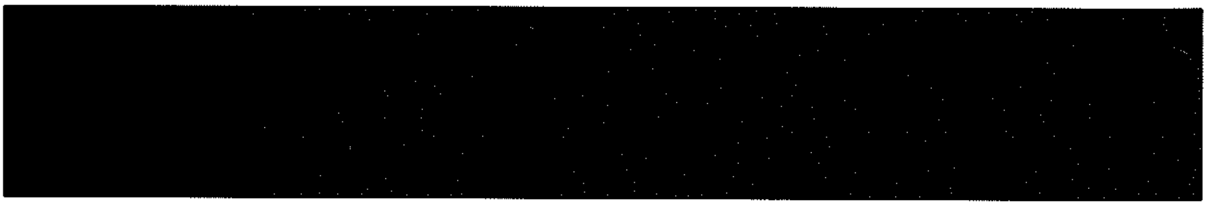


Fig. 4 Force-time curves for impact on an unprotected substrate and a substrate with a protection layer (T800/5245, tup ∅25)

ⓐ **Spec. no. 631; 20 Joule Unprotected**



ⓑ **Spec. no. 232; 20 Joule C1S1**



ⓒ **Spec. no. 322; 20 Joule C1S2**

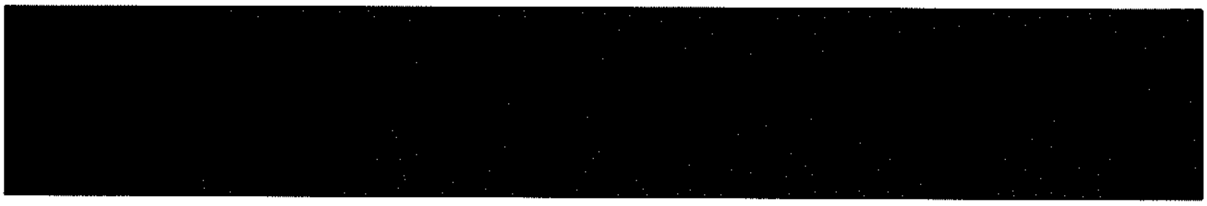


Fig. 5 Cross sections of impacted laminates

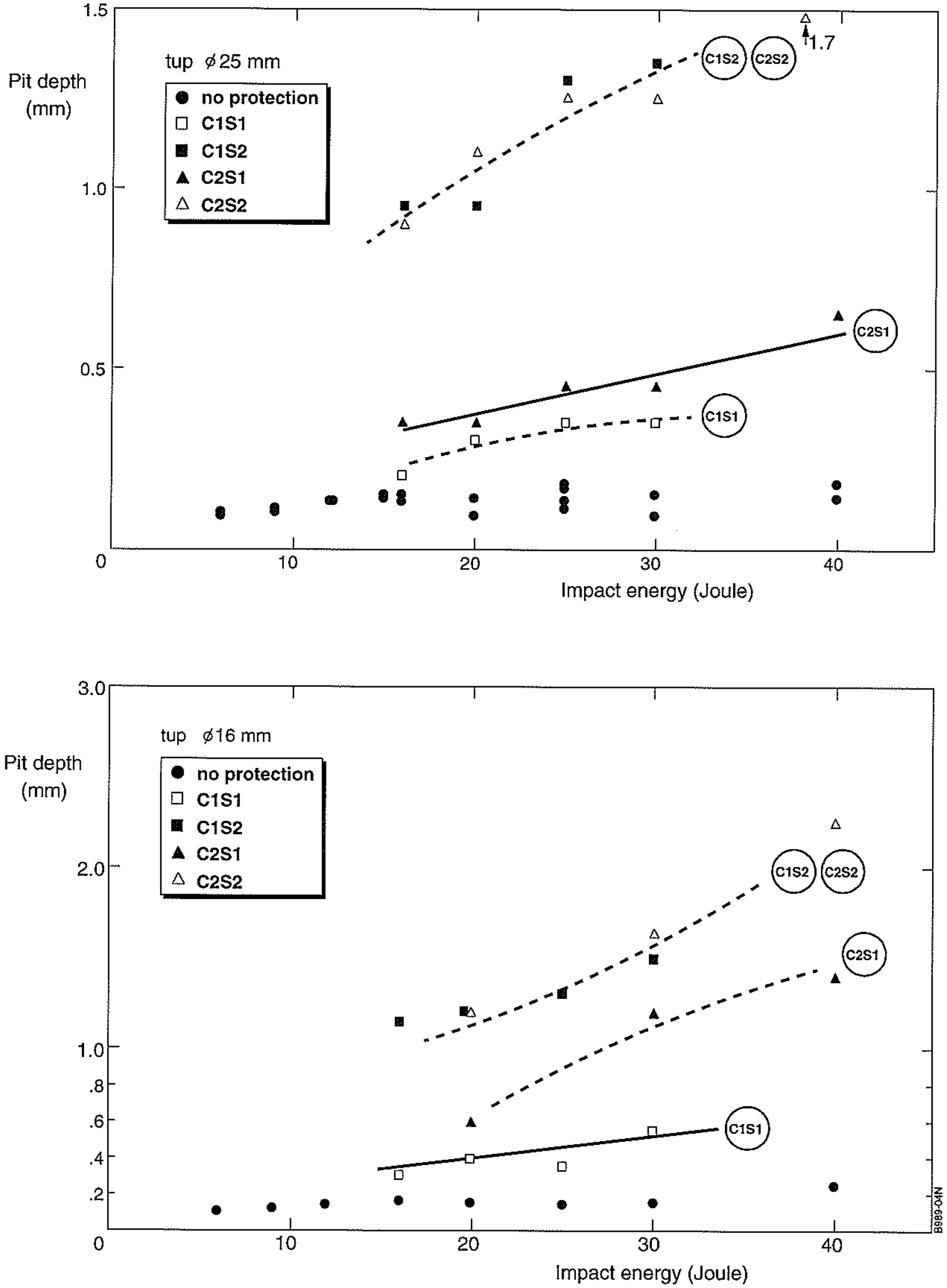


Fig. 6 Pit depth as a function of impact energy (T800/5245)

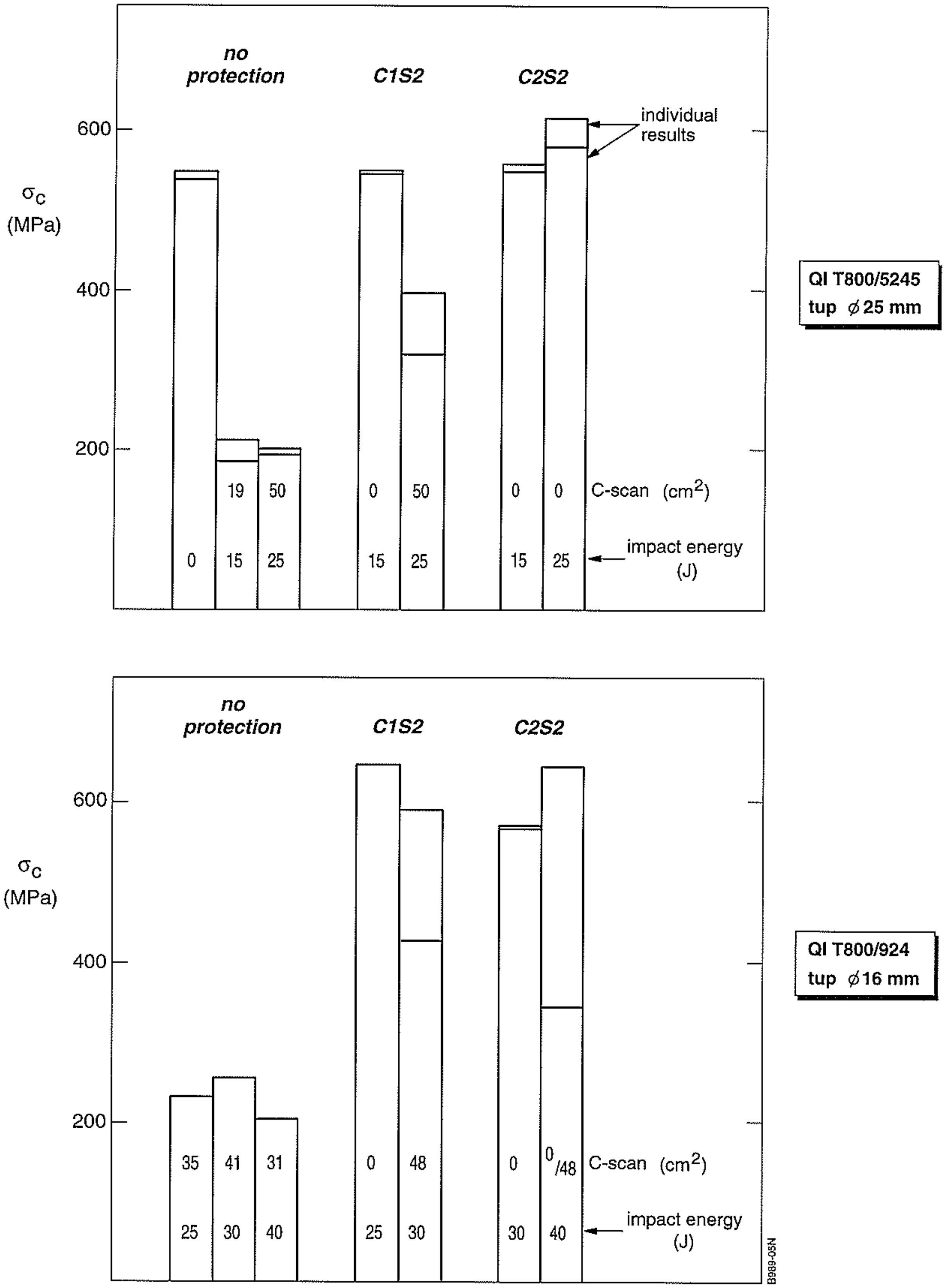


Fig. 7 Compression after impact strength for unprotected and protected coupon specimens

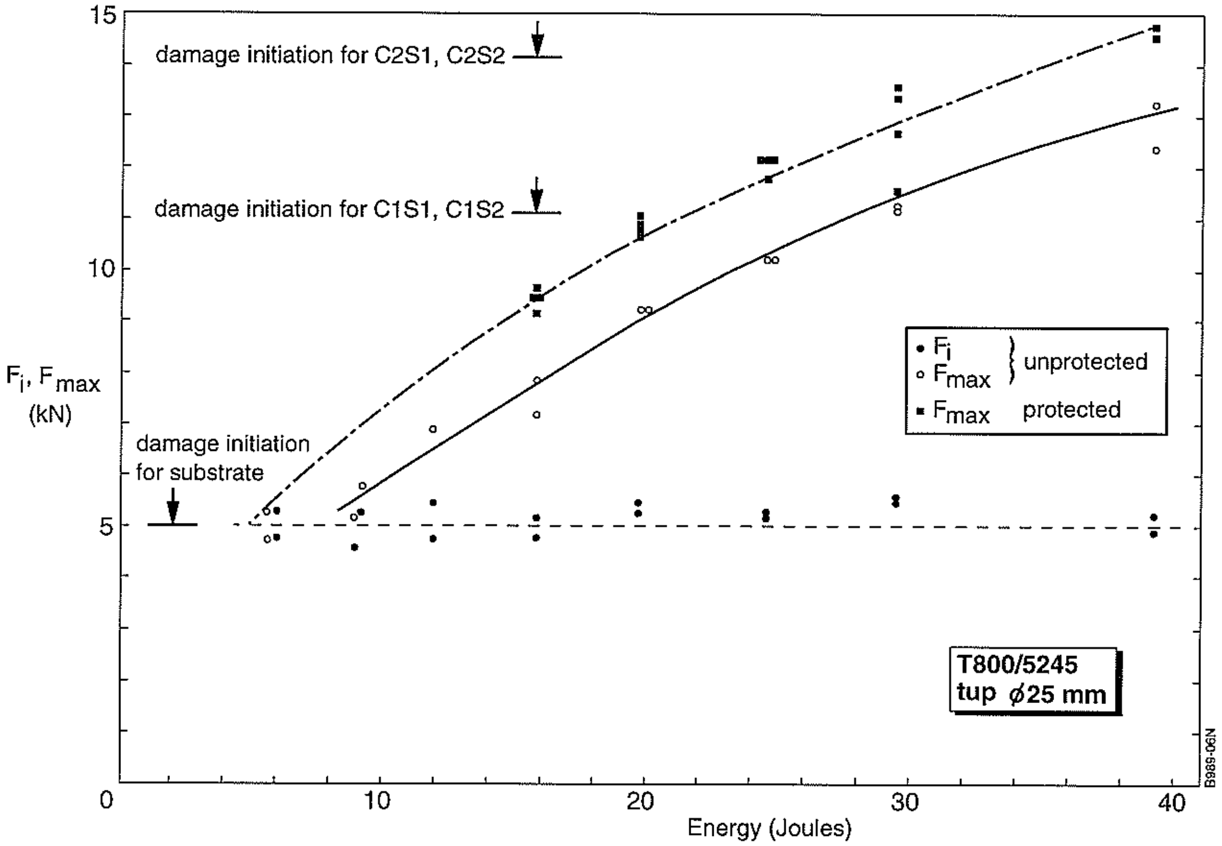


Fig. 8 Contact forces as a function of impact energy for plain and protected laminates