Experimental investigation of low-velocity impact on woven glass-fibre-reinforced plastics composites

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1. Introduction

Composite materials are now being used in aircraft structures, particulary in light aircraft and helicopters, because of numerous advantages including low weight, high specific stiffness and strength. However, these materials are sensitive to impact damage, especially out-of-plane impact, which can induce damage even at very low impact energies.

Damage of composite structures through impact events is perhaps one of the most important aspects of mechanical behaviour which limit the wide applications of these materials. Whilst high-energy impact loading causes complete penetration or damage which may be detectable on the surface, low-energy impact can produce extensive sub-surface delamination with little visible surface damage. The presence of internal damage was found to cause degradation in important mechanical properties. Damage due to impact substantially reduces the residual strength after impact of composite structure [1, 2]. The principal mechanism of compressive strength reduction is local buckling of the sub-laminates formed in the delaminated area [3]. In tensile loading the strength reduction mechanism is dominated by fibre fracture. For these reasons, impact damage is generally recognized as the most severe threat to composite structures [4, 5].

Impact damage consists of complex mixtures of delaminations, matrix cracking and fibre failure. Transverse impact first initiates critical matrix cracks, due to transverse shear or bending stresses, in a layer within laminated composites with a brittle matrix. Such cracks can generate delaminations immediately along the bottom or upper interface of the cracked layer, depending on the position of the layer in the laminate.

The objective of this study is to investigate the effects of impact energy of the low-velocity impact on woven glass-fiber-reinforced composites and is to compare absorbed energy and damaged area of woven- and multiaxial non-crimp fabric composites. Here the effects of the propagation of stress waves through the material are negligible, the structure has time to respond to the impact. Following the impact tests, the laminates were examined visually for the extent of damage.

2. Experimental details

A twelve-ply panel was laminated by hand using epoxy resin L285 reinforced with 280 gm^{-2} glass-fiber balanced woven roving at a fibre mass-fraction of 45%. The curing is carried out under a pressure of 0.8 kg/cm^2. The post-curing is carried out at 50 ºC for 12 h. The laminated specimens prepared by cutting out 150 x 100 mm^2 with 3.8 mm nominal thickness for impact testing are presented in Fig. 1.

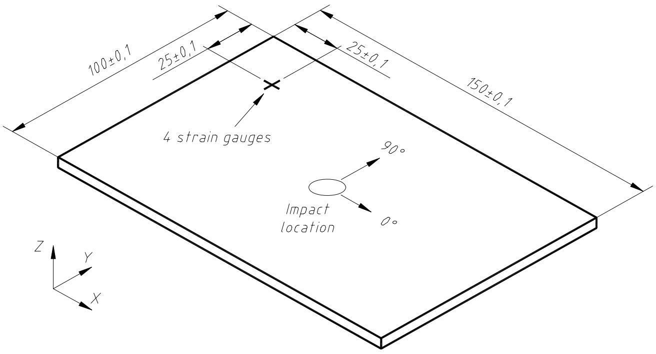

Fig. 1 Twelve-ply panel impact specimen according to Airbus-Norm AIITM 1-0010

For the low-velocity impact, a vertical drop-weight testing machine was developed at EADS (European Aeronautic Defence and Space Company) Corporate Research Center Germany with max impact energy 120 J. To measure the impact force and displacement history, a Kistler Press Force Sensor Typ 9333 and a Heidenhain Displacement Sensor Typ LIDA 100 are mounted. The force transducer has a force capacity of 50 kN. The tip of the impactor (Fig. 2) is of hemispherical shape and made of hardened steel R_m=2000 MPa according to EN 2760. The impactor head is 15.75 mm in diameter.

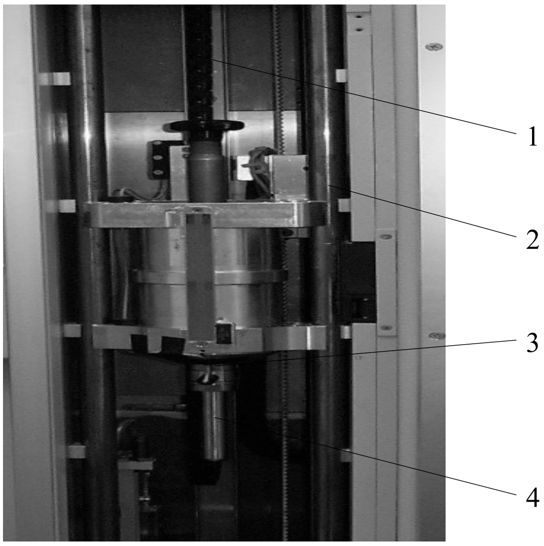

Fig. 2 Impactor equipment of impact test with max impact energy 120 J: *1* - guide tube; *2* - support beam; *3* - force sensor; *4* - impactor

The tests were performed according to Airbus-Norm AIITM 1-0010 [6]. The specimen is clamped between steel plates (Fig. 3) and the impactor is dropped from a known, variable height, and hence at a known incident velocity, onto a horizontally supported plate target.

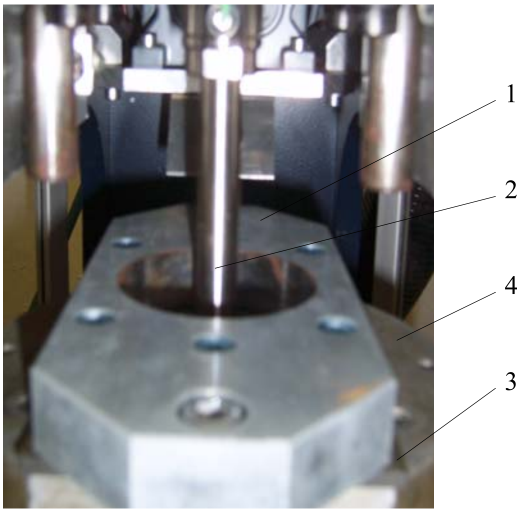

Fig. 3 Clamp arrangement for impact test: *1* - upper part of steel plate; *2* - impactor; *3* - specimen; *4* - lower part of steel plate

A variable mass (1920 and 2610 g) attached to the impactor allows variation of the velocity at a given incident energy. The height of the impactor was maintained between 344 and 1140 mm. Impact tests were performed with nominal impact energies of 6, 10, 16, 22 and 28 J and with impact velocities of 2.54, 3.25, 4.08, 4.11 and 4.63 m/s, respectively.

The post-processing of force-time and deflection–time data enables calculation by the software of the velocity of the impactor and also of the energy absorbed by the specimen. The glass-fibre laminates were translucent and it was possible to view the damage simply by back-lighting specimens. This revealed the approximate damaged area.

3. Results of low-energy impact tests

The experimental results for maximum deflection and maximum force, for different impact energies and velocities are presented in Table 1.

Table 1

Experimental results of low-energy impact tests

Low impact energy, J	Impact velocity, m/s	Max force, kN	Max defln., mm
6	2.54	3.08	4.22
10	3.25	4.09	5.29
16	4.08	5.19	6.98
22	4.11	5.20	7.17
28	4.63	5.66	7.79

Fig. 4 compares typical load-time curves (*F*, kN - *t*, ms) for glass-fibre composite laminates with incident impact energies in the impact tests varied between 6 and 28 J and impact velocities between 2.54 and 4.63 m/s, respectively.

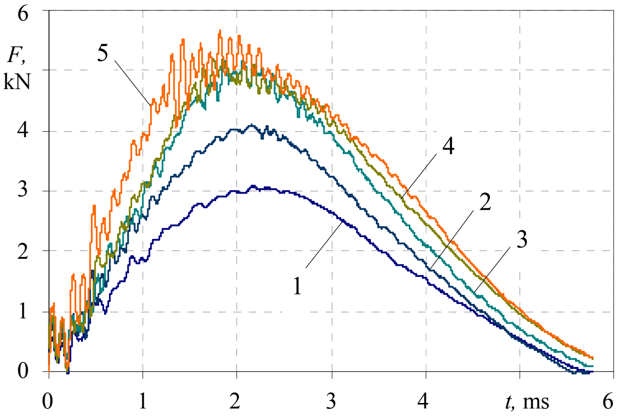

Fig. 4 Force-time curves of the impact test on glass fibre/epoxy matrix composites and the exclusion line: *1* - 6 J (2.54 m/s); *2* - 10 J (3.25 m/s); *3* - 16 J (4.08 m/s); *4* - 22 J (4.11 m/s); *5* - 28J (4.63 m/s)

It can be seen for the low energies impact of about 6 J that the woven-fabric laminates constantly exhibit high plateau load of 3.08 kN until it decreases gradually to zero. But at higher energies, the peak becomes sharper as damage occurs under impactor with the larger total displacement. After an impact time of about 6 ms, the force remains constant, indicating that the damage process is completed.

3.1. Transferred energy during impact

In low-velocity impact of glass fibre composites, transverse cracking, delamination, and fibre fracture are three dominant energy absorbtion mechanisms. In structures a significant proportion of the incident energy is also absorbed through elastic structural response. The contact force of impact loads is dictated by the mass and velocity of the striker. For simple drop-weight impact tests, the initial velocity before the specimen damage is determined by the height of the projectile as given in the equation

$$v_0 = \sqrt{2gh} \tag{1}$$

The impactor velocity is decreased gradually as the kinetic energy is absorbed by the impacted specimen. The impact energy or the incident kinetic energy of the striker is transferred to the specimen

$$E_{impact} = E_{elastic} + E_{absorbed} \tag{2}$$

Upon non-penetrating impact the total impact energy can roughly be divided into two parts (Fig. 5). A fraction of the impact energy of 6 J is stored as elastic energy of 3.15 J that is transferred back in the rebounding striker. The other fraction of the impact energy E_{im} is absorbed by the system, and is known as the absorbed energy of 2.85 J. It is related to the energy creating damage.

The absorbed energy $E_{ab}(t)$ as a function of time is calculated by the following equation (3)

$$E_{ab}(t) = \frac{mv_0^2}{2} - \frac{1}{2}m\left(v_0 - \frac{1}{m}\int_0^t F(t)dt\right)^2 \qquad (3)$$

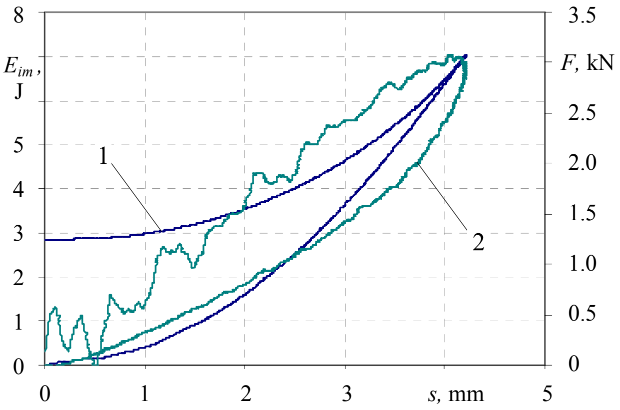

Fig. 5 Absorbed energy and impact force plotted against the impactor displacement by impact energy of 6 J. The exclusion line: *1* - absorbed energy; J, *2* - impact force, kN

Fig. 5 shows the transferred energy on the structure of laminates and the contact force plotted against the impactor displacement. In the case of non-perforating impact test, the maximum transferred energy of 6 J and maximum impact force of 3.08 kN are located at the maximum impactor displacement of 4.22 mm.

3.2. Damage development

The incident impact energies in the impact tests were varied between 6 and 28 J, which is sufficiently high to initiate the damage consisting of delaminations and fibre failure on composites. The damage by the woven-roving specimens may be grouped into three categories; front face buckling delamination under the impactor, internal shear delamination and back-face matrix and fibre degradation.

The delamination after impact tests of the glass-fibre laminates was detected by visual observations.

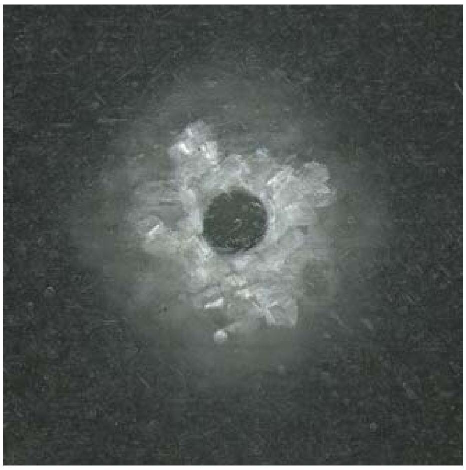

Fig. 6 Front face damage and the internal delamination by impact energy of 16 J

The mid-plane delamination was generally seen to have the largest area of the damage mechanisms, and where possible this area was measured. The damaged areas D_a, obtained by visual inspection, and the absorbed energy E_a of the specimens with woven fabrics reinforcement are presented in Table 2.

Table 2

Experimental results of low-energy impact tests

Low impact energy, J	Impact velocity, m/s	Absorbed energy, J	Damage area, mm^2
6	2.54	2.85	177
10	3.25	5.18	283
16	4.08	10.0	380
22	4.11	11.2	415
28	4.63	15.3	452

The differences in damage area (size and shape) are observed by means of back-lighting the impacted specimens of woven glass-fiber-reinforced plastics composites.

The front-face and internal delaminations in woven composites showed a more circular damage area by impact energy of 6, 10 and 16 J, whereas in the case of 22 and 28 J extensive splitting along the fibre direction at the back surface ply resulted in a noncircular damage area. For the impacted specimens of 16 J this internal delamination becomes diamond shaped with the elongating in the warp and weft directions of glass-fibre composites, Fig. 6.

In Fig. 7 the back-face damage of low-velocity impact tests with nominal impact energies of 16 J are presented. The back-face damage consisted of a central area of matrix cracking and progressive degradation, and then associated fibre damage and failure at medium energies.

Total perforation of the impacted specimens of woven glass-fiber-reinforced plastics composites subjected to the highest energies of 28 J did not occur, although these specimens suffered a high degree of fibre failure and indentation.

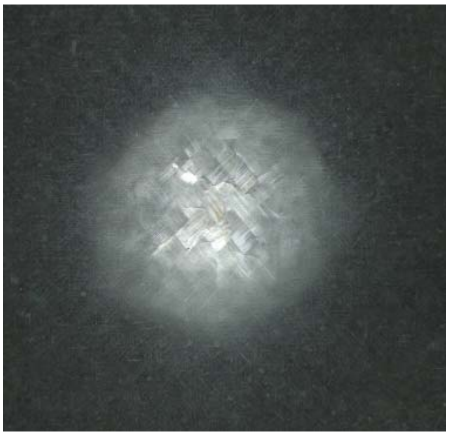

Fig. 7 Back face damage with a central area of matrix cracking by impact energy of 16 J

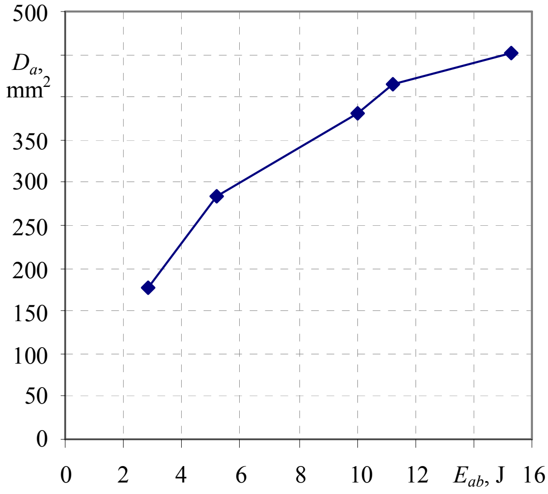

Fig. 8 Damage area plotted against the absorbed energy of woven glass-fiber-reinforced composites

In Fig. 8 the damaged area of woven-fabric laminates with increasing absorbed energy is shown. It can be high-lighted that the damage area increase with absorbed energy is about 10 J. The low increase of damage area shows that the most of absorbed energy is the result of fibre breakage.

In Fig. 9 the absorbed energy and the glass delaminated area are plotted as functions of the incident energy. It can be expected that higher levels of absorbed energy result in more damage.

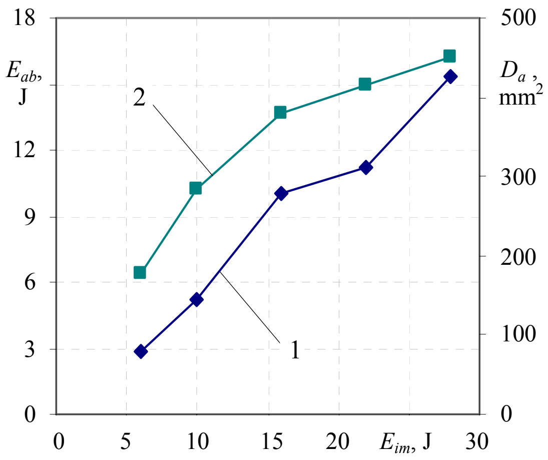

Fig. 9 Absorbed energy and damage area plotted against the impact energy of woven glass-fiber-reinforced composites. The exclusion line: *1* - absorbed energy; *2* - damage area

3.3. Comparison with multiaxial non-crimp fabric composites

In Figs. 10, 11 trends of the damage area and energy absorbed by the specimen with increasing incident impact energy are shown. Where trend lines have been fitted, these are quadratic polynomials except. The R^2 values indicate goodness of fit, there a value of one means perfect fit, that is, all of the data points lie exactly in the line.

Compared to multiaxial fabric composites [7], woven-fabric composites absorbed more energy of about 45 % during impact loads as shown in Fig. 10.

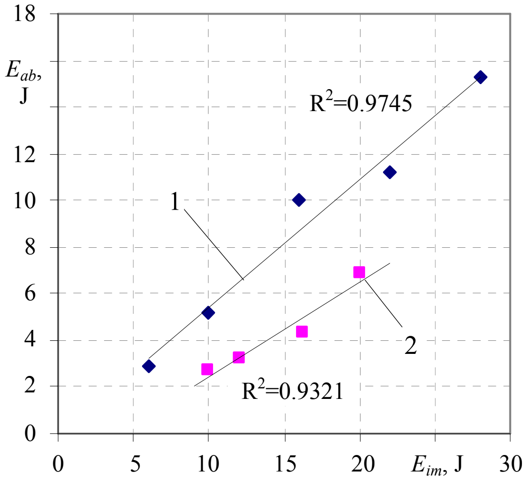

Fig. 10 Absorbed impact energy plotted against the impact energy. Comparison of laminate configuration: *1* - woven fabric; *2* - non-crimp fabric

Fig. 11 shows the delaminated area after the impact damage as a function of the absorbed energy. The overall level of damage in impacted structures increased proportionally with increasing impact energy. At relatively low energy non-penetrating impacts the delaminated area at the absorbed energy is higher for non-crimp composites.

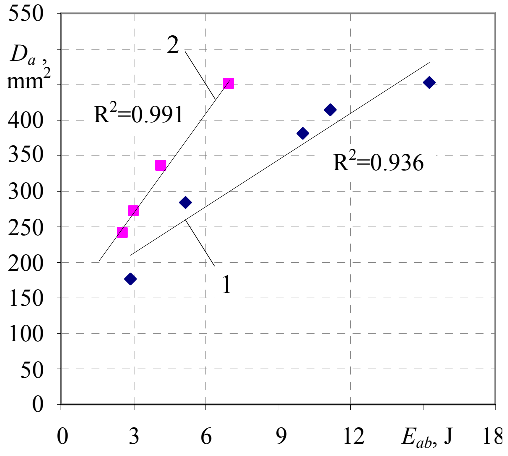

Fig. 11 Damage area plotted against the asorbed energy. Comparison of laminate configuration: *1* - woven fabric; *2* - non-crimp fabric

According to the results of drop-weight impact test, delaminated area is significantly lower for the woven material.

4. Conclusions

1. Deflection, force, absorbed energy and damaged area results of low-energy drop-weight impact tests on woven-roving glass-fiber-reinforced composites have been presented and compared.

2. The peaks of impact load in the case of low-velocity impacts of about 10 and 16 J impact energy increase by 32 and 25% respectively. But at the impact energy of 22 J the lower increase of the peak is observed.

3. For woven glass-fiber-reinforced composites it was possible to estimate the extent and form of the damage sustained visually, without the need for more expensive

techniques such as C-scan.

4. The damage area of woven glass-fiber composites increase with absorbed energy of 10 J. The lower increase of damage area shows that the most of absorbed energy is the result of fibre breakage. The damage area increase of about 55% with impact energy of 16 J.

5. The impact behaviour of laminated composites is influenced by the reinforcement. Absorbed energy and damaged area was compared of woven- and multiaxial non-crimp fabric composites.

6. The absorbed energy in the case of low-energy impact tests of the specimens with woven fabrics reinforcement was 45 % higher than that of the specimens with stitched multiaxial reinforcement. In the case of high-energy impact tests the highest energy absorption of cross-ply laminates configurations were investigated.

7. The smallest delaminated areas are obtained in the case of woven-fabric laminated specimens. Delaminated areas in woven composites showed a more circular damage area, whereas in the case of multiaxial fabric composites extensive splitting along the fibre direction at the back surface ply resulted non-circular damage area.

8. The reduction in damage area in the case of woven composites resulted in a significant improvement in residual tensile and, especially in compressive strengths after impact.

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EKSPERIMENTINIS STIKLO PLUOŠTU SUSTIPRINTŲ KOMPOZITŲ TYRIMAS MAŽO GREIČIO SMŪGIU

Reziumė

Šiame darbe aprašomas eksperimentinis stiklo pluošto audiniu sustiprintų kompozitų tyrimas mažos energijos krintančio svorio smūginiu bandymu.

Tyrimas susideda iš smūgio energijos, besikeičiančios nuo 6 iki 28 J, įtakos pažeidimo ploto didėjimui ir pažeidimui sugertos energijos nustatymo krintančio svorio smūgio bandymu. Nustatyta, kad didžioji dalis kompozitų sluoksnių sugertos energijos sunaudojama atsisluoksniavimui ir stiklo pluošto lūžimui. Palyginta tekstilinio audinio ir daugiaašio nebanguoto kompozito sugeriama energija ir pažeidimo plotas.

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EXPERIMENTAL INVESTIGATION OF LOW-VELOCITY IMPACT ON WOVEN GLASS-FIBRE-REINFORCED PLASTICS COMPOSITES

Summary

This study describes the experimental investigation of low-energy drop-weight impact tests on woven glass-fiber-reinforced composites.

The test program consisted of drop weight impact tests for the determination of the absorbed energy for the impact damage and the influence of impact energy, varied between 6 and 28 J, on damage area development. The most of the energy absorbtion of the composite laminates appeared to be the result of delamination and fibre breakage. Absorbed energy and damaged area of woven- and multiaxial non-crimpe fabric composites was compared.

Н. Кершене, А. Жилюкас

ЭКСПЕРИМЕНТАЬНОЕ ИССЛЕДОВАНИЕ ТКАНЬЮ СТЕКЛОВОЛОКНА УКРЕПЛЕННЫХ КОМПОЗИТОВ УДАРОМ НИЗКОЙ СКОРОСТИ

Резюме

Описано экспериментальное исследование укрепленных стекловолокном композитов ударом низкой энергии.

Определена поглощенная энергия повреждения ударом и влияние энергии удара, значение которой менялось от 6 до 28 J, на развитие области повреждения. Определено, что большинство поглощаемой энергии слоями композита является результатом расслаивания и разрыва волокон. Сравнены поглощенная энергия и область повреждения тканевых и мультиосевых неволновых композитов.

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