DESIGN OF COMPOSITE WING ACCESS COVER UNDER IMPACT LOADS

A.F. Johnson, G. Kempe and J. Simon

German Aerospace Center (DLR), Institute of Structures and Design
Pfaffenwaldring 38-40, D-70569, Stuttgart, Germany

SUMMARY: The paper describes a design concept and prototype development study for a composite wing access cover panel which may be subjected to high velocity impact loads from burst tyre fragments. A number of design variants were fabricated in unidirectional (UD) carbon fibre reinforced polyetheretherketone (CF/PEEK) using the vacuum forming method. Emphasis in the paper is on the use of impact simulations at the design stage to assess various design concepts for the composite panel using finite element (FE) simulation techniques. These predict a damage state in the structure after impact loading, which allows the panel concepts to be ranked for impact resistance. This led to a successful design concept, which was verified by structural impact tests, in which the CF/PEEK access panel had an impact resistant liner of high performance polyethylene fabric.

KEYWORDS: aircraft structures, carbon fibre/PEEK, impact simulation, impact damage, high performance polyethylene fibres

INTRODUCTION

Advanced composite materials are expected to be used increasingly in civil aircraft primary structures. Current application areas for composites include wings, control surfaces, radomes, aeroengine nacelles, fan casings, etc. These are all **safety critical components** which may be subjected to **high velocity impacts** due to bird strike or foreign object damage (FOD), typically on wing leading edges, nacelles, or on fan blades causing fan blade debris to impact fan casings and wing or fuselage structures. Analysis tools, such as finite element (FE) codes for predicting structural stiffness and strength of laminated composite structures under quasistatic loading with relevant materials data are currently available to the aircraft designer and are used to analyse load cases associated with normal flight, take-off and landing. Safety critical aspects, such as the ability of an aircraft structure or component to withstand high velocity impact loads or explosions are investigated mainly empirically by impact testing critical components and substructures, which is both time consuming and expensive for the industry. A design methodology for predicting impact damage in composite aircraft structures is urgently required because of the increased usage of composite materials with their low failure strains in safety critical structures.

The objective of this paper is twofold: firstly to consider how the impact resistance of a prototype composite aircraft component can be improved, and secondly to evaluate an explicit FE code as a design tool for modelling the impact response of the structure. This is based specifically on a design concept and prototype development study for a composite wing access cover panel which may be subjected to high velocity impact loads from burst tyre fragments. It is found that a basic panel which meets the internal pressure and tank sealing requirements is severely damaged under impact loads. Impact resistant design concepts were then investigated, using FE techniques to simulate impact response and to compare panel variants.

The access panels under investigation are on the underside of a commercial aircraft wing, as shown schematically in Fig. 1. They are not primary structure since the wing box is designed to carry bending and torsion flight loads, and the service load requirements are internal pressure loads, excess pressure during tank filling and bending displacements imposed by the wing. However, the access panels in the inner wing, above landing gears, are safety critical structures since they must withstand high velocity impact loads on take-off or landing from runway debris, particularly rubber fragments from burst tyres. Panels must retain a fuel-tight seal when impacted by a 2.7 kg tyre fragment with 12.2 kJ energy at 40° incident angle. The first part of the paper describes the development of a cost-effective lightweight design concept in composite materials which meets these impact requirement. The material chosen was CF/PEEK (Fiberite APC2/AS4), a tough thermoplastic composite prepreg system with airworthiness certification and suitable for rapid automated fabrication techniques such as hot press forming or vacuum forming. Alternative impact resistant design variants were fabricated and impact tested. These were based on welding a CF/PEEK stiffening panel on the outer panel face. Then in order to prevent leakage from the wing fuel tanks after impact, concepts such as an inner CF/PEEK cover plate and a liner of sintered ultra high molecular weight (UHMW) polyethylene (PE) plain weave fabric were also investigated.

One method of reducing development costs in the design-fabricate-test procedure for this component is to use FE techniques for simulating impacts on composite structures. In the second part of the paper we build on experience gained with the explicit FE code PAM-CRASH^{TM} for the crash analysis of composite structures [1]. The code is well suited to the simulation of short duration events such as impact, with nonlinear materials response and contact. It contains special elements and materials laws for UD laminated composites, which are modelled as elastic materials whose initial shear and transverse stiffness properties are degraded by microcracking, described by internal damage parameters. A number of FE models were developed for the panel structure based on laminated shell elements, and simulations were then carried out on the basic access panel and on the impact resistant panel concepts. These simulations were used to rank the various design concepts for impact resistance and gave guidelines on the thickness of the welded-on stiffening plate.

DESIGN AND FABRICATION CONCEPT FOR WING ACCESS COVERS

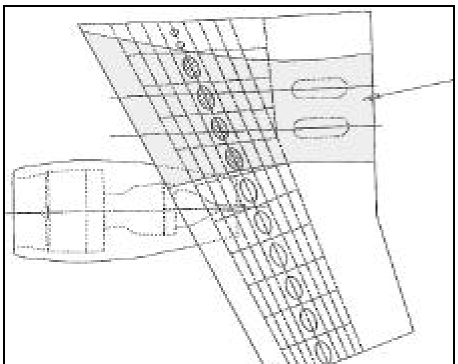


Fig. 1: Wing showing position of access covers

Fig. 2: CF/PEEK access cover

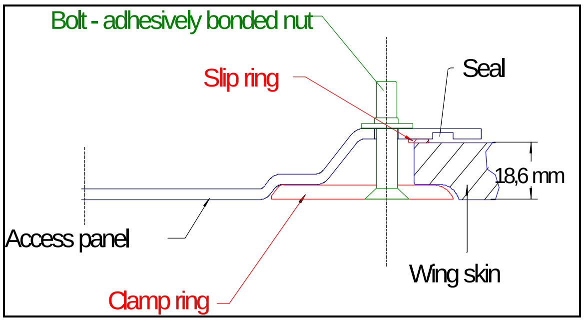
Outer Wing Access Panel

The access panels in the outer wing serve as fuel tank covers, which are removable for wing box maintenance and tank inspection. Primary wing loads are carried by the wing box and at the position of the prototype panel the wing skin wall thickness is 18.6 mm. The main access panel function is to withstand internal pressure loads, excess pressure during tank filling and bending displacements imposed by the wing, and to provide a fuel tight tank seal under these conditions. They should be low weight components suitable for series production, since a wing may have 20 or more such covers. The current state of the art panel for the wing in question is a superplastic formed titanium (Ti) panel, with 20 riveted nuts, sealing and a slip ring, having a total mass of 1.27 kg. The target for the prototype composite design is a significant weight reduction compared with the Ti design.

The access cover is an elliptical shell structure with dimensions c. 500 mm × 300 mm, with plane face and flanged edge, as seen in Fig. 2. The basic design selected for the outer wing cover consists of a 3.5 mm laminate of CF/PEEK with 28 UD plies and a quasi-isotropic layup. It is attached to the wing by 20 bolts at the flange which act through a 4 mm thick CF/PEEK clamping ring, as seen in Fig. 3a. Nuts are bonded to flange on the inside of the panel and sealed to prevent leakage. Assembly of the cover on the wing skin is by bolting from the outside through the clamping ring to the nuts bonded on the inside of the flange, which is sealed by compressing a rubber ring against the inside of the wing skin. Fabrication of the access panel was by vacuum forming preconsolidated CF/PEEK plates in a one-sided tool on a heated vacuum table at about 410°C. Cycle times were 20 minutes preheating, 10 minutes forming under vacuum, followed by slow cooling under vacuum.

The basic cover plate design was analysed with the structural FE code ANSYS under internal pressure, bolt loads and loads applied due to wing bending, see [2]. Laminated shell elements were used together with orthotropic elastic constant data for a UD CF/PEEK ply provided by ICI and summarised in [3]. A first ply failure analysis was carried out to compute the Tsai-Wu reserve factors in the cover, and the normal displacement at the flange was determined under the maximum load. The analyses showed that the cover had adequate reserve strength, and that the maximum flange displacement at the sealing ring was less than 1 mm, which was below the compression deformation in the rubber seal thus ensuring a fuel tight seal at the design load. A prototype access cover based on this design has been mounted on a wing section at DA-Airbus and the fuel sealing function tested under internal pressure loads. The cover survived 30000 simulated flights without problems. The weight of this basic composite cover with clamping ring and titanium bolts is 0.875 kg which is about 30% less than the corresponding Ti cover.

Impact Loaded Inner Wing Access Panel



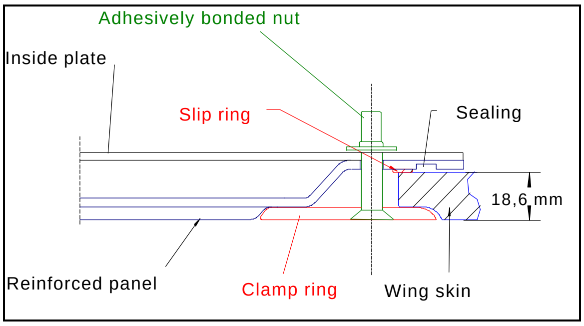


Fig. 3a. Design of basic panel attachment

Fig. 3b: Design of double panel attachment

However, the panel above was severely damaged in the impact test programme and is thus suitable for the outer wing region, but not for the impact loaded inner wing. Thus attention turned to design modifications to the basic panel which can meet the tyre fragment impact load requirements. The first design variant is shown in Fig. 3b. The basic cover is modified to a double shell design in which impact loads are carried by the outer shell, which is reinforced by the addition of a stiffening panel welded to it, with the tank sealing function carried by an additional inner plate. The stiffening panel and inner plate are again laminates of CF/PEEK with UD plies and a quasi-isotropic layup, having thicknesses of 4 mm (32 plies) and 3 mm (24 plies) respectively. Both laminates were preconsolidated as flat plates with the correct ply layup, then the stiffening panel was welded to the outer face of the standard panel using vacuum forming on a heated table with the above processing conditions. In a similar manner the inner plate was welded to the rim of the standard panel. Attachment to the wing box is again by bolting through a CF/PEEK clamping ring. In order to reduce the load per bolt under impact the number of bolts was increased to 28 in the inner wing panels.

In the second design variant the inner tank sealing plate is replaced by a polymer fabric liner, based on Dyneema® SK65 PE fibres. These UHMW PE fibres fabricated by the gel-spun process have high failure strains and energy absorption properties, and are used in applications requiring high velocity impact resistance such as body armour and helmets. Here a 2.5 mm thick HPPE fabric laminate is produced by hot compaction or sintering 8 individual fabric plies at temperatures of about 150°C, as described in [4], [5]. At higher temperatures the highly crystalline PE fibres become amorphous and lose their high stiffness and strength properties. At this temperature the plies bond together to form a single component fibre composite, whilst retaining most of their impact resistant properties. Using the vacuum forming technique this PE fabric liner is formed onto the inside of the CF/PEEK access cover. It is not possible to weld it to the cover since this would require much higher temperatures at which the PE fibres would lose their mechanical properties. It was not possible to bond the inner nuts to the PE liner, as in the case of the CF/PEEK shell, thus an additional inner metal clamping ring was required to which nuts were riveted. The function of the liner is to seal the tank in the case of impact damage to the outer CF/PEEK access cover.

Fig. 4: PE lined panel after impact -outer CF/PEEK shell

Fig. 5: PE lined panel after impact - inner PE liner

An impact test programme was carried out by DA-Airbus in which the access covers were mounted in a lower wing box and impacted with a ball of tyre rubber with mass 1.47 kg, impact velocity of 99 m/s, kinetic energy 7200 J and impact angle of 38° to the normal direction. Under these impact conditions the outer wing access panel was severely damaged with cracks in the shell wall and at the bolt holes nearest to the impacter, such that it no longer fulfilled the fuel sealing requirements. For the impact resistant variants the outer stiffening shells reduced the bending deformations considerably, but there was still damage to the outer

CF/PEEK shell due to extensive delaminations under the impacter and some permanent deformation in the clamping ring. However in the double shell concept the inner plate was undamaged and in the PE liner concept the liner had some small permanent deformations. In both cases the access covers retained their sealing function, showing that the impact resistant design concepts were successful. The PE liner concept is shown clearly in Figs. 4 and 5, which show the impacted access panel with the delaminated CF/PEEK outer shell and the inner PE liner almost undamaged with just a small plastic deformation. With clamping ring, seals and 28 titanium bolts the total weight of the double shell panel concept was 1.895 kg compared with 1.273 kg for the standard titanium panel with 20 bolts. However the titanium cover is for the outer wing and has not yet demonstrated compliance with the impact test condition, so that a proper comparison is not possible. Assuming this also requires additional reinforcement for the inner wing region it is anticipated that the composite concept inner wing panel will again be competitive on a weight basis. Taking into account the total number of panels on the complete wing, it is clear that the total weight is reduced when the CF/PEEK panels are used to replace the titanium panels.

FE SIMULATION OF IMPACT IN COMPOSITE STRUCTURES

It is apparent from above that impact resistant composite components can be developed, and also that the procedures adopted here based on design, fabricate and then concept validation by impact testing is very time consuming and expensive. One method of reducing these development costs is to develop and validate FE simulation tools for impact loaded composite structures. For metals there is extensive information in the literature on dynamic materials properties at large strains and high strain rates, and appropriate constitutive equations have been implemented into FE codes for structural impact simulations. For composite materials dynamic failure behaviour is very complex due to the different fibres and matrices available, the different fibre reinforcement types such as unidirectional (UD) fibres and fabrics, the possibility of both fibre dominated or matrix dominated failure modes, and the rate dependence of the polymer resin properties. Thus at present there are no universally accepted materials laws for impact simulations with composites. The work described here is based on the commercial explicit FE code PAM-CRASH® [6] which contains several materials models and special elements suitable for simulating crash and impact response of both metal and composite structures.

Materials modelling in PAM-CRASH

The materials model used here for composites is referred to as an orthotropic elastic damaging material, which is appropriate for brittle materials whose properties are degraded by microcracking. Rate dependence is not included at present. For UD laminates each ply may be modelled as a bi-phase material, in which fibre and matrix damage are modelled separately. However this model requires extensive ply data including ply degradation properties, which are not all available. Since the C/PEEK laminates being used in the access covers here have a quasi-isotropic laminate layup a simpler modelling procedure was adopted. The quasi-isotropic sub-laminate is then modelled in PAM-CRASH as a 'degenerate bi-phase' model in which the UD fibre phase is omitted, and the 'matrix' phase is assumed to be orthotropic. The assumed stress-strain relation in the model then has the general orthotropic form

$$\boldsymbol{\sigma} = \mathbf{E}\ \boldsymbol{\varepsilon}, \qquad \mathbf{E} = \mathbf{E_0}\,[\,1 - d(\varepsilon_{II})\,]\,,$$

where $\boldsymbol{\sigma}$, $\boldsymbol{\varepsilon}$ are the stress and strain tensors, $\mathbf{E}$ the stiffness matrix with initial values $\mathbf{E_0}$, and d is a scalar damage parameter. This takes values 0 < d < 1 and is assumed to be a function of the second strain invariant $_{II}$, or the effective shear strain. The composite sublaminate has then orthotropic stiffness properties, but a single 'isotropic' damage function which degrades all the stiffness constants equally.

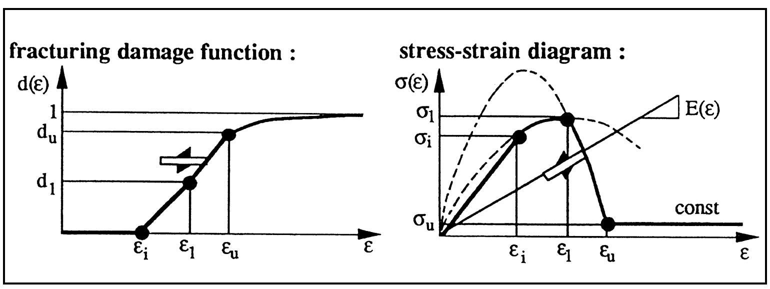


Fig. 6 Schematic fracturing damage function and corresponding stress-strain curve.

Uniaxial stress-strain curves for a quasi-isotropic sublaminate are assumed to have the general form shown in Figure 6, where ε_i is strain at the onset of initial damage, ε_1 is the strain at the peak failure stress σ_1, and ε_u is a limiting strain above which the stress is assumed to take a constant value σ_u. These curves can be modelled by a bilinear damage function (Figure 6) with two damage constants d_1 and d_u to be determined. Typical stress-strain curves for CF/PEEK laminates in tension and compression are in this general form [3] with failure strains of about 1.5% and can be used to calibrate the materials model and to determine the damage parameters d_1 and d_u for the analysis. The parameter d_1 measures the departure from linearity at the first knee in the stress-strain curves, and is thus small in tension, whilst the parameter d_u determines the residual value σ_u. For the FE analysis it is not good practice to reduce the material stresses directly to zero at material fracture, as this may lead to numerical instabilities. Thus under tensile stresses typically $d_u \cong 0.9$, indicating that the element is nearly fully damaged, whilst in compression $d_u \cong 0.5$ to model the compression crush stress allowing the element to retain a compression load carrying capability after initial damage.

Tensile tests carried out on the sintered PE fabric laminate indicate a pronounced yield stress with failure strains in excess of 20%, which is the reason for the high energy absorption properties. The PE liner was thus modelled in PAM-CRASH as an elastic-plastic material with appropriate values of modulus, and yield stress. It is known that the PE fabric properties are rate dependent [5] but in the absence of suitable data this was neglected in the computations. In the impact test the rubber ball undergoes considerable deformation, which needs to be taken account of in the analysis. Here the Blatz-Ko finite elastic model is available in PAM-CRASH and was used to model the rubber ball properties.

Panel impact simulations

The aim of the FE simulations was to compare the various panel concepts under impact loads. Three FE models were set up for the standard outer panel, the double shell panel and the panel with the PE liner. The panels were modelled with 4-node layered shell elements, with 8-node solid elements for the spherical impacter. The model consisted of the panel shell and clamping ring, but without the bolts. As boundary conditions the panel was rigidly fixed at the bolt holes, and the spherical impacter diameter 150 mm, mass 1.5 kg, was given an initial impact velocity of 100 m/s and it impacted the panel at the centre with an impact angle of 38° to the panel normal. PAM-CRASH has a number of different contact algorithms available to prevent interpenetration during the simulation, mainly based on penalty function methods. Here sliding interfaces with appropriate friction coefficients were defined between the PE liner and the composite shells, and between the rubber ball elements and the composite shells.

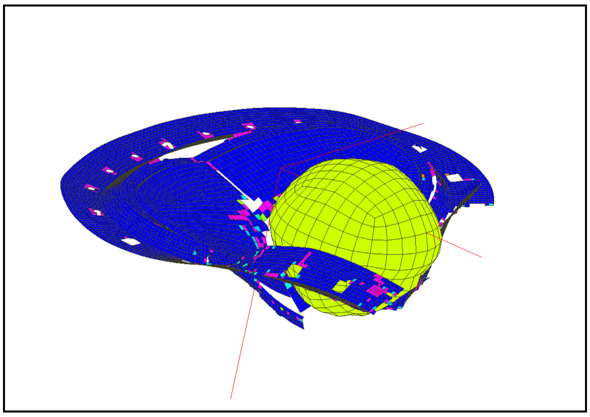


Fig. 7: Basic panel at 1.5 ms after impact

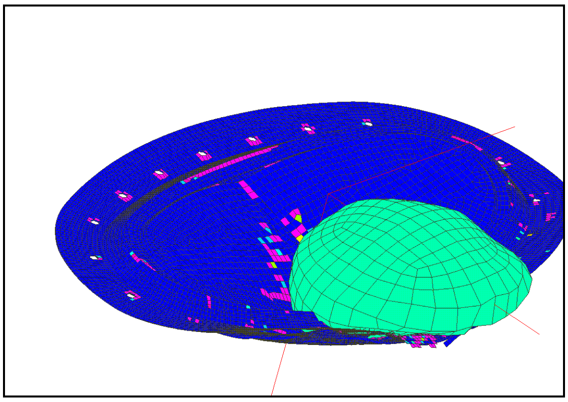


Fig. 8: PE lined panel at 1.5 ms after impact

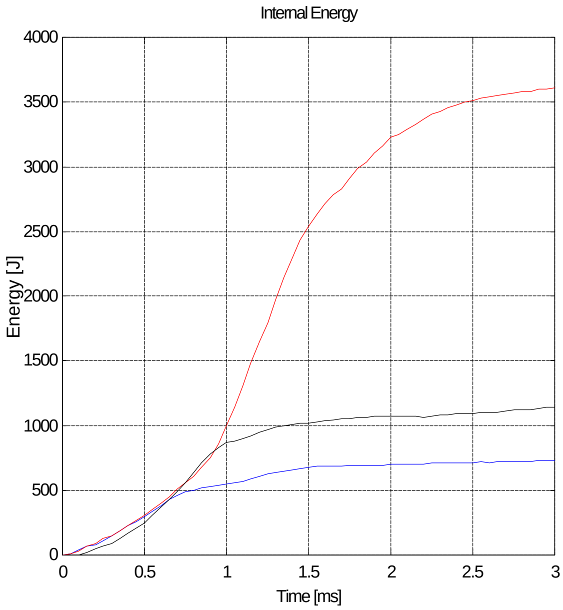


Fig. 9: Comparison of energy absorbed during impact
(Upper curve - with PE liner, middle curve - double shell, lower curve - basic panel)

Figs. 7 and 8 show typical simulations of panel and impacter deformations with values of the shear damage parameter in the elements 1.5 ms after impact for two panel concepts. Fig. 7 shows that the basic panel is severely damaged with the ball sliding into the clamping ring, with composites damage and fracture at the bolt holes and in the impacted region, so that the ball is starting to penetrate the panel. By contrast in Fig. 7, which shows the panel with the PE liner at the same time after impact, the composite outer panel is damaged but the PE liner has high membrane strains without fracture. Thus the ball does not penetrate the liner and itself undergoes large elastic deformations. This simulated response is in qualitative agreement to Figs. 4 and 5 which show the damaged panel after the impact test. In order to obtain a better comparison of the panel concepts, we compare in Fig. 9 the internal energy absorbed by the three panel types as a function of time after impact. The figure shows that the double shell concept absorbs about twice as much of the impact energy compared to the single shell, as might be expected, but the shell with the PE liner absorbs about 3500 J after 2.5 ms which is about 3 times as much energy as the double walled panel. Note that this absorbed energy is still considerably below the initial kinetic energy of the rubber sphere, which shows that further improvements are required in the materials and numerical models being used and more reliable materials property data are required. However, the FE simulations allow us to predict failure modes and rank different panel concepts which is important for the designer.

CONCLUDING REMARKS

The paper has presented design concepts for transport aircraft wing access panels in composite materials. Several prototype panels were fabricated from CF/PEEK thermoplastic prepreg sheets using thermoforming on a vacuum table. Panels in the inner wing region have a severe impact load requirement and impact resistant design concepts were fabricated and evaluated in impact tests from rubber fragments. A successful panel concept was demonstrated in which the CF/PEEK panel had an impact resistant liner of UHMW PE fabric. In parallel with the fabrication study FE simulation methods were developed to predict the high velocity impact response of the composite panels. These were shown to have the potential to be a valuable design tool for ranking panel concepts. However, the simulation methods here are idealised, and a number of important effects are not included. Thus the composites modelling is based on a single in-plane damage function, with no rate dependency, and more importantly there is no delamination failure included since the panel is modelled by single layered shell elements which cannot delaminate. These aspects are being studied in ongoing projects along with improved techniques for measuring high rate composites properties. It is hoped this work will lead to better quantitative predictions of high velocity impact damage in composite structures.

REFERENCES

1. A.F. Johnson and D. Kohlgrüber, Modelling the crash response of composite aircraft structures, ECCM-8, Naples, 3-6 June 1998.

2. K. Maier, Entwurf für einen Mannlochdeckel aus CF/PEEK für einen CFK-Flügel, DLR Report, IB 435-98/25, 1998.

3. F. N. Cogswell, Thermoplastic Aromatic Polymer Composites, Butterworth-Heinemann, 1992.

4. K. Stellbrink and R. Steegmüller, Semi-crystalline polymers as gradient materials, SAMPE Europe, Paris, 1998.

5. S.S. Morye, P.J. Hine, R.A. Duckett, D.J. Carr and I.M. Ward, A comparison of the properties of hot compacted gel-spun PE fibre composites with conventional gel-spun PE fibre composites, Composites **A 30,** 649-660, 1999.

6. PAM-CRASH, Engineering Systems International SA, F-94588 Rungis, France.

Acknowledgements: The authors wish to thank their colleague K. Stellbrink for his valuable assistance and DaimlerChrysler Aerospace Airbus for their cooperation and for performing the impact tests.