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REVIEW OF IMPACT DAMAGES MODELLING IN LAMINATED COMPOSITE AIRCRAFT STRUCTURES

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Preliminary notes
Laminated composites have an important application in modern aeronautical structures. They have extraordinary properties, like high strength, stiffness and lightweight. Nevertheless, a serious obstacle to more widespread use of those materials is their sensitivity to impact loads. As a consequence of that, impact damage initiation and growth are appearing in them. Failures that occur in laminated composite structures can be intralaminar and interlaminar. To date a lot of models for impact damages in laminates have been developed with higher or lower accuracy. Those models can replace real and expensive testing in laminated structures with some approximation. By using specialized software the damage parameters in laminate aircraft structures can be predicted (at certain conditions). In that way numerical simulation of impact on certain laminates can be done and the obtained results from the simulations presented in a form of graphic damage distributions.

Keywords: *damages, impact, laminated composite structures*

Pregled modeliranja udarnih oštećenja u laminatnim kompozitnim konstrukcijama letjelica

Prethodno priopćenje
Laminatni kompoziti imaju značajnu primjenu u suvremenim zrakoplovnim konstrukcijama. Oni imaju izvanredna svojstva, kao što su visoka čvrstoća, krutost i mala težina. Bez obzira na to, ozbiljna prepreka za mnogo širu uporabu ovih materijala je njihova osjetljivost na udarna opterećenja. Kao posljedica toga, u njima se pojavljuju inicijacija i razvoj udarnih oštećenja. Otkazi koji nastaju u laminatnim kompozitnim konstrukcijama mogu biti intralaminarni i interlaminarni. Do sada je razvijeno mnogo modela za udarna oštećenja u laminatima, s većom ili manjom točnošću. Ovi modeli mogu zamjeniti realna i skupa testiranja u laminatnim konstrukcijama, s izvjesnom aproksimacijom. Uporabom specijaliziranih softvera mogu se predvidjeti parametri oštećenja u laminatnim konstrukcijama letjelica (pri specifičnim uvjetima). Na taj način može se provesti numerička simulacija udara u određene laminate, a dobiveni rezultati ove simulacija mogu se predstaviti u obliku grafičkih distribucija oštećenja.

Ključne riječi: *laminatne kompozitne konstrukcije, oštećenja, udar*

1 Introduction

The laminated composites are increasingly used in load-carrying structures due to the number of advantages over conventional materials, especially in aircraft structures. They have exceptional characteristics such as: high specific strength and stiffness, low density, good fatigue performance, resistance to corrosion and high temperatures, ability to create complex shapes. For implementation of composite materials in aviation, the most important feature is their behaviour on dynamic loads and resistance to fatigue [1].

Composites have shown to be very vulnerable especially to out of plane impact, which causes barely visible impact damage (BVID) and contributes to the loss in structure compressive strength and major reason for catastrophic damage and failures. BVID is a hidden menace and the residual strength in compression may be only 30 % of the undamaged value.

Due to the anisotropy of composite laminates and non-uniform distribution of stress under dynamic loading, the failure process of laminates is very complex. The dynamic response of composite structures subjected to transient dynamic loading has been studied for years in terms of analytical, numerical and experimental works [2].

Physical phenomena associated with impact damage and accordingly progressive collapse of composite structures is very complex, because the impact is defined as highly nonlinear and dynamic event. For this reason predictive models (2D and 3D) and simulation tools for the design and analysis of impact have been widely investigated in the past years. In order to examine this problem multiscale modelling techniques are required, because impact damage is localized and requires fine scale modelling of delamination and also ply damage at the micromechanics level, while the structural length scales are much larger.

The failure of composite laminates involves sequential accumulation of various types of intra- and inter-laminar damages, which gradually lead to the loss of the laminate's load-carrying capacity. The main damage mechanisms that appear in composite laminates, are those associated with matrix and fibre. Generally, it is difficult to simulate numerically or analytically, the behaviour of those systems under impact loads because of the complexity of damage mechanisms.

Predicting damage in laminated composite aircraft components due to impact events such as runway debris, hail, bird, is an area of on-going research. To reduce certification and development costs, computational methods are required by the aircraft industry to be able to predict structural integrity of composite structures under high velocity impacts from hard objects, such as metal fragments, stone debris and from soft or deformable bodies such as birds, hailstones and tyre rubber. Key issues are the development of suitable constitutive laws for modelling composites in-ply, determination of composites parameters from dynamic materials tests, materials laws for deformable impactors, and the efficient implementation of the materials models into finite element (FE) codes.

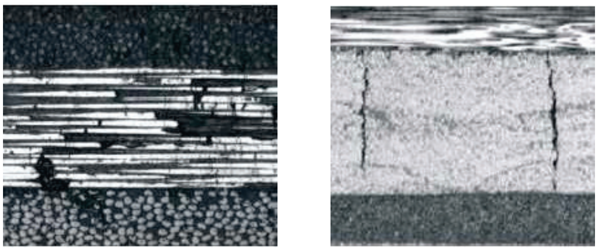
2 Impact damages in composite laminates

The energy absorbed during impact process is often very large. That energy is mainly dissipated by a combination of matrix damage, fibre fracture and fibre-matrix debonding. These facts lead to the significant reductions in the load-carrying capabilities in such structures. In ballistic impacts (short contact between impactor and target) the damage is localized and clearly visible by external inspection, while low velocity impact involves long contact time between impactor and target, which produces global structure deformation with undetected internal damage at points far from the contact region [3].

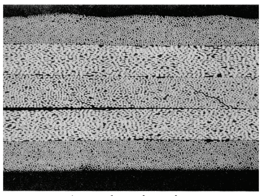
Damages in composites are different from those in metals. Composite failure is a progressive accumulation of damage, including multiple damage modes and complex failure mechanisms. Impact on the structure has a dynamic nature and therefore it is necessary to take into account the effects arising from inertia and spreading voltage waves in the material. Often the material response is highly nonlinear and large deformations occur [4].

To experimentally characterize the behaviour of some samples different loading rates were used. Then numerical models were proposed for continuous or discontinuous damages. Finally, numerically predicted impact damages are compared with real test impact experiments.

The most common damage mechanisms in laminated composites are: fibre fracture, transverse matrix crack and delamination. Those mechanisms are clearly presented in Fig. 1. Formed damages may or may not influence one another [5].



a) Fiber fracture b) Transverse matrix crack



c) Delamination

Figure 1 Damage mechanisms in laminated composites [5]

Damage mechanisms in composite laminates can be studied theoretically following two approaches. Using the continuum damage mechanics approach, different types of damage are accounted for via the damage tensor. By the application of the damage micromechanics approach, stress analysis of the damaged composite structure is carried out in the explicit presence of damage.

Transverse low velocity impact on the laminated composites induces intra-ply matrix cracking and inter-ply delaminations. Key aspects are to develop a numerical simulation/algorithm to identify the location and extent of damage on any structure with the given input of impact force history [6].

We should not neglect the fact that structure of polymer matrix composites (PMC) is made of matrix and fibre [7]. As an impact response in those materials some damages are occurring over time in certain phases.

Damage observed during the initial stages of the failure process is the intralaminar damage in the form of matrix cracks. Matrix cracking is initiated long before the laminate loses its load-carrying capacity. It gradually reduces the stiffness and strength of the laminate.

Further design needs development and implementation of computational models and simulations to obtain valid and reliable results. Some of the main tasks of these researches are aimed to: improve impact response methodology; enhance and validate results through correlation with experimental test data; use this simulation model to analyse typical impact events to gain further understanding of the characteristics of impact damage processes [3].

The classic theory of laminated composites is based on a series of simplifying hypotheses. Thus, the laminae are considered as very thin, made of a homogeneous, orthotropic, linear elastic material in a plane stress state. Also, perfect adhesion between the laminae and the Kirchhoff hypothesis is assumed. Most of the algorithms and models based on these facts lead to a global stress and strain state analysis without characterization of the mechanical behaviour of these materials.

Because of the anisotropy of composite laminates and non-uniform distribution of stress under dynamic loading, the failure process in laminates is very complex [8]. The dynamic response of composite structures subjected to transient dynamic loading and investigation of impact damages involves analytical, experimental and computational approach. Impact damage is a major concern of safety and reliability in laminated composite structures. Certain impact on structure frequently causes damage which severely reduces structural strength, stiffness and stability.

Generally, impacts are categorized into low and high velocity, but there is not a clear and definite transition between those categories. Usually limited velocity is in the range of 10 up to 100 m/s. However, a pure difference in the form of damage developed after each impact event exists. Sjöblom and Shivakumar claim that damage is much localized due to the high velocity impact, since the incident energy is dissipated in a very small volume; high velocity impact is characterized by penetration induced fibre breakage. During low velocity impacts, damage is initiated by matrix cracks which create delaminations at interfaces between plies with different orientations.

Low velocity impact events occur with some frequency on composite applications such as airplane components. From ground operations to unavoidable birds, there is a range of situations where an aircraft component may be subjected to unexpected impact loads. In most cases, such as tool dropping, the impactor has a relatively high mass but low velocity. The damage produced in such cases is mostly in the form of delaminations, which are not easily noticeable through routine eye inspections. Special technologies are used for detailed inspection of this form of damages. Delaminations are primarily induced by interlaminar shear stresses, which are enhanced by matrix cracks and ply stiffness mismatch. However, the spread of those delaminations over wide structure areas may severely compromise the residual compressive structure strength, possible even below the limit load for which it was initially designed. Therefore, the ability to predict the impact damage from impact events likely to happen is of outmost importance in the aeronautical industry.

Traditionally, impact damage models rely on either analytical calculations or extensive experimental data. Analytical predictions of the impact damage resistance and tolerance of composite laminates are overly simplified and unreliable. On the other side, testing each promising design is time consuming and costly. Low-cost virtual testing by means of nonlinear finite element analyses can replace most of the actual impact testing of laminates. Once the dynamics of the impact phenomena and the damage mechanisms are correctly simulated, progressive failure analyses can be a valuable tool in the accurate prediction of impact damage resistance of composites.

Impact damage induces significant reductions in stability and strength of laminated composite structures. Low velocity impact damage from bird strike, runway debris, dropped tools during fabrication or maintenance operations may cause damages below the BVID limit. These types of damages could lead to catastrophic failure and that is important to be taken into consideration in the design process of a composite structures. Since such damage is difficult to detect, especially in-service, structures must be safe and with present BVID. That is a hidden threat and the residual strength in compression may be only 30 % of the undamaged value [9].

The complex problem of determining the effects of impact damage may be divided into two domains:

1) impact damage resistance, associated with the response and damage caused by impact, and
2) impact damage tolerance, linked with the reduced strength and stability of the structure due to the damage [9].

Usually, impact damage is internal and cannot be detected by visual inspection. It can grow under load and significantly reduces the load carrying capacity of the structure [10].

Under high velocity impacts, the pressures generated in a material can reach high values. Under such a condition, materials exhibit a hydrodynamic type of behaviour with no shear strength. An equation of state (EOS) is used to model the constitutive law and defines relationship between thermodynamic parameters such as pressure, volume and temperature [11].

Significant research efforts on impact damage resistance of composite structures have been conducted in the last two decades. The state of the art of this subject has been thoroughly reviewed by Abrate (1991, 1994, 1998). Most of the studies are based on the Hertzian contact law, which was originally developed for static loading on an isotropic linear elastic half-space.

The aim concerning impact on composites is to develop reliable methods to evaluate the effects of damage and the residual strength properties after impact. Experimental testing is an efficient way to determine the effects of impact damage. Due to the issue that testing is expensive and time-consuming, there is a great need to develop calculation methods that are rapid and reasonably accurate and with the opportunity to perform appropriate parametric studies.

In studies of impact damage on carbon fibre reinforced plastics (CFRP) three major damage types are present: fibre breakage, matrix cracks and multiple interlaminar delaminations. The reduction of compressive strength due to the impact is more significant than the reduction in tensile strength and other classes of strength. Residual strength is focused on delamination buckling, which reduces the flexural properties of the damaged laminate and may also cause significant reduction in compressive strength [9].

Emphasis is on failure models suitable for use in explicit FE codes to predict damage arising in composite structures under crash and impact loads. This is a multiscale problem, since composites damage is at the microscale level, while crash and impact loads are applied at the structural level [12].

Aircrafts are primarily designed for certain in-service load conditions, but they also need to be able to withstand impact loading. In an impact event, the material and the structure are deformed at higher rates, which potentially could give a completely different behaviour compared to a quasi-static (low speed) loading [13].

In-plane loads can alter impact damage in composite materials significantly. The formed damage model can predict the impact response and damage approximately [14].

Fibres which have high tensile strengths and strain to failure are able to absorb significant amount of energy. Primary energy absorbing mechanism is a penetration failure of impacted composite laminates [15].

In service aircraft loads commonly include impact which may result in a large internal damaged area of the laminate that is not detectable from visible observation. Fluctuating in-service loads, in particular compression, can continuously grow the damage area, possibly resulting in complete structural collapse of the damaged part. Impact damages may have negligible influence, but they may be critical for the integrity and service life of constructions from composites. It is necessary to predict accurately where damages will appear, how they will spread and when they will eventually produce a fracture and failure of constructions [16].

The element-failure approach was extended in composite structures to analyse damage and delamination propagation in low-velocity impact of composite laminates. An advantage of this analysis is that it eliminates the need to use contact algorithms to ensure that the interpenetration of delamination surfaces does not occur [17].

Damage resistance of a composite material is measured by its ability to resist impact damage. Alternatively, damage tolerance can be considered as a measure of residual strength after a certain period of service and history of load application [18].

Materials with low fracture toughness have better ballistic performance than those with high toughness. Fracture toughness requires matching with laminate tensile strength for best ballistic performance, low toughness and high strength is desirable [19].

In [20] a genetic algorithm (GA) was adopted to optimize the response of a composite laminate subjected to impact and two different impact scenarios were presented: low-velocity impact and high-velocity impact.

3 Finite element modelling of impact on laminates

To date modelling of impact on composite laminate structures has been investigated by many scientists and engineers. The most used approach for this type of problem is FEA (Finite Element Analysis).

In order to analyse this phenomenon the dynamic response of laminated plate due to the impact has been considered. FEA involving short-time large deformations dynamics requires the solution of transient dynamic problems over a short-time length. Explicit and implicit solution techniques or a combination of both have been used as the basis for FE crash codes [21].

The two degree of freedom model accounts for the mass of the target and the local indentation in the contact zone. That model (Fig. 2; m – mass, S – spring stiffness) was presented by Abrate [10]. It supposes a contact between impactor and the target laminated plate and the force is applied at the centre of the plate.

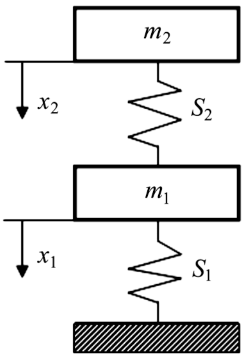


Figure 2 Two degree of freedom spring-mass model for impact

Fig. 3 describes the impact of the rigid body (impactor; m – mass, r – radius and v – velocity) on the laminate composite plate [22]. Introducing the conventional stress and moment resultants (N_x, N_y, N_{xy}, M_x, M_y, M_{xy}, Q_x, Q_y), the laminate constitutive equation is as follows:

$$\begin{Bmatrix} \boldsymbol{N} \\ \boldsymbol{M} \\ \boldsymbol{Q} \end{Bmatrix} = \begin{bmatrix} \boldsymbol{A} & \boldsymbol{B} & 0 \\ \boldsymbol{B}^{\mathrm{T}} & \boldsymbol{D} & 0 \\ 0 & 0 & \boldsymbol{F} \end{bmatrix} \begin{Bmatrix} \boldsymbol{\varepsilon}^0 \\ \boldsymbol{\kappa} \\ \boldsymbol{\gamma} \end{Bmatrix}, \tag{1}$$

where $[\boldsymbol{A}]$ is the extensional stiffness matrix, $[\boldsymbol{B}]$ is the bending-extensional coupling matrix, $[\boldsymbol{D}]$ is the bending stiffness matrix and $[\boldsymbol{F}]$ is the transverse shear stiffness.

The governing equation of the structures dynamical behaviour is given by the Hamilton's principle. Since it deals with the piezoelectric continuum, the Lagrangian is properly adapted in order to include the contribution from the electrical field besides the contribution from the mechanical field [23].

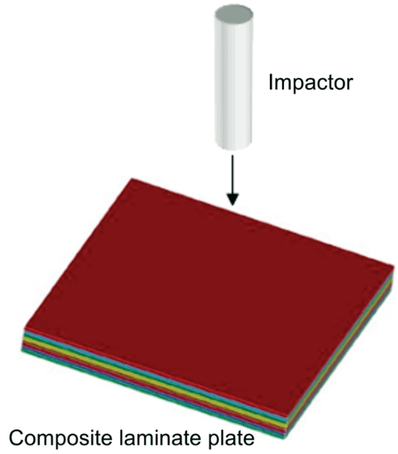


Figure 3 Impact of the impactor on the composite laminate plate

The dynamic equation for a plate is given as:

$$[\boldsymbol{M}]\{\ddot{\boldsymbol{u}}\}+[\boldsymbol{K}]\{\boldsymbol{u}\}=\{\boldsymbol{F}\}, \tag{2}$$

where $[\boldsymbol{M}]$ and $[\boldsymbol{K}]$ are, respectively, the mass and stiffness matrix of the composite plate. In Eq. (2) $\{\boldsymbol{u}\}$ and $\{\ddot{\boldsymbol{u}}\}$ are, respectively, the displacement and acceleration vector, $\{\boldsymbol{F}\}$ is the equivalent of external load, which includes the impact force [9].

The dynamic equation of a rigid ball (impactor) is given by the use of Newton's second law:

$$m_{\mathrm{i}} \cdot \ddot{w}_{\mathrm{i}} = -F_{\mathrm{c}}, \tag{3}$$

where m_{i} is the mass of the ball and F_{c} is the contact force.

It considers the contact between a spherical ball made of an isotropic material and a target laminated composite plate containing N transversely thin layers. The contact is located at the centre of the plate.

This contact force between the impactor and the plate for loading is calculated using a modified nonlinear Hertzian indentation law proposed by Tam and Sun:

$$F = k \cdot \alpha^{3/2}, \tag{4}$$

where α is indentation, k is the Hertzian contact constant.

For a plate α is given by the following equation:

$$\alpha(t) = w_{\mathrm{i}}(t) - w_{\mathrm{s}}(t), \tag{5}$$

$w_{\mathrm{i}}(t)$ and $w_{\mathrm{s}}(t)$ are the displacement of impactor and displacement of the impact point on the mid surface of the plate. The solution of nonlinear equation obtained from equations (1), (2), (3) and (4), is carried out by an iterative procedure using Newton-Raphson method.

In order to solve equations (1) and (2) Newmark algorithm can be adopted. Newmark's integration scheme is employed to solve the dynamic equations of the plate and the impactor for each time step [24].

Modelling of damage in composite materials is a challenging task and modern simulation tools are limited in their capabilities to predict it. More details about that it can be seen in [25].

FEA is used to simulate the structural behaviour of textile composites, multi-layered composite armours and assess the effect of the material selection and fibre architecture. Such computer simulations give better understanding of different geometric and material effects in armour ballistic resistance.

A preliminary comparison of the simulation with experimental results showed clearly that the numerical modelling of the impact process captures the major aspects of the physical phenomena, providing even more information on the behaviour of different target constituents during the ballistic impact [16].

In order to numerically optimize the design of composite structures in impact damage tolerance, it is necessary to model two required phases. In the first step it is the impact phase (in particular the permanent indentation) and in the second step it is the residual strength phase [26].

Engineering models are usually based on basic assumptions regarding the interaction between the projectile and the target. These models are shown to capture the main features observed in experimental results while remaining simple [27].

In [28] the main damage mechanisms (intralaminar and interlaminar failure) were included in the simulations of impact damages. The finite element model explicitly included the microstructure of the laminate material. Each plate was meshed using eight node brick elements with reduced integration (C3D8R in ABAQUS). The mechanical behaviour of each plate was defined using the continuum damage mechanics framework where the elastic constants of the composite material were degraded progressively as a function of the damage variables.

A finite-element model based on a higher-order shear deformation plate theory was developed to investigate the response of Graphite/Epoxy laminated composite nonprismatic folded plates subjected to impact loads. It was demonstrated that the model developed compares very well with reported results from the literature. The model was used to carry out a parametric study on the effects of span-to-thickness ratio, fibre angles, stacking sequence, and crank angle of plates on the response of the folded plates subjected to impact loads [29].

Several elastic and elasto-plastic models for composite laminates under wave-controlled impact and prestresses were developed. The effects of permanent indentation are particularly taken into account in those impact models. The combined theoretical and numerical approach can provide validated models for impact analysis of elastic and elasto-plastic laminates.

4 Multiscale modelling of damage

The damage in composite laminates occurs due to different mechanisms. Some of them (fibre fracture, matrix crack and delamination) are already presented in Fig. 1. In the section below it will be addressed as the multiscale modelling damage in composite materials [30].

To fully understand the underlying phenomena of structure degradation and characterize its effect on material performance, it is essential to link the two scales: the length scale at which these processes take place (the "micro" scale), and the length scale at which we use the material (the structural or "macro" scale). In reality these two scales may be different from each other and may require consideration of in-between scales (also known as "meso" scale). The process of linking material behaviour at these different scales is termed as the "multiscale modelling". In Fig. 4 is described the hierarchy of all possible length scales (structural scales) involved in multiscale materials modelling (damage modelling) [31]. Another issue, particular to multiscale damage modelling, is that the total damage may be due to multiple damage mechanisms, whose length scales might be quite different from one another. Moreover, these length scales may evolve as loading is increased. The microstructural configuration and driving forces for damage initiation and progression determine the length scales of damage. Thus, the length scales of damage and their hierarchy are not fixed, but are subject to evolution as a function of loading [31].

The multiscale model does not reproduce exactly the same response as the single-scale model. It is recommended to investigate other well-known and possibly new methodologies, to carry out more efficient simulations of impact damage in composite laminate structures [32].

To predict damage exactly in a general multidirectional laminate, under a complex loading situation, is rather difficult. The resulting boundary value problem for multidirectional laminates is too complicated to achieve any reasonable elastic solution, and the common strategy has been to use computational tools. Hence, there has been a need to develop a simpler approach, which could be used for predicting the damage behaviour of such laminates [33].

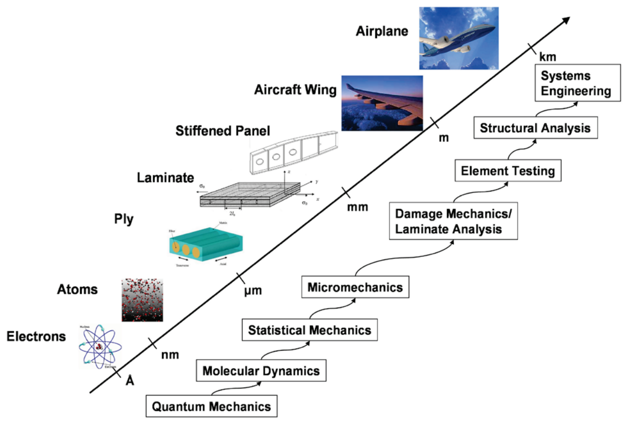


Figure 4 Hierarchy of structural scales in damage modelling of aircraft composite materials

5 Numerical simulation of impact on composite laminated structures

Finite element analysis (mentioned earlier) is a numerical technique used to solve mathematical models of solid structural components, heat transfer and fluid flow. FEA can be used to determine strains, stresses, deflections and natural frequencies of structural components, as well as velocities and pressures in fluid flow analysis.

The node movements can be small for structures but large for fluids. Conventionally CFD adopts the Eulerian approach where the fluid flows through a fixed grid, and structural analysis uses the Lagrangian approach which follows the small nodal displacements on the original geometry. This can cause problems if the structural displacements are very large as can happen in bird-strike or ballistic and hypervelocity impact.

For the numerical simulation of impact on composite structures the two- or three-dimensional models were developed. Each of them has appropriate characteristics, accuracy and accordingly application in certain areas.

Several elastic and elasto-plastic models for composite laminates under wave-controlled impact and prestresses were developed. The effects of permanent indentation are particularly taken into account in those impact models. The combined theoretical and numerical investigations can provide validated models for impact analysis of elastic and elasto-plastic composite laminates. The proposed methodologies are useful for designing model tests and numerical simulation of complex composite structures [34].

A two-dimensional (2D) micromechanics model is used in order to discuss the transverse shear deformation effects that are important in high velocity impact problems. A higher order laminated theory has a capability to capture the strain rate dependent inelastic deformations of composite laminates and then the procedure is implemented by using finite element techniques. The 2D micromechanics model is coupled with the modified higher order laminated theory, based on the finite element procedure, resulting in a multiscale numerical procedure capable of accurately modelling strain rate dependent, inelastic composite laminated plate/shell panels under impact loadings [35].

A three dimensional (3D) incremental micromechanics model describes the strain rate dependent inelastic behaviours of composite materials under complex state of stress. A 3D progressive failure model can be developed to address the failure behaviours of composite materials subjected to high velocity impact, including various failure modes, stress and stiffness degradations during the post failure stages. A multiscale numerical procedure accurately shows the model strain rate dependent inelastic composite structures under high velocity impact, by implementing the 2D/3D incremental micromechanics models and the 3D progressive failure theory into certain commercial transient dynamic finite element code [35].

To reduce development and certification costs for composite structures, efficient computational methods are required. It is essential to predict structural integrity and failure under dynamic loads, such as impact and crash events. Failure in PMC is initiated at the microscopic level, with length scales governed by fibre diameters, whilst the length scale of aircraft structures is in meters, which poses a severe challenge for FEA of composite structures. By using meso-scale models based on continuum damage mechanics (CDM), proposed by Ladevèze and co-workers, it is possible to define materials models for finite element codes at the structural macro level. CDM provides a framework within which in-ply and delamination failures may be modelled. Ply failure models can be developed for unidirectional (UD) fibre with three scalar damage parameters representing in ply microdamage and associated damage evolution equations, which relate the damage parameters to damage energy release rates in the ply [36].

Over the years researchers have conducted numerous endeavours to optimize the impact performance of multi-layered systems. The majority of these efforts are experimental, which can be time consuming and costly. More recently, numerical simulations coupled with experiments have been reported to provide a more cost-effective way of studying the impact performance of laminated systems. Additionally, numerical simulations provide insight into the material response and failure mechanisms that occur in the laminates during the impact process. However it can be concluded that the weakness in simulating impact was the lack of adequate material models and the corresponding material characterization [37].

With sophisticated numerical analysis techniques and increasing computational power, models that can accurately describe the response and failure behaviour of composite materials undergoing large deformations and failure at high strain rates are essential. When simulating dynamic events, the material response is typically described by: an equation of state, internal energy and temperature; a constitutive relationship which describes the strength of the material to resist distortion; and a failure model that can describe the failure of a material under a multiaxial stress state at various strain rates [37].

In a modern design for impact analysis of structures a wide range of software packages are used. Among them the greatest applications are achieved by ABAQUS, LS-DYNA, ANSYS, Pro/ENGINEER.

In Fig. 5 simulation of the spherical ball impact on laminate plate is presented. The figure clearly demonstrates distribution of impact damages on plate. This model was created and analysed in commercial software ABAQUS. The impact may generate unseen material failure in the form of fibre breakage or matrix cracking that radiates through the underlying plies and could significantly weaken the part causing early failure. The software enables analysts and designers to simulate both the impact and the effects of the impact on part strength. These simulations help analysts to identify areas of the laminate that call for additional reinforcement [38].

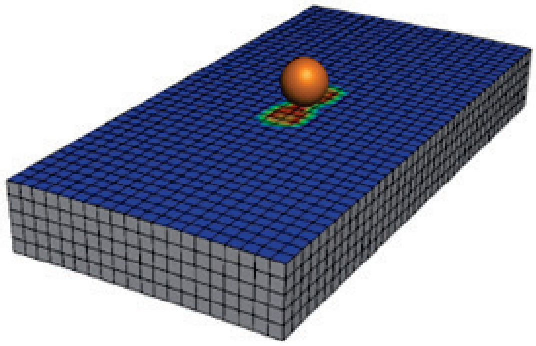


Figure 5 Simulation of the impact damage on composite laminate (ABAQUS) [38]

There are different possibilities to define composite materials in the finite-element program ABAQUS/ Explicit. The application of ABAQUS/Explicit within the impact analysis of composite aircraft structures can be of great importance.

In order to explore the role of textile reinforcement in armour impact performance, 25 000 3D eight-node finite elements with 28 611 nodes were generated using both a newly developed FE-FGM algorithm and an ABAQUS computer code. It is shown that mutual contribution of both the textile architecture and the ceramic facing layer influences the ballistic performance of the specific armour structure [39].

The performance of the interface element approach available in the finite element code ABAQUS for modelling delamination can be used to produce a realistic damage growth at an impact site. These included a combination of interface elements and the virtual crack closure technique (VCCT) [40].

Using the 3D progressing damage theory and the finite element software ABAQUS/Explicit, a user-defined material subroutine (VUMAT) was employed to simulate low velocity impact and predict residual tensile strength accurately. The process of damage initiation and development for composite laminate under impact loading and subsequent tensile loading was analysed [41].

Specific model for analysis of impact damage in laminated composites can be viewed in [42]. Preliminary results for delaminating prediction are presented in this model. The user-defined material subroutine (VUMAT) capability in ABAQUS/Explicit provides the ability to incorporate the most applicable damage and failure model for the impact problem.

LS-DYNA is a general purpose non-linear finite element code for analysing impact problems and dynamic response of structure. The solution methodology is based on explicit time integration. In Fig. 6 delaminations in composite laminate is shown [34].

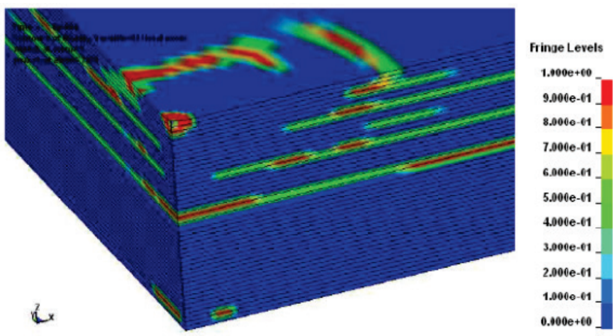


Figure 6 Delaminations in composite laminate (LS-DYNA) [34]

A finite element model using LS-DYNA was developed to simulate the high-velocity impact response of a Kevlar29/Phenolic composite plate. Numerical analyses for finite element model using LS-DYNA to simulate the high-velocity impact response of a Kevlar29/Phenolic composite plate were conducted at impact velocities of 483, 545, and 586 m/s of a steel impactor. The results of finite element analysis were in good agreement with the test results. The present finite element model also successfully simulated the progress in damage from the initial impact to the final penetration of the composite plate [43].

User defined cohesive finite elements are implemented in the non-linear explicit finite element analysis (FEA) code LS-DYNA to model the dynamic delaminating opening. At the same time a user defined deterministic continuous damage unidirectional composite material model is developed on the basis of the Matzenmiller-Lubliner-Taylor model. Initiation and growth of damage are predicted up to saturation and fracture for various pure and coupled damage mechanisms including delamination and matrix cracking, with criteria based on the experimental characterization. Impact induced damage from experimental measurements and numerical predictions are compared for aeronautical samples impacted at different energy levels [44].

In bird strike simulations there are interaction of complex numerical tasks including contact, various damage initiation and evolution models, failure of elements, modelling of loads exerted during the impact. ABAQUS/Explicit has been chosen to perform nonlinear transient numerical analyses in order to use its large library of elements and material models [45].

To improve the damage prediction procedure presented and increase analysis stability, the Coupled Eulerian Lagrangian (CEL) capability of ABAQUS/Explicit was utilized. The main improvement in the bird strike damage prediction procedure has been achieved by replacing the Lagrange bird model with the CEL formulation implemented in ABAQUS. This new modelling technique enables better capturing of fluid-like bird behaviour upon impact in the velocity range at which bird strikes usually occur. The fact that the CEL analysis does not suffer from numerical instabilities caused by extreme material deformation enables simulation of impact conditions in which the Lagrange bird model formulation failed to complete analysis due to excessive distortion of bird finite elements [46].

The damage prediction is based on nonlinear explicit finite element methods in combination with complex structural finite element models, various failure and degradation modes and an Eulerian impactor model. Compared to the previous work, improvements have been made in the field of damage modelling of composite structures by implementation of Puck's failure and degradation model. The ability of presented methodology to simulate the bird strike on a complex aeronautical structure is demonstrated in an impact simulation on a typical large airliner flap structure. The flap structure is able to withstand the impact of the bird mass used for certification requirements without complete penetration or loss of load carrying ability [47].

According to theoretical assumptions, an algorithm for the propagation of delamination in composite materials is developed and implemented in the PAK software package. Also, the failure criteria for laminated composite materials have been analysed [48].

A number of finite element analyses were performed in order to evaluate the effect of membrane initial stresses on the low velocity impact behaviour of composite laminates, and to study how this effect changes for different span-to-thickness ratios of the target. The results show that this ratio actually has a major importance in determining the influence of membrane stresses [49].

Simulation of composite helicopter subfloor beam structures under low velocity crash loading conditions was performed to assess the code and materials models. Structural failure modes were modelled in a quasi-isotropic Carbon/Aramid hybrid laminate. These should result from implementation into FE codes of damage mechanics failure models and improvements in the measurement of dynamic composites properties at large strains [50].

In [51] some aspects of the impact simulation of a soft body in a composite circular plate have been presented. The problem is solved in LS-DYNA with a FE code and some qualitative comparisons were made with performed experiments.

The comparison of simulation and experimental results demonstrated that the model successfully simulated the high velocity impact damage process in CFRP laminates. The model for simple FEA and damage simulation of CFRP laminates was based on the finite element model, which included the cohesive elements and the continuum damage mechanical model [52].

It has been carried out an extensive edge impact and damage tolerance test programme for near edge and on edge impact on glass fibre reinforced plastics (GFRP) laminates. Edge impact leads to more concentrated damage but shows higher damage tolerance in compression after impact as compared to near edge impact [53].

One computational model has been developed for simulation of global and local buckling to predict and estimate compressive strengths and BVID which can be a cause of catastrophic failure. The damage induced strategy was adopted to predict regions of high stress concentration in the contact area leading to a localized damage, and independent models were prepared to address local damaged buckling. These phenomena were modelled and simulated in the commercially available software Pro/ENGINEER (MECHANICA) to study the buckling behaviour of the impacted specimens. Barely visible damage areas are presented in Fig. 7. This study simulates the global and local sublaminate buckling to predict the reduction in compression strength for thin laminates after impact. The simulation gave good correlation with test data, which means that FE simulation models are reliable [54].

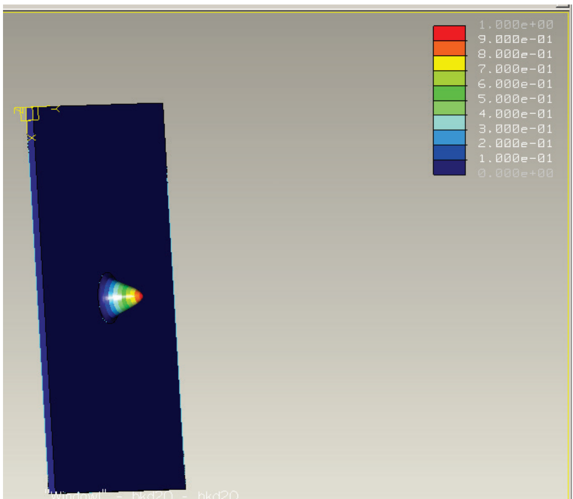


Figure 7 Image of barely visible damage areas [54]

Some software packages, like Impact (Finite Element Program) were designed to be a free alternative to the advanced commercial finite element codes available today. Impact has been written in Java and it is based on an explicit time stepping algorithm. It has several types of elements including shell elements and involves large deformations and high velocities. Simulations are made on a three dimensional model which can be created with a pre-processor. Results are viewed in a post-processor. For more details about that see www.impact.sourceforge.net.

6 Failure criteria of laminated composites

Failure analysis of laminated composites is usually based on the stresses in each lamina [41]. To date various theories based on the normal and shear strengths of lamina have been developed. The stresses acting on the lamina are resolved into the normal and shear stresses in the local axes. Among all the failure criteria for composite materials, Tsai-Wu, Chang-Chang and Hashin are the most widely used.

Failure criteria proposed by Tsai-Wu and Chang-Chang are two-and three-dimensional and associated with lamina failure. On the other hand, Hashin proposed failure criteria for both two-dimensional and three-dimensional cases. Failure criteria associated with a thin lamina do not include the out-of-plane stresses and they are very effective for the application of shell structures, like facesheet of sandwich structures and the shell structures where out-of-plane stresses are negligible. However, for the thick composite laminate, the effect of out-of-plane stresses is important [55].

Chang and Chang proposed a 2D failure criterion for unidirectional composite lamina which is as follows:

For the tensile fibre mode:

$$\text{If } \sigma_{11} > 0 \text{ then } \left(\frac{\sigma_{11}}{X_\mathrm{t}}\right)^2 + \left(\frac{\sigma_{12}}{S_X}\right)^2 = 1. \tag{6}$$

For the compressive fibre mode:

$$\text{If } \sigma_{11} < 0 \text{ then } \sigma_{11} = -X_\mathrm{c}. \tag{7}$$

For the tensile matrix mode:

$$\text{If } \sigma_{22} > 0 \text{ then } \left(\frac{\sigma_{22}}{Y_\mathrm{t}}\right)^2 + \left(\frac{\sigma_{12}}{S_X}\right)^2 = 1. \tag{8}$$

For the compressive matrix mode:

If $\sigma_{22} < 0$ then

$$\left(\frac{\sigma_{22}}{2S_Y}\right)^2 + \left[\left(\frac{Y_\mathrm{c}}{2S_Y}\right)^2 - 1\right]\frac{\sigma_{22}}{Y_\mathrm{c}} + \left(\frac{\sigma_{12}}{S_X}\right)^2 = 1, \tag{9}$$

where σ_{11} is the stress of the lamina in the fibres direction (X), σ_{22} is the stress of the lamina in the transverse direction to the fibres, σ_{12} is the in-plane shear stress of the lamina, X_t is the tensile strength of the fibres, X_c is the compressive strength of the fibres, Y_t is the tensile strength of the fibres in the transverse direction (Y), Y_c is the compressive strength of the fibres in the transverse direction (Y), and S_X are the in-plane shear strengths [55].

The Tsai-Wu failure criteria for tensile and compressive fibre modes are same as those for the Chang-Chang, except the Tsai-Wu failure criteria specify a single equation for the tensile and compressive matrix failure modes ($\sigma_{11} = 0$; $S_X = S_Y = S_{XY}$) [58]:

$$\frac{\sigma_{22}^2}{Y_c Y_t} + \left(\frac{\sigma_{12}}{S_{XY}}\right)^2 + \frac{(Y_c - Y_t)\sigma_{22}}{Y_c Y_t} = 1. \quad (10)$$

Hashin [59] proposed the following 3D (quadratic) failure criteria for unidirectional composites:

For the tensile fibre mode ($\sigma_{11} > 0$):

$$\left(\frac{\sigma_{11}}{X_t}\right)^2 + \frac{1}{S_X^2}\left(\sigma_{12}^2 + \sigma_{13}^2\right) = 1. \quad (11)$$

For the compressive fibre mode ($\sigma_{11} < 0$):

$$\sigma_{11} = -X_c. \quad (12)$$

For the tensile matrix mode:

If $(\sigma_{22} + \sigma_{33}) > 0$ then

$$\frac{1}{Y_t^2}(\sigma_{22} + \sigma_{33})^2 + \frac{1}{S_Y^2}\left(\sigma_{23}^2 - \sigma_{22}\sigma_{33}\right) + \frac{1}{S_X^2}\left(\sigma_{12}^2 + \sigma_{13}^2\right) = 1. \quad (13)$$

For the compressive matrix mode:

If $(\sigma_{22} + \sigma_{33}) < 0$ then

$$\frac{1}{Y_c}\left[\left(\frac{Y_c}{2S_Y}\right)^2 - 1\right](\sigma_{22} + \sigma_{33}) + \frac{1}{4S_Y^2}(\sigma_{22} + \sigma_{33})^2 + \frac{1}{S_Y^2}\left(\sigma_{23}^2 - \sigma_{22}\sigma_{33}\right) + \frac{1}{S_X^2}\left(\sigma_{12}^2 + \sigma_{13}^2\right) = 1 \quad (14)$$

where σ_{13} is the out-of-plane shear stress of the laminate, σ_{23} is the out-of-plane shear stress of the laminate, σ_{33} is the stress of the laminate in the thickness direction, and S_c is the transverse shear strength [2].

None of these failure criteria consider the strain rate effect of the material, which is very important for the PMC, since under impact loading the properties of the polymer matrix composites vary with strain rate [55].

One analysis was found to predict the extent of damage and failure using the standard criteria, which provides opportunity to effectively describe the progressive damaged behaviour of composite panels. The work showed that one of the governing factors in the impact damage resistance is the pseudo-damage [56].

Energy methods also can be applied to studying the failure of composite materials. These energy techniques have demonstrated their ability to indicate the onset of damage, as well as the ability to create load vs. displacement relationships [57].

7 Conclusion

Impact damages in aircraft structures from laminated composites are very complex and the most common are: matrix cracking, fibre failure and delamination. The ability to predict the initiation and growth of damage is crucial for predicting performance and developing reliable and safe designs of composites. By using simulation in modelling the impact damage the test costs of aircraft structures from composite laminates will be reduced.

Due to the wide use of composite materials in different aircraft structures, it is necessary to introduce new approaches for impact damage modelling. Efficient methodologies are modelling composite structures with specialized finite element methods that take into account macromechanical structural properties and by use of numerical methods with complicated analysis codes. In order to validate those methodologies, for further use in the strength structures design, verification of the numerical model is necessary. A comparison of the obtained experimental and numerical results is further made in order to establish if the proposed models are accurate and valid.

Composite damages exist at the microscale level, while impact loads are applied at the structural level. Because of that it is needed to consider multiscale approach for that kind of problem.

The development of suitable constitutive laws for modelling composite laminate failures and material models with finite element codes under impact provides significant assistance in the design and exploitation phases of specified structures. The most known failure criteria (2D, 3D) for composite materials are: Tsai-Wu, Chang-Chang and Hashin. They are used in order to predict the level or degree of damage, fracture and failure of composite structures.

The development of the computational models and simulations are needed in studying the onset and growth of impact damages. In numerical simulation of impact on composite structures two- or three-dimensional models exist. For impact damage analysis of composite laminates commercial software ABAQUS and LS-DYNA is most frequently used. Pro/ENGINEER, ANSYS and some non-commercial software is also suitable for the same purpose. By using it at some circumstances (geometry, boundary conditions, mesh, load etc.) distribution of damage, stress, strain, deformations can be analysed and presented.

Essentially in considering impact damages modelling in laminated composites of aeronautical structures is to investigate the dynamic response of composite laminates under impact and predict the damage initiation/growth in such structures. For that analysis numerical modelling and simulations provide important and valuable results.

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