# Impact damage modeling in laminated composite aircraft structures

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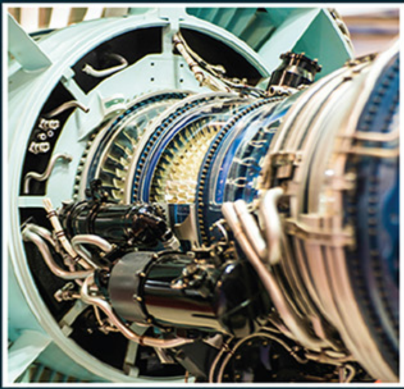

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# Sustainable Composites for Aerospace Applications

*Edited by*

*Mohammad Jawaid*

*Mohamed Thariq*

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# Preface

Aerospace industries are looking for alternative materials for the development of sustainable and biodegradable products to replace carbon/Kevlar fibers in aerospace internal components to enhance the fuel efficiency of aircraft. A major problem for aircraft component manufacturers is the disposal of aerospace components after the service life of aircraft finishes. Research centers and industrial organizations have started to develop interior components for aircraft using natural fibers and agricultural biomass. Agricultural biomass such as natural fiber is abundantly available worldwide, but is not being properly utilized due to its limitation in processing, properties, and applications. Biomass such as rice husk, wheat straw, bagasse, pineapple leaves, oil palm, date palm, kenaf, jute, flax, hemp, etc., are potential materials in the development of a new generation of composite materials with enhanced multi-functionality in a broad range of application fields. By careful reinforcement of biomass fillers in polymer, researchers can develop innovative products for aerospace components with better mechanical and physical properties and novel behavior.

The central aim of this book is to present the development, characterization, and applications of composite materials developed from natural fiber/biomass as fillers and reinforcements to enhance material performance for utilization in aerospace components. This book has been written by leading experts in the field of composite materials, and covers composite materials developed from different natural fibers and their hybridization with synthetic fibers. The book chapters will provide cutting-edge, up-to-date research on the use of composite materials in aerospace components from eminent researchers worldwide.

This book covers topics such as materials selection for aerospace components, the role of advanced polymer materials in aerospace, eco-friendly polymer composites for interior parts of aerospace applications, manufacturing techniques of composites for aerospace applications, composite materials overview and testing for aerospace components, sustainable biocomposites for aircraft components, impact damage modeling in laminated composite aircraft structures, natural lightweight hybrid composites for aircraft structural applications, composite patch repair using natural fiber for aerospace applications, sustainable composites for aerospace applications, high performance machining of carbon fiber-reinforced plastics, ultrasonic inspection of natural fiber-reinforced composites, the potential of natural fiber/biomass filler-reinforced polymer composites, the potential of natural composite materials in structural design, the low velocity impact properties of natural fiber-reinforced composite materials for aeronautical applications, and the potential of natural/synthetic hybrid composites for aerospace applications.

The book will fill the gap in the published literature (published books on composites do not pay much attention to natural fiber-based composites in aerospace components), and provide reference material for future research in natural fiber and hybrid composite materials, which is much in demand due to sustainable, recyclable, and eco-friendly composites needed for different applications. This book is written by renowned experts from India, Malaysia, Italy, Serbia, Japan, and the USA. We are very grateful to all the authors who contributed to this book, and thus have made our thoughtful idea or dream into a reality. We are also grateful to the Elsevier, UK, supporting team, especially Andrae Akeh, Narmatha Mohan, and Debasish Ghosh for helping us to finalize this book.

**Mohammad Jawaid and Mohamed Thariq**
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# Impact damage modeling in laminated composite aircraft structures

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## 7.1 Introduction

Studying the effects of impact loads, and the resulting damage in an aircraft composite structure, is extremely difficult and complex. This comes from the very nature of this process, which is a dynamic event, and the problem of characterizing the resultant damage. Modeling of impact damage is essentially important in the design of laminate composite structures for various technical structures. Generally, there are three separate approaches to examination of the effects of impact on structures.

The first is an empirical approach, in which experiments are performed and the resulting data are collected, connected, and further analyzed.

The second approach is the foundation and development of engineering models with different complexity that approximate impact events with a certain accuracy.

The essence of the third approach is the discretization structure into smaller elements, and application of fundamental physics laws for each structure element. This approach includes the analysis by finite element method, finite difference method, and finite volume method.

Each of these three approaches to study the impact has some advantages, and also inevitable disadvantages. The empirical approach is suitable for solving a specific problem, but can usually be interpolated from outside the parameters of testing. The engineering models usually focus on particular aspects of the problem, by reducing the equation to one- and two-dimensional algebraic or differential equations, assuming certain simplifications. Numerical analysis has proven to be able to provide accurate solutions to very complex problems, but it is necessary to spend a lot of time for the required calculations. In many cases, the best answer (optimum) is a combination of all three approaches [1–4].

Until today, a lot of models (two- and three-dimensional) have been developed for the characterization of impact damage effects in structures. For years, they have been the subject of numerous engineering studies and tests. These models are described theoretically, and functional characteristics and equations are listed. However, they are mainly the results of approximations, and apply in specific cases,

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that is, they have certain limitations and therefore the field of application is limited. From the literature, probably the most famous and relevant are impact models according to Abrate, which are also very often used.

Numerical simulations have great applications in engineering analyses of impact on laminated composite aircraft structures. Numerical values and graphical distributions obtained by specified calculations for the damage parameters are extremely important to assess the integrity of those structures. For that operation, highly sophisticated software packages are available and very usable in engineering domain.

## 7.2 Analysis of impact damage in aircraft structures from composite laminates

### 7.2.1 Impact loads

Generally, impact is a dynamic event which is characterized by a high load in a very short time period. The same is categorized into low and high velocity, but there is not a clear and definite transition between those definitions. Usually, limited velocity is in the range of 10 up to 100 m/s.

However, a pure difference is in the form of damage developed after each impact category. 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 by fiber breakage. During low velocity impacts, damage is initiated by matrix cracks, which create delaminations at interfaces between plies with different orientations [5].

In structural composites, impact load can cause damage that does not result in instant failure. It may later lead to failure under the influence of workloads [5].

As is known, certain low-velocity impact energies can be absorbed through the bending of the composite, allowing the energy to be transferred to a location away from the point of impact. Since the time of contact between the projectile and the composite material is considerably less at higher velocities, the impact load induces localized deformations without a general response. These two impact types have been investigated by Cantwell and Morton [5]. They have demonstrated this concept by observing delamination in beams of various lengths under the impact of low and high velocity. It was found that the lesion size decreases when the length of the beam increases at low velocity. At high velocities, however, the level of damage was independent of the beam length.

Composites are sensitive enough to impact load, as they absorb impact energy mainly through fracture mechanics, rather than elasticity and plasticity [5]. How the different loading conditions are applied to the composite element can damage the inner structure by mechanisms such as cracking, delamination, fiber breakage, and local buckling [6].

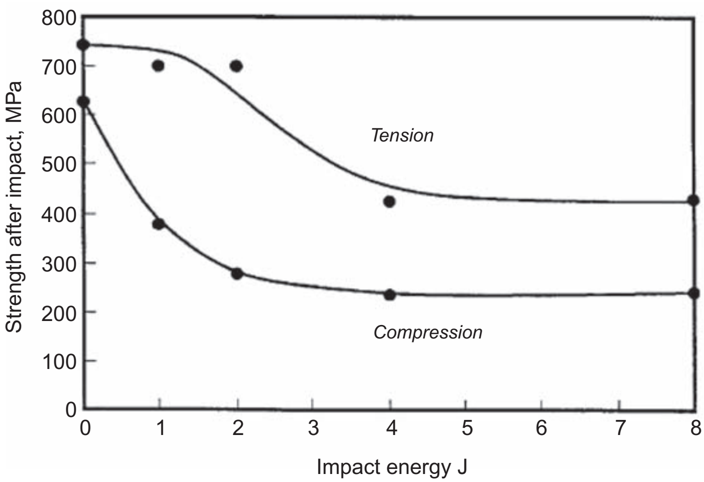


**Figure 7.1** Tensile and compression strength degradation due to impact damage.

The primary matrix failure mode is characterized by cracks which move parallel to the fibers in the layers, and they are not aligned with the direction of the main tensile loads.

Secondary matrix failures cause cracks that spread to neighboring layers; therefore, initiating the delamination in a structure.

A typical variation of strength degradation as a function of impact energy is shown in Fig. 7.1, for both tensile and compression loading. This figure shows that compression loading causes much more reduction in strength, as compared to tensile loading.

At low impact energy levels, the reduction in tensile strength is not significant, but reduction in compression strength is quite large. This is due to the fact that impact damage at low energy levels initiates primary delaminations, which cause strength degradation due to buckling (compression loading) [7].

In the case of higher impact energy levels, damage causes fiber breakage, which results in significant tensile strength reduction [8].

### 7.2.2 The mechanism of impact damage accumulations

Composite laminates are prone to impact damage for several reasons. Because of this, there are different mechanisms of damage accumulation in structures from those types of materials.

First, there is usually no reinforcement in the direction of the composite laminate thickness. Thus, outside the plane the behavior of the laminate is mainly dependent on the characteristics of the matrix. Therefore, low resistance composite laminates, with thin resin rich interfaces between adjacent layers, lead to the mechanism of delamination under impact loading [5].

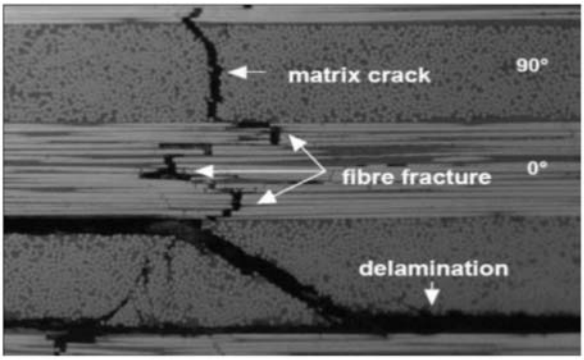


**Figure 7.2** Types of impact damage in the fiber-reinforced laminates [10].

In addition, due to the brittle properties of the composite, and lack of a mechanism of plastic strain, carbon-reinforced composites are more susceptible to impact damage in comparison with metals. It should be noted that metals can have plastic deformation at high load/stress levels, but they still have the ability to retain their integrity.

Moreover, the laminated structure is used to reduce the anisotropy of the layers in different directions, and that makes composites sensitive (vulnerable) to impact damage [9].

Failures in composites caused by impact typically occur in the form of a single or a combination of the following modes (Fig. 7.2):

1. Delamination
2. Matrix cracking
3. Fiber fracture [10].

Several parameters affect the quantity and quality of impact damage in composite laminates. Obviously, impactor initial kinetic energy plays an extremely important role, but there are many other parameters that must be taken into account. The large mass of the impactor with a low initial velocity can have exactly the same kinetic energy as well as less mass with higher initial velocity. However, the amounts and the contours of such damage are quite different. The damage can be localized in a small area of attack in one case, but it can also affect the overall response of the structure in another [9].

The material properties are considered to have a large effect on impact structure response by means of overall structure rigidity and stiffness of contact between the projectile and target. The target is not only under the influence of material properties, but also the thickness of the laminate, the size of the structure, and boundary conditions.

Dynamics of impact and the resulting damage are also influenced by the characteristics of the so-called impactor. These include the following impactor properties: density, elastic properties, shape, initial velocity, and incident angle [10].

The effects of overloading and environmental conditions are also relevant parameters that must be taken into account. They determine the final impact response of selected tested composite structures [9].

When the structure is exposed to high amplitude or repeated loads, the strength and integrity of the same may be affected. Then, there is a reduction of elasticity, which may possibly lead to the structure failure over time. In addition, by heterogeneous materials, there are several damage mechanisms, leading to the failure of the same [6].

Composites can be more sensitive to the load, such as an impact, so that they absorb the energy mainly through fracture mechanics, rather than elasticity and plasticity [5].

Because there are different loading conditions applied to the composite element, the internal composition of the same can be damaged with mechanisms such as: matrix cracking, delamination, fiber breakage, and local buckling. Then, damage is accumulated due to delaminations and material properties are changed, until finally the structure terminates in the form of fiber fracture [5].

In a laminated composite at locations where failure is initiated, stiffness is reduced and the surrounding material must carry the service loads. Because the fibers are the supported material in the composite, when they fail the structure is consequently endangered. Failures occur in stages, where one case of damage can lead to a series of failures in the material, as shown in the stress-deformation curve, shown in Fig. 7.3.

Failures within layers are referred to as intralaminar, while those between the layers are called interlaminar. Each point in Fig. 7.3 displays a basic failure within a singular layer of the composite laminate panel.

As a result of the layer failures, the final state is the total failure of the composite laminate. This figure implies that the failure in the layer is almost sudden. Nevertheless, in reality, failure is progressive, since the present mechanisms, such as matrix cracking, occur gradually, rather than all at once [5].

Structural failures in aircraft composite materials can be initiated and then guided by the various circumstances caused by load processes. They can occur as a result of errors in the manufacturing process of these materials. In some cases, the failure occurs due to a gradual load, such as fatigue, stress, low amplitude, etc.

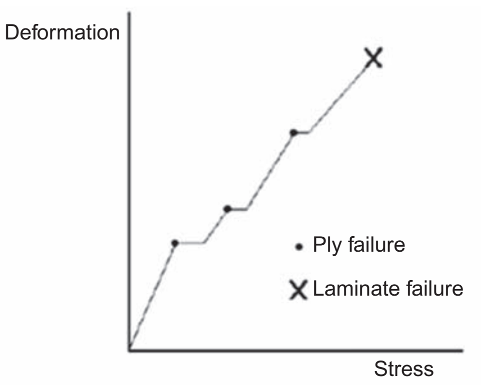


**Figure 7.3** The failure process in composite laminate [9].

Failures can be immediate and catastrophic due to high energy loads, such as impact. In many cases, the overall strength is not compromised, as long as a significant number of carrier fibers are functional [11].

The damage in composite laminates determines the life of the primary carrying structure. The extent of damage consists of damage in the inside layer of the lamina, such as fiber breakage, fiber separation, or matrix cracking. Also, delaminations between the layers are created. The formed defect may or not affect already existing structure damage [12–15].

Impact response phenomenon of composite laminates has been widely theoretically discussed in the expert literature. Moreover, great numbers of experiments have been carried out with the same aims.

The impact of the manufacturing process on the mechanical behavior of materials is undoubtedly an important aspect in the test studies of polymer composites. Many of these materials require treatment with high temperatures, causing residual stresses in the final structures. These stresses are caused by inadequate thermal expansion and chemical constituent's shrinkage polymers. Residual stresses are caused by the thermal mismatch between the laminates and the tools on which the polymers are processed [16–18].

However, analytical and numerical formulations were carried out with consideration for the interaction between materials/contact, forecasting the amount of induced damage and the assessment of residual structure properties. In particular, the efforts of many researchers focused on the modeling of impact history. Because of that, quite closed free solution forms, easy to use and effective, but limited to specific cases of impact, were often used [19].

Transverse cracking, also known as matrix cracking in multidirectional laminate, is shown in Fig. 7.4 (micrographic display). It is due to the stress generated by mechanical or thermal loads. This form of damage also endangers the structures integrity.

Residual stresses arise due to differences in coefficients of thermal expansion between adjacent layers and resin shrinkage. System fiber/epoxy at high temperature is very sensitive to micro cracking. In this special case, only matrix cracking develops in a weaker lamina of the multidirectional laminate.

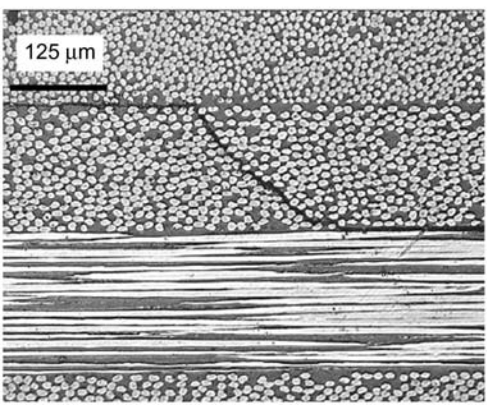


**Figure 7.4** Micrographic matrix cracking in multidirectional laminate [20].

Failure of weaker lamina will be limited by the nearby stronger laminates, which prevent the cracking extending across the whole laminate. These limits are referred as a matrix cracks, because they have been observed in the matrix. When these cracks reach the upper limit for the density (number of cracks per unit length), the state is designated as the characteristic damage state (CDS) [20].

Fiber fracture, as is shown in Fig. 7.5, is another type of damage which occurs during the operation time of the multidirectional composite laminate. This can happen when the stress in the fiber exceeds the fiber's ultimate strength. The characteristic material contours can clearly be seen [20].

Delamination, as is shown in Fig. 7.6, is one of the major defects in composite laminates, which can occur during the service life of the composite in a multidirectional laminate structure. This type of damage affects the strength and the lifetime

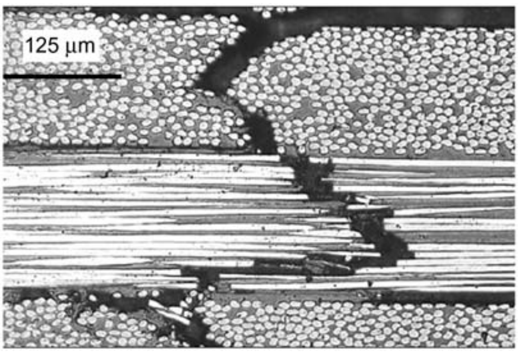


**Figure 7.5** Micrographic fiber fracture in multidirectional laminate [20].

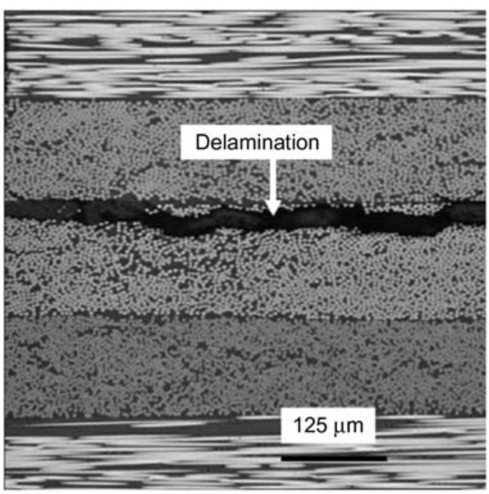


**Figure 7.6** Micrographic delamination in multidirectional laminate [20].

of composite components and structures. Fiber pulling usually occurs after fiber breakage and fiber separation from the matrix. It is also discussed in a number of expert studies [20].

The stress causing the first damage appearance is designated as the first-ply failure stress (FPF). First-ply failure observed stress will be much smaller than the ultimate laminate failure (ULF), and is often used in exploitation of the laminate [5].

Numerous theoretical and experimental studies were carried out on the development of damage during tensile testing of composite laminates and their influence on the time independent properties [20].

### 7.2.3 The effects of impact damage

Impact damage induces significant reductions in stability and strength of laminated composite structures. Low velocity impact damage from bird strike, runway debris, or dropped tools during fabrication or maintenance operations, may cause damage below the barely visible impact damage (BVID) limit. These types of damage could lead to catastrophic failure, and that is important to be taken into consideration in the design process of 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 [21].

The complex problem of determining the effects of impact damage may be divided into two domains (Fig. 7.7):

1. Impact damage resistance, associated with the response and damage caused by impact;
2. Impact damage tolerance, linked with the reduced strength and stability of the structure due to the damage [21].

It is important to develop reliable methods for assessing the effects of damage and the parameters of residual strength after impact, that is, to determine the tolerance of impact. Studies in this area are mainly related to impact damage tolerance and residual strength prediction of composite structures containing certain impact damage size [22].

Experimental testing is an efficient way to determine the effects of impact damage. Due to the fact that testing is expensive and time-consuming, there is a need to develop calculation methods that are rapid and reasonably accurate that provide the opportunity to perform parametric studies [23].

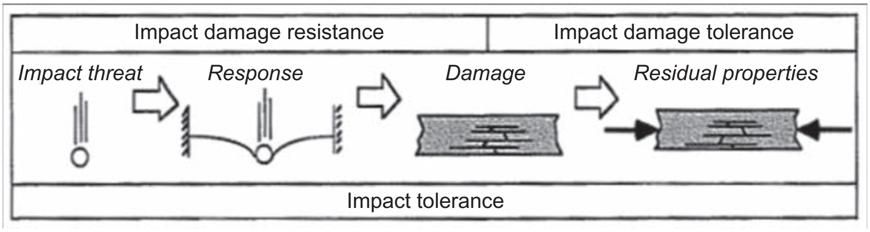


**Figure 7.7** Impact damage resistance and tolerance [21].

The reduction of compressive strength due to impact is more significant than the reduction in tensile strength and other strengths. Therefore, the work on residual strength is focussed on delamination buckling which reduces the flexural properties of the damaged laminate, and may cause significant reduction in compressive strength [21].

The damage tolerance of composite structures is intimately linked to the morphology and extent of flaws or damage. Impacts are a commonly occurring source of threat to composites, which can produce a “key” damage state, which inherently controls the subsequent durability and damage tolerance of the affected structure. Transverse impact to composites is of particular concern, due to the possibility of exciting damage modes that are difficult, or even impossible, to visually detect from the exterior (impact-side) surface [24].

Some examples of such damage are the following: delamination, backside-only fiber failure, debonding of internal substructure (e.g., stringers and stiffeners, doublers, joints), and crushing and separation of sandwich panel core. Damage appearing is highly dependent upon the nature of the threat and conditions associated with the impact event [25].

Fiber composite structures are more brittle than tough. Unlike the tough metals for aircraft (such as aluminum), which are subjected to permanent deformation on impact, composites show little (or no) impact damage on the surface, until the occurrence of failure.

Barely visible impact damage has the option to expand, and at the same time to weaken the structure. As a result of such circumstances, impact damage to the composite aircraft can remain undetected for a longer period of time, until the reporting of a catastrophic failure (such as a separation of the main structures) [26].

Vulnerability is one of the most important exploitable characteristics of modern aircrafts. Research has shown that with respect to the survivability, composite laminated materials have the best behavior and results compared to other aviation materials. That is the reason for their widespread use in high demand aeronautical engineering [14].

By appropriate analysis of the dynamic behavior of damaged structures, a crucial fact is the acceptable level of damage and probable chances for the aircraft to survive can be calculated. The aircraft’s ability to survive after being exposed to quite severe damage on vital and load-carrying structure parts is imperative for combat aircrafts, moreover, civil aircraft are not an exception in this engineering aspect [15].

Helicopters are very specific aircraft, because they are highly vulnerable and greatly exposed to threats due to their vertical take-off and landing, low speed, low flight altitude, etc. They are characterized by a high frequency occurrence of impact loads, and damage according to them. The typical ballistic damages to the helicopter windshield are presented in Fig. 7.8. The characteristic damage after ballistic impact on the helicopter main rotor blade are depicted in Fig. 7.9 [7,13].

More details about extensive analysis of examined helicopter structures are given in Ref. [13].

**Figure 7.8** Ballistic damage of helicopter's windshield [13].

**Figure 7.9** Ballistic damage of the main rotor blade [13].

## 7.3 Finite element modeling of impact on laminates

### 7.3.1 Finite element method (FEM)

The finite element method (FEM) is a powerful numerical method for simulation, analysis, and technical calculations, such as differential equations, integration, etc. The finite element method has become one of the dominant tools for designs by engineers at the present time. This is partly due to the increased performance of desktop computers, workstations, and so-called "mainframe" computers. In the FEM, structures with complex boundaries and characteristics can be discretized into a series of small finite elements. Within each element, approximations can be made in parameter variations, such as displacements, strains, and stresses (by using differential equations of motion). For a general problem, when the boundary conditions are satisfied, a unique solution can be obtained by solving the variable elements. The FEM is suitable for computer use, because the iterative process of solving can be programmed for automatic execution (numerical solution) [27].

The FEM solution process consists of the following procedures:

1. Divide structure into elements with nodes (discretization/meshing).
2. Connect the elements at the nodes to form an approximate system of equations for the whole structure (element matrices).
3. Solve the system of equations involving unknown variables at the nodes.
4. Calculate desired variables (displacements, strains, stresses) at selected elements.

The two main techniques for solving by the FEM are:

- Implicit methods
- Explicit methods [28].

#### 7.3.1.1 The implicit method

In the implicit method, general equilibrium is achieved by iteration at first, followed by evaluation of local element variables. If the balance is not achieved, this method becomes expensive for calculation, since the matrix coefficients should recalculate with different time steps. The implicit method is unconditionally stable, allowing the use of larger increment time steps. It is suitable for problems that tend to be highly linear, static, and quasi-static. Commercially available software for the application of implicit methods are: ABAQUS, ANSYS, and NASTRAN [29].

#### 7.3.1.2 The explicit method

The explicit method allows solving problems element by element. Compared with the implicit method, it does not require the general matrix, since the velocity and displacement nodes can be counted directly, using the central difference integration scheme. However, the time step is limited by the size of the numerical stability. Accordingly, this method is considered as conditionally stable, because if the time step is too large, there will be a significant numerical error. In this method, there is no requirement for balance, so it is suitable for highly dynamic analysis, such as high velocity impact.

Explicit finite element codes are now used extensively in aerospace, nuclear, and rail technology. In this way, bird strike, safety of transport bottles, train crash, etc., can be simulated. The best-known commercial software analyses for the explicit method are: PAM-CRASH, LS-DYNA, and RADIOSS [30].

### 7.3.2 Impact on laminate plate

In order to fully analyze impact on laminate composite plate, the dynamic response of such a structure must be considered. Finite element analysis (FEA) involving large deformations require the solution of transient dynamic problems in a short time period. Explicit and implicit solution techniques, or a combination of both, have been used as the basis for FE crash codes.

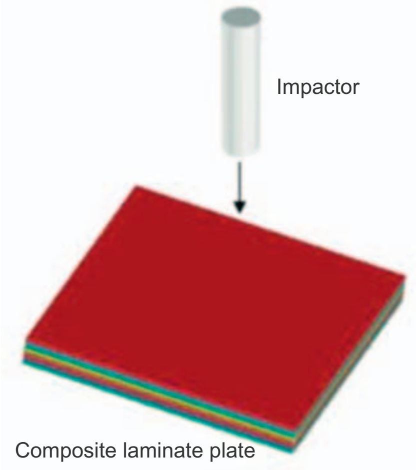


**Figure 7.10** Impact on laminate plate.

Fig. 7.10 describes the impact of the rigid body (for impactor: $m$—mass, $r$—radius, and $v$—velocity) on the laminate composite plate [21]. Introducing the conventional stress and moment resultants ($Nx$, $Ny$, $Nxy$, $Mx$, $My$, $Mxy$, $Qx$, $Qy$), the laminate constitutive equation is as follows:

$$\begin{Bmatrix} N \\ M \\ Q \end{Bmatrix} = \begin{bmatrix} A & B & 0 \\ B^T & D & 0 \\ 0 & 0 & F \end{bmatrix} \begin{Bmatrix} \varepsilon^0 \\ \kappa \\ \gamma \end{Bmatrix} \tag{7.1}$$

where $[A]$ is the extensional stiffness matrix, $[B]$ is the bending-extensional coupling matrix, $[D]$ is the bending stiffness matrix, and $[F]$ is the transverse shear stiffness [28].

The dynamic equation for a plate is in general given as:

$$[M]\{\ddot{u}\} + [K]\{u\} = \{F\} \tag{7.2}$$

where $[M]$ and $[K]$ are, respectively, the mass matrix and stiffness matrix of the composite plate. In Eq. (7.2) $\{u\}$ and $\{\ddot{u}\}$ are, respectively, the displacement and acceleration vector, $\{F\}$ is the equivalent of external load, which includes the impact force [21].

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

$$m_i \ddot{w}_i = -F_c \tag{7.3}$$

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 center 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:

$$F = k\alpha^{3/2} \tag{7.4}$$

where $\alpha$ is indentation, and $k$ is the Hertzian contact constant [5].

For a plate $\alpha$ is given by the following equation:

$$\alpha(t) = w_i(t) - w_s(t) \tag{7.5}$$

$w_i(t)$ and $w_s(t)$ 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 Eqs. (7.1), (7.2), (7.3) and (7.4), is carried out by an iterative procedure using Newton−Raphson method [28].

In order to solve Eqs. (7.1) and (7.2), the Newmark algorithm can be adopted. Newmark's integration scheme is implemented to solve the dynamic equations of the plate and the impactor for each time step [21].

### 7.3.3 Impact models according to abrate

To study the dynamics of impact, a complete model fully takes into consideration the dynamic behavior of projectiles, namely structures and the contact between them. In many cases, the structure is modeled using a simplified beam, plate, or shell. However, in some cases a three-dimensional elasticity model is applied [5].

One of the most detailed reviews of impact mechanics and dynamics of complex structures was made by Abrate [5]. Depending on how the structure is modeled dynamically, response to impact on the composite structures can be classified as: spring-mass models, energy balance models, complete models, and models of impact in an infinite plate.

Spring-mass models are relative simple and can provide accurate analysis for a kind of impact during tests on samples of small size. There are models with two degrees of freedom (TDOF) and one degree of freedom (single degree of freedom, SDOF) for the impact in composite panels and beams [27]. This is shown in Fig. 7.11 (A) and (B).

The TDOF model consists of a linear spring stiffness of the structure, other nonlinear spring stiffness of the membrane ($K_m$), nonlinear contact rigidity (K), the effective mass of the structure ($M_2$), and the mass of the projectile ($M_1$). For the SDOF model, the overall deformation of the structure is ignored. Local deformation is taken into account using nonlinear contact stiffness ($K$).

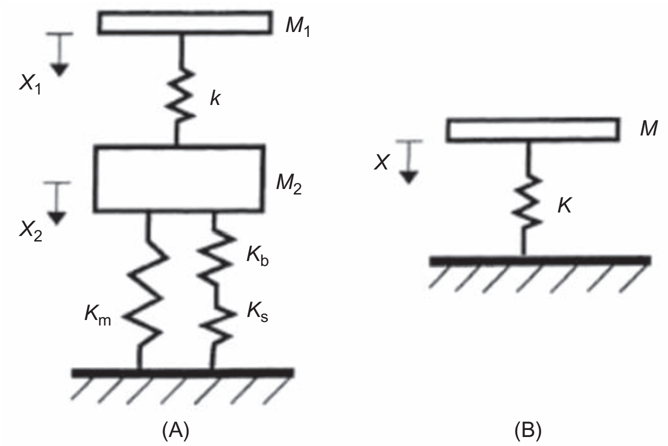


**Figure 7.11** The spring-mass models [27].

## 7.4 Multiscale modeling of impact damage on laminated composites

### 7.4.1 General

The damage in composite laminates occurs due to quite different mechanisms. Some of them (failure fibers, matrix cracking, delamination) were presented earlier. But the specific so-called "multiscale" modeling of damage in composite materials is especially important.

For a full understanding of the degradation structure phenomenon and characterization of its effects on material performance, it is essential to connect two scales: the first scale on which these processes occur ("microscale"), and the second scale for the materials used (structural level or "macroscale") [31].

In reality, these two scales can be different from each other and may require consideration and interscale ("mesoscale"). The process of linking the behavior of materials on two different scales is referred as a "multiscale" modeling. "Multiscale" modeling does not give exactly the same answer as the "single scale" model [31].

Prediction of damage in general multidirectional laminate, under complex loads, is rather difficult, but the problem boundary values for multidirectional laminate is too complicated, and to achieve a reasonable elastic solution the common strategy was to use computer tools. Hence, it was necessary to develop a simpler approach, which could be used to predict damage in such laminates, and also that is easily integrated into a "multiscale" model analysis [31].

In order to apply the more developed models of failure of composites in the analysis of composite structures, it is necessary to implement and then validate the "multiscale" modeling of composite material systems in suitable FE codes.

In the previous period, explicit FE methods have proven to be successful for the analysis of dynamic, highly nonlinear problems, especially where contact in impact plays an important role [32].

In Fig. 7.12 the summary hierarchy of all possible scales (structural scales) involved in the so-called "multiscale" modeling damage in aircraft composite laminates is shown [22].

A more suitable approach for multiscale modeling of composite materials would rather be the synergistic damage mechanics (SDM), which is proposed by Talreja. Conceptually, SDM combines continuum damage mechanics (CDM) and micro damage mechanics (MDM) to characterize response function in terms of fields variables (stress, strain, etc.) and internal variables representing the certain field of evolving damage entities. The multiscale SDM approach considers the substructure as a potentially critical region, which must be fully identified and analyzed.

This substructure is first analyzed in detail to determine the loading on its boundary. In the next step, damage induced from this loading is characterized using the CDM in terms of internal variables.

To characterize the microstructure using MDM, it is necessary to make an appropriate zoom in this region and perform micromechanic calculations over a representative unit cell to obtain constraint like certain structure parameters.

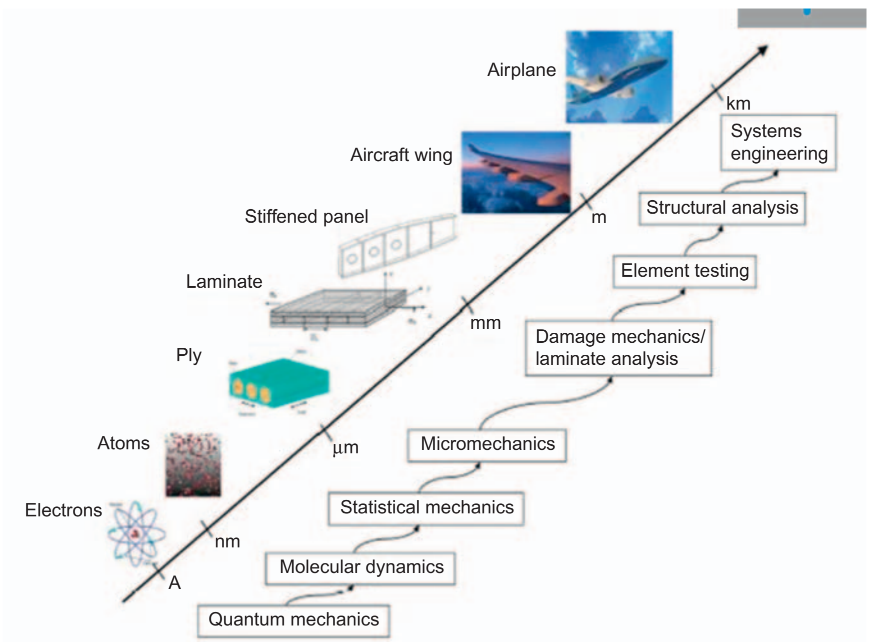


**Figure 7.12** Structural scale hierarchy (multiscale) for the modeling of damages in aircraft composite materials [22].

On the micromechanical scale, the representative volume element is introduced to model the initiation and growth of microscopic damage and their effects on material behavior.

Thus, unlike in the hierarchical approach, in this case the guideline is moved up to the lowest length scale of interest. This ensures accurate representation of the processes at the lowest length scales, and also allows it to connect to the macroscale in an, above all, easier way.

### 7.4.2 Explicit multiscale modeling of impact damage on laminated composites

The complexities encountered in the damage modeling of composite structures arise from the microstructural level heterogeneities of the composites. Therefore, multiscale approaches are becoming increasingly used to improve the failure prediction methods for heterogeneous materials. For multiscale modeling of impact damage in laminated composites, the explicit approach can be an optimal solution.

Multiscale impact damage prediction methodology for laminated composite structures is based on the high fidelity generalized method of cells (HFGMC) micromechanical model, and the mixed mode continuum damage mechanics (MMCDM) theory and damage formulation.

The development and verification of a multiscale methodology applicable for modeling of impact damage in laminated composite structures employs the HFGMC micromechanical model. This model predicts the local stress/strain fields within the unidirectional composite material. The micromechanical model also has been coupled with Abaqus/Explicit, where the structural scale computations have been performed [33].

The MMCDM is used to model damage within the composite microstructure. The micromechanical damage model parameters have been determined by correlation with available experimental data for the nonlinear behavior of the homogenized composite material at in-plane shear and transverse compressive loading.

The obtained results demonstrate the ability of the micromechanical approach to model accurately the failure modes of the composite materials, as well as the nonlinear behavior of the composite plies at the in-plane shear and transverse compressive loading [33].

The numerical approach is intended for application within explicit Finite Element Analyses, and has been used for modeling the high-velocity impact damage in laminated composite structures. By applying the structural scale applications and the multiscale framework method, the micromechanical model calculates the local stress and strain fields within the unidirectional composite material, whereas the structural-scale computations have been performed employing Abaqus/Explicit. The MMCDM theory has been utilized to model the damage and failure modes of the composite material at the micromechanical level [33].

The HFGMC and MMCDM models enable modeling of the microdamage nonlinearities at in-plane shear and transverse compressive loading of certain composite plies. The micromechanical damage modeling approach has been employed at high-velocity soft-body impact on CFRP and GFRP composite plates.

Results of the multiscale damage model have been validated using available experimental data and by comparison with the numerical results, which have been obtained using the commonly used ply-level failure criteria and damage models [33].

# 7.5 Numerical simulation of impact on composite laminated structures

## 7.5.1 Numerical approach

As mentioned in Section 7.2, FEA is a numerical technique used to solve mathematical models of solid structural components, heat transfer, and fluid flow. The 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.

For the dynamic impact on fixed structure, the next energy equation is relevant, it considers energy before and after an impact event:

$$\frac{1}{2}(M_{\text{initial}})\,(V_{\text{initial}})^2 = \frac{1}{2}(M_{\text{final}})\,(V_{\text{final}})^2 + E_{\text{absorb}} \tag{7.6}$$

$M_{\text{initial}}$—initial mass (kg); $V_{\text{initial}}$—initial velocity (m/s); $M_{\text{final}}$—mass after impact (kg); $V_{\text{final}}$—velocity after impact (m/s); $E_{\text{apsorb}}$—total absorbed energy (J).

The basic partial differential equation for a dynamic system is written in general form as:

$$M\ddot{r} + C\dot{r} + Kr = R(t) \tag{7.7}$$

In the previous equation labels are as follows:

$M$—mass matrix; $C$—damping matrix; $K$—stiffness matrix; $R$—force/changeable; $\dot{r}$—velocity; $\ddot{r}$—acceleration; $r$—displacement.

The node movements can be small for structures, but large for fluids. Conventionally, computer fluid dynamics (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 cases of 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.

To reduce development and certification costs for composite structures, efficient computational methods are unavoidably 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 fiber diameters, until the length scale of aircraft structures is in meters, which poses a severe challenge for FEA of composite structures. By using mesoscale 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. Continuum damage mechanics provides a framework within which in-ply and delamination failures may be modeled. Ply failure models can be developed for unidirectional (UD) fiber with three scalar damage parameters representing ply microdamage and associated damage evolution equations, which relate the damage parameters to damage energy release rates in the ply [34].

Over the years, researchers have conducted numerous endeavors to optimize the impact performance of multilayered 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 [35].

With sophisticated numerical analysis techniques and increasing computational power, models that can accurately describe the response and failure behavior 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 [35].

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, and PTC Creo (Pro/ENGINEER) [36].

### 7.5.2 Damage modeling with the finite elements

Damage modeling always has been a challenge for researchers of impact effects on structures. So far, significant studies using progressive models to explain the failure of composite laminate, subjected to loading conditions in the plane, were performed. Usually, these models are connected the finite element method (FEM), in order to perform stress analysis in composite laminates under quasi-static loading [5].

Analytical methods are rarely used to analyze stresses, because the failure mechanisms of composites commonly are so complicated, and this method is therefore impractical. Moreover, the progressive failure analysis of laminated composites involves introduction of certain three-dimensional stresses, and effects along the free edges and the fronts of the multidirectional delamination. These problems require a large amount of computation phase. Therefore, the usual research projects are focussed on the use of the finite element method for modeling the development of damage in composites [37].

The two-dimensional (2D) finite element method, based on the Classical Laminate Plate Theory (CLPT), has been used by Sandhu for failure of composite laminates. Experiments were first performed to obtain stress–strain curves of uniplanar composites under load. These curves were later presented as part of a continuous long cubic functions interpolation for finite element analysis. Failure criterion of the total strain energy was developed by Sandhu in order to calculate failure of the basal layer and methods of easing (Tsai and Azzi), and was used to reduce the stiffness of the damaged laminae [5].

Another use of the 2D finite element method, based on the classic CPLT, is also given in the works of Chang. They performed a progressive failure analysis of composite laminates with a notch on tensile. Nonlinear dependence of the stress–strain was proposed by Hahn and Tsai, and was used to shear stress level. The resulting nonlinear equations are solved by finite element modified Netwon–Raphson iterative technique [37].

The full three-dimensional (3D) finite element method was used by Lee to analyze load for biaxial loading of the composite laminate with a central hole. He later developed 3D FE codes to analyze the progressive accumulation of damage and the failure of the same problem. Reducing the stiffness was conducted at the level of the element and the stress-based failure criterion was used to identify three failure modes: fiber fracture, transverse cracking, and delamination. However, his code never detected delamination [37].

In Ref. [38] the impact damage of the composite laminate in the form of intra- and inter-laminar damage has been modeled, using criteria based on the stress for initiation of damage and fracture mechanics techniques to encompass the development of damage. Nonlinear shear strength of the composite is described with a semi-empirical Soutis stress–strain formula. The FEM was used to simulate the behavior of composite impact due to low impact, cohesive interface elements are inserted between the layers with the applicable law of mixed damage for delamination modeling. A damage model has implemented in the FE code (Abaqus/Explicit) the subroutine VUMAT. Numerical results generally had good agreement when compared with the experimental curves of impact force and absorbed energy versus time. Different damage mechanisms have been observed with nondestructive technique (NDT) X-rays, and have been successfully covered by the proposed numerical damage development model.

The use of so-called numerical “Layerwise” theory in the analysis of composite plates was investigated by Y. Zhang in a Ph.D. thesis. Research on delamination buckling effects of laminated composite plates with a square hole was done using three-dimensional FEM analysis (Zor). Numerical analysis of composite plates with “multiple” delamination exposed to uniaxial buckling load was studied by Cappello. Analytical and numerical study of buckling delaminated composite beams were conducted by Wee [39].

Design models capable of simulating and predicting the residual strength with impact damage caused by variable factors on laminates are necessary to assist in the interpretation of experimental results and reduce demand testing. Simulation has yielded good results in comparison with the tests, which means that the FE model simulations are adequate and reliable [39].

In a study of laminated plates or scales, analytical solutions are available only for some special problems, even in the case of the linear static analysis, which is the easiest case overall. As for the problems of impacts, closed forms solutions can be obtained for free from extreme models, which introduce appropriate assumptions, that lead to the linearized equations to be solved. In the impact phenomenon view, several nonlinear effects are present: contact between the impactor and the target, large displacement, and nonlinear constitutive equations. According to these effects, even the model with one degree of freedom requires a certain form of numerical solution [40].

In Ref. [41] the progressive failure analysis using a finite element model that is characterized by impact damage in the unidirectional reinforced carbon/epoxy composite laminate has been investigated. Low velocity impact can cause substantial damage, in terms of matrix cracking and delamination. Such defects are very difficult to detect, and can lead to severe reductions in rigidity and strength of the structure. For this reason it is very important to provide for them through the finite element approach.

Contact force, position, and size of delamination, as well as its expansion according to the low velocity impact process, were characterized by the progressive failure analysis in specified software GENOA/LS-DYNA and NASTRAN. Fig. 7.13 gives an overview of the analysis conducted for the laminate plate. The model (i.e., impactor plus plate) is presented in Fig. 7.13. Also, simulation analysis for the laminate plate has a graphical outline on the same figure.

One appropriate example of dynamic implicit analysis is given in Ref. [42]. It considered a flat composite plate (cuboid), from the composite material T800H, dimensions of 50 mm × 20 mm × 1 mm (0/90/90/0 degrees). This plate has been modeled in program ABAQUS, using 3D solid composite elements (C3D8), with the time-varying compressive load in the central upper surface and the boundary conditions on all edges. In Fig. 7.14 the resulting location of the first delamination appearance in the adoptable model evident is shown.

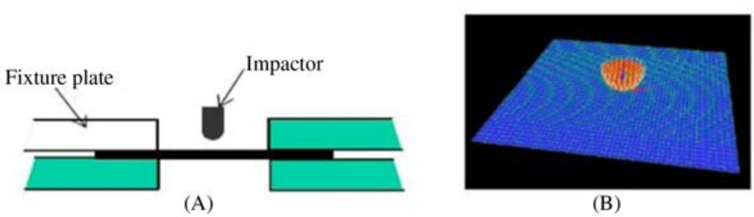


**Figure 7.13** Overview of the model (A) and simulation (B) of low velocity impact on laminate plate [41].

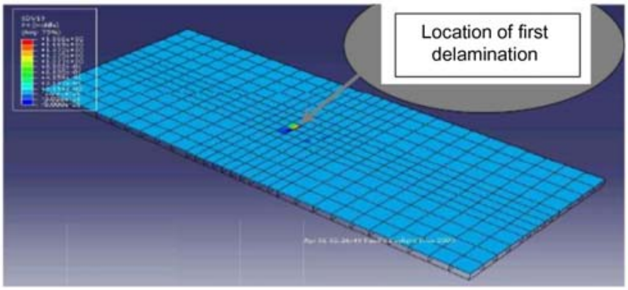


**Figure 7.14** Prediction of delamination location in the model [42].

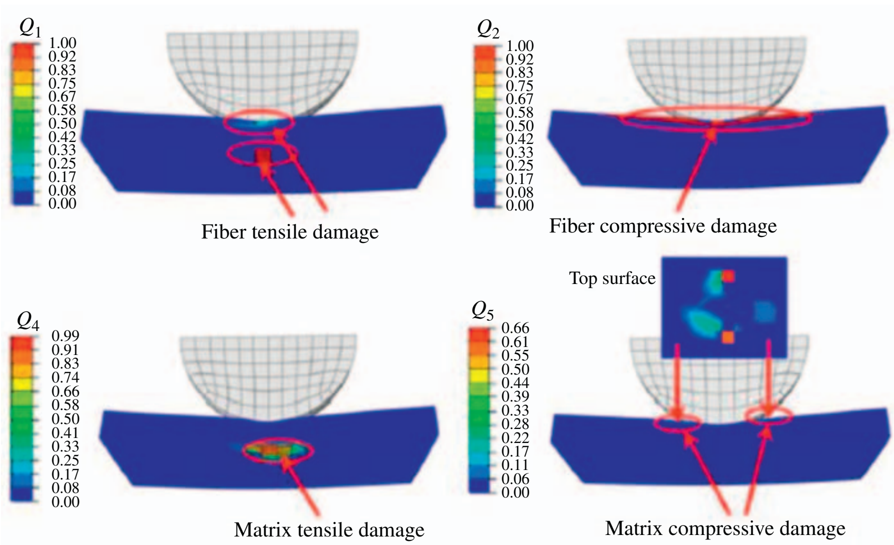


**Figure 7.15** Fringe plots of internal variables: $Q_1$ (fiber tensile damage), $Q_2$ (fiber compressive damage), $Q_4$ (matrix tensile damage), and $Q_5$ (matrix compressive damage) at $t = 0.52$ ms [43].

Transient FEM analysis of elastic−plastic deformation in composites can be fully seen in Ref. [43]. Testing material is fiber-reinforced AS4/PEEK laminate, under the low velocity impact of the rigid sphere. It is assumed that the matrix deforms elastic−plastic and fibers elastic. Consideration of failure and damage to the fiber-reinforced laminates is connected by a continuous damage mechanics approach and micromechanics.

Delamination occurs over a wider region below the spherical impactor. The fibers below the impactor fail due to compression load, but matrix mostly by tension load. The provided damage developments in matrix and fiber well agree with the conducted experimental observations. In Fig. 7.15 the damage variables—Q (for fiber and matrix damage) during impact process are presented [43].

### 7.5.3 Modeling and simulation of projectile impact on carbon fiber-reinforced panels in software ABAQUS

The ABAQUS (Simulia) is sophisticated software for a complex dynamic impact analysis. The program package offers accurate, robust, high-performance solutions for challenging nonlinear problems, large-scale linear dynamics applications, and routine design simulations [44].

The key ABAQUS features, possibilities, and benefits for this kind of unique impact simulation are the following:

1. Ability to model progressive damage and failure of composites in Abaqus/Explicit with general user-defined material capabilities.
2. Automatic contact capability facilitates the definition of complex contact conditions.
3. Element erosion with automatic activation of contact faces based on failure of the underlying elements [44].

In this simulation, the projectile is a cold-rolled steel ball (5 mm diameter) with an initial velocity specified in a direction normal to the plate plane. The specified model configuration is shown in Fig. 7.16.

Both the projectile and the plate are meshed with first order, reduced integration, solid continuum elements (type C3D8R).

The composite ply lay-up used for this simulation is a simple orthotropic design [0/90/0]3 s, and 18 ply layers of 0.2 mm thickness are modeled individually using solid continuum elements (see Fig. 7.17).

The complete formed test model (impactor plus plate) developed in software ABAQUS has graphical presentation in Fig. 7.18 [7,45].

Fig. 7.19 shows a top view of the damage in the composite plate, as the steel ball penetrates through the material. Significant damage occurs both locally as the

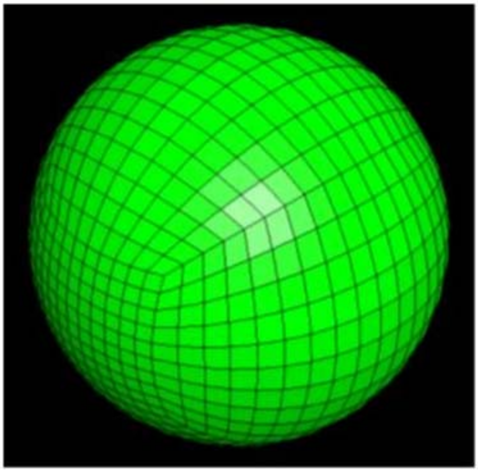

**Figure 7.16** Finite element mesh applied to the steel missile ball shape [45].

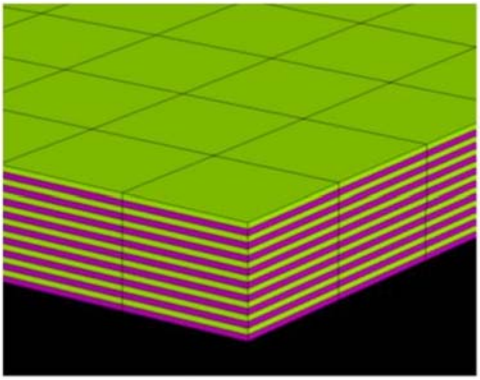

**Figure 7.17** Finite element mesh applied to the composite panel across to the thickness [45].

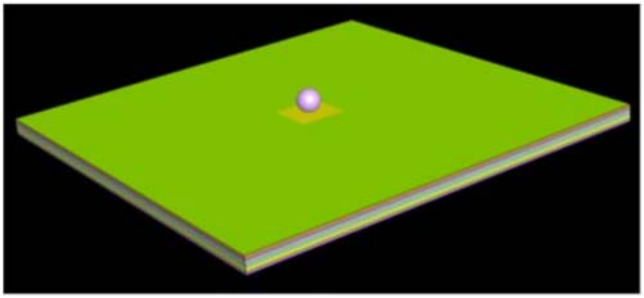

**Figure 7.18** Geometry model for the impact simulation in the composite plate [45].

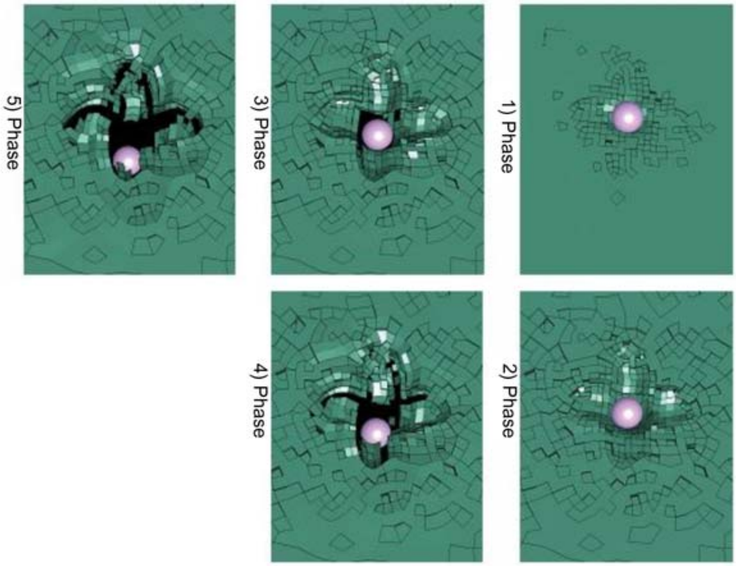


**Figure 7.19** Graphical representation of steel ball impact simulation on the composite panel (phase 1–5) [45].

ball penetrates composite, and also globally, due to propagation and reflection of stress waves through the composite plate. The total impact process and various characteristic damages formed are presented in detail through phases (1−5). On the same figure pronounced development and propagation of damages are shown [45].

## 7.6 Result analysis and discussion

Based on all information presented in this chapter, some engineers analysis and scientific views can be carried out and considered. The following relevant expert facts are exposed for future research in the domain of modeling impact on laminated composite aircraft structures.

During aircraft operation on structural elements, beside common operational loads, impact loads from foreign objects occur that can cause serious structural damage. In order to determine the results of impact damage, it is necessary to consider the dynamic response of different aircraft structures under various types of impact, and issues related to the development of engineering models for such type analysis.

In an effort to fully predict and analyze the resulting impact damage, it is evident that there are a lot of problems, due to complexity and many influencing factors.

Despite numerous improvements, existing models (2D and 3D) fail to fully determine the impact effects on structures and their severe consequences.

However, the tasks for future models, which are being developed or will be developed later, are that they have to be closer to real conditions, i.e., more specifically characterized impact damages in certain structures, and its parameters on the remaining capacity and thus importantly the safety of those laminated composite structures.

This chapter provides an overview of existing models, which consider the impact effect in certain composite laminate structures. The damage quantitatively and qualitatively varies for low and high velocity impacts.

Moreover, specific features and limitations of defined models have been precisely listed. Also, impact simulations on composite structures, which have been performed in sophisticated software packages and the results obtained have been presented.

The properties of high velocity impact have been discussed in detail, especially the ballistic damage on helicopter structures, i.e., windshield and main rotor blade have been shown, with the focus on the vulnerability and survivability.

Composite laminates have some extraordinary properties, such as great strength, high stiffness, and light weight. However, a serious obstacle to more widespread use of those materials is their sensitivity to impact loads. As a consequence of that, impact damages through initiation and growth are occurring.

In general, failures that appear in laminated composite structures after impact events are intralaminar or interlaminar. In the previous time period, many models for impact damage in laminates have been developed with some approach and accuracy. Those models can replace real and expensive tests in laminated structures, but with some approaches.

Impact behavior is a very important fact in the process of designing aircraft structures. This structure must be able to withstand the primary and secondary wear energy, and damage from impacts are almost daily (in service life). Such cases are influences from dropping tools (maintenance), hard landing, then hail, bird, and stone on take-off (rule and driving on a runway). Subsurface damage in structures caused by these types of loads is known as barely visible impact damages.

Multiscale methodology is applicable for clear modeling of impact damage and assessment of structural integrity in laminated composites at different observation levels.

By using specialized software packages, numerical simulation can be done and the damage parameters in laminate aircraft structures accurately predicted and calculated.

## 7.7 Conclusions

Impact events in aeronautical structures often occur. Under existing impact loads, the formed damages grow, extend, and further develop. As a final result, these factors significantly reduce the structure load capacity, even to total failure. In such cases material properties, kinematic and dynamic conditions are of great influence for research. Methods and approaches for impact modeling can be considerably distinguished according to introduced assumptions for establishing and deriving the necessary and relevant equations.

Laminated composites are a relatively new generation of technical materials, which are widely used in contemporary structures. They are characterized by a number of advantages compared to conventional materials, among them the most important are: high specific strength, significant stiffness, low density (weight), good performance to fatigue, and corrosion resistance.

A serious obstacle to their increasing use in modern structures represents the sensitivity to impact and static load, especially in the thickness direction.

In general, when defining impact, there is a limit of velocity (usually in the certain range), which separates low velocity and high velocity impact. The characteristics of these impact types are mainly clearly specified and damage also has distinctive sizes and forms.

Modeling of impact and consequently impact damage in composite laminates are very complex, comprehensive, and very demanding processes. The created models (2D/3D) successfully, or with a certain deviation, approximate the real damage due to the impact in composite laminate structures.

In general, the characterization of the damage can be derived analytically, experimentally, and numerically. Combination of these irreplaceable methods probably represents the optimal and leading strategy for the general structural analysis of composite laminate plates.

Research into the impact damage resistance and tolerance domains provide complete and detailed insight into structural integrity and safety. The crucial assignment is to determine the failure points/zones and possibly final fracture in the aircraft structures.

The essential objectives in the design and maintenance of aircrafts, and generally in the aviation industry, are the following: shorten the process of mapping defects, determine the residual strength of vulnerable structures, and finally flight authorization.

One suitable engineering approach for this problem is FEM, which can simulate the behavior of composite structures under the influence of impact loads. Development of appropriate FEM simulation impact models varies, from those in composite beam, plate, shell, and panel, to the parts and components of aircraft structures.

Modern software such as ABAQUS, LS-DYNA, ANSYS, etc., can be used to perform impact simulations on composite laminate structures. The results should closely reflect the true test conditions as in certain real structures. However, final confirmation of accuracy thereof must be tested and proved experimentally.

Explanation and analysis of existing, and creation of new, impact damage models will fully complete in-depth understanding of impact, characterization of this phenomenon, and the resulting damage in some structures.

All of the mentioned and analyzed engineering facts and procedures are of great importance in the design, but also for the maintenance of laminate structures during exploitation in present and future aircrafts.

## 7.8 Sources of further information and advice

- Composite Structures Damage Tolerance Analysis Methodologies: http://www.ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov
- Damage Tolerance of Composite Structures in Aircraft Industry: http://www.carbon-composites.eu
- Probabilistic Design of Damage Tolerant Composite Aircraft Structures: http://www.faa.gov/about/office_org/headquarters_offices/ang/offices/tc/
- CODAMEIN (Composite Damage Metrics and Inspection, EASA): http://easa.europa.eu
- Crashworthiness of Composite Aircraft Structures: http://www.dtic.mil/dtic
- Rotorcraft Structures and Survivability: http://vtol.org/events/rotorcraft-structures-and-survivability
- Structural Composites "Armour Works – Expert In Survivability": http://www.armourworks.co.uk/products/exterior-platform-protection/composites
- The Aircraft Combat Survivability Education Web Site: http://www.aircraft-survivability.com
- Survivability/Vulnerability Information Analysis Center: http://www.bahdayton.com/SURVIAC/index.htm
- ISO: International Organization for Standardization: www.iso.org
- CEN: European Committee for Standardization: https://www.cen.eu
- ASTM (American Society for Testing and Materials): http://www.astm.org

- Journal of Testing and Evaluation (JOTE):www.astm.org/DIGITAL_LIBRARY/JOURNALS/TESTEVAL
- ASNT (The American Society for Nondestructive Testing): https://www.asnt.org
- http://www.arc.aiaa.org

The most important benefits of modeling impact damage in laminated structures for the aviation industry are:

1. Can aid maintenance engineers in assessing whether an incident could have caused damage to a structure, and if so what inspection technique should be applied to resolve damage.
2. Helpful for design engineers to:
   a. improve resistance of composite aircraft structures to wide-area impact damage, as well as a variety of other sources such as hail- and bird-strikes, runway debris, lost access panel, etc.
   b. provide critical information on mode and extent of damage, particularly nonvisible impact damage (NVID), resulting from a wide gamut of impact threats (from low to high velocity).

The complexity of the considered phenomena that occur on impact indicates the numerous directions for further research. In the analysis of impact damage it is necessary to consider the dynamics of the system projectiles and target (where both of them can be deformable), behavior of materials in plastic deformation zone and fracture criteria.

The future needs for research and engineers would consider:

1. More accurate numerical approach for modeling of impact damages.
2. Better quality/quantity assessment of structure integrity after impact.
3. Incorporation of Non Destructive Inspection (NDI) into impact studies.

# References

[1] Rasuo B. Aircraft Production Technology (in Serbian), Faculty of Mechanical Engineering, University of Belgrade; 1995.
[2] Rasuo B. Aeronautical Safeguarding (in Serbian), Military Academy, Belgrade; 2004.
[3] Rasuo B, Djuknic G. Optimization of the aircraft general overhaul process. Aircraft Eng Aerospace Technol 2013;85(5):343−54.
[4] Zivaljevic M, Rasuo B. Application of fuzzy logic in solving problems from the area of reliability and maintenance of aircraft systems. In: Reusch B, editor. Lecture Notes in Computer Science 1226. Berlin: Springer Verlag; 1997. p. 583−4.
[5] Kreculj D. Modeling of impact damage in laminatecomposite structures. Doctoral Thesis, (in Serbian), Aeronautical Department, Faculty of Mechanical Engineering, University of Belgrade; 2013.
[6] Rasuo B. Design, fabrication and testing of the helicopter tail rotor blade from composite materials: an experience. RAeS Structures & Materials Conference - 2nd Aircraft Structural Design Conference, London (UK); 2010.
[7] Rasuo B. Testing of the helicopter tail rotor blade made of composite laminated materials after ballistic damages. 11th International Conference on Composite Materials, ICCM-11, Gold Coast, Queensland, Australia, Cambridge (England), Woodhead Publishing Limited; Proceedings Volume 2 (Impact); 1997. pp. 485−95.

[8] Ratwani MM. Effect of damage on strength and durability. PhD thesis, RTO-EN-AVT-156-05.
[9] Sabet SA. Investigation of multi-scale modeling strategies to simulate high velocity impact damage. Master Thesis, Universität Stuttgart; 2010.
[10] Davies GAO, Olsson R. Impact on composite structures. Aeronautical J 2004.
[11] Rasuo B. Helicopter tail rotor blade from composite materials: an experience. SAE Int J Aerospace SAE Int 2011;4(2):828−38.
[12] Rasuo B. Design, fabrication and testing of the helicopter tail rotor blade from composite laminated materials. In: Zhang Y, editor. 13th International Conference on Composite Materials, ICCM, Beijing, China, Proceedings; 2001.
[13] Rasuo B. An experimental methodology for evaluating survivability of an aeronautical constructions from composite materials: an overview. International Journal of Crashworthiness, Volume 12/Issue 1, Taylor & Francis, London, England, 2007. p. 9−15.
[14] Rasuo B. Experimental study of the structural damping of composite helicopter blades with different cores, plastics rubber & composites, Volume 39, Number 1, Maney Publishing, Institute of Materials, Minerals and Mining, London; 2010. p. 1−5.
[15] Rasuo B. On structural damping of composite aircraft structures, reference module in materials science and materials engineering. <https://doi.org/10.1016/B978-0-12-803581-8.10338-8>, Elsevier Ltd., Current as of 24 April 2017.
[16] Rasuo B. Experimental techniques for evaluation of fatigue characteristics of laminated constructions from composite materials: full-scale testing of the helicopter rotor blades, Journal of Testing and Evaluation (JTE), Volume 39/Issue 2, ASTM International; 2011. pp. 237−42.
[17] Grbovic A, Rasuo B. FEM based fatigue crack growth predictions for spar of light aircraft under variable amplitude loading, engineering failure analysis, Volume 26, Elsevier Ltd; 2012. pp. 50−64.
[18] Dinulovic M, Rasuo B. Dielectric modeling of multiphase composites, composite structures, Volume 93/Issue 12, Elsevier Ltd; 2011. pp. 3209−15.
[19] Menna C, Asprone D, Caprino G, Lopresto V, Prota A. Numerical simulation of impact tests on GFRP composite laminates. Int J Impact Eng 2011.
[20] Birur A. Time-dependent damage evolution in multidirectional polymer composite laminates. Master Thesis, Department of Mechanical and Manufacturing Engineering, University of Manitoba, Canada; 2008.
[21] Nilsson E. Residual strength prediction of composite laminates containing impact damage. Master Thesis, Linköping University; 2005.
[22] Singh CV. Multiscale modeling of damage in multidirectional composite laminates. Doctor Thesis, Texas A&M University; 2008.
[23] Rasuo B. An experimental methodology for evaluating survivability or damage tolerance of an aeronautical construction from composite materials, a joint sheffield-cambridge conference, deformation and fracture of composites (DFC-11) & structural integrity and multi-scale modelling (SI-5), The University of Cambridge, Cambridge, UK; 2011.
[24] Rasuo B, Dinulovic M, Veg A, Grbovic A, Bengin A. Harmonization of new wind turbine rotor blades development process: a review. Renew Sustain Energy Rev, 39. Elsevier Ltd; 2014. p. 874−82.
[25] Kim H. Impact damage formation on composite aircraft structures. San Diego: University of California; 2012.

[26] Rasuo B. Damage tolerance and survivability of composite aircraft structures. In: Beaumont PWR, Soutis C, Hodzic A, editors. Structural integrity and durability of advanced composites: innovative modelling methods and intelligent design. Woodhead Publishing Series inComposites Science and Engineering, Elsevier Science; 2015. p. 641−58.
[27] Zheng D. Low velocity impact analysis of composite laminated plates. Doctor Dissertation, The University of Akron; 2007.
[28] Kreculj D, Rasuo B. Review of impact damages modelling in laminated composite aircraft structures. Technical Gazette 2013;20(3):485−95.
[29] Brown KA. Finite element modeling of the static and dynamic impact behavior of thermoplastic composite sandwich structures. Doctor Thesis, The University of Nottingham; 2007.
[30] Othman RB. Finite element analysis of composite ballistic helmet subjected to high velocity impact, Universiti Sains Malaysia, Master Thesis; 2009.
[31] Talreja R. Multi-scale modeling in damage mechanics of composite materials. J Mater Sci 2006;41:6800−12.
[32] Soutis C, Beaumont PWR. Multi-scale modeling of composite material systems. Cambridge: Woodhead Publishing Limited; 2005.
[33] Ivancevic D, Smojver I. Explicit multiscale modelling of impact damage on laminated composites. Compos Struct 2016;145:248−58.
[34] Tippetts T, Hemez FM. Non-linear models of composite laminates. IMAC: Conference and Exposition on Structural Dynamics, Orlando; 2005.
[35] Laliberté J, Poon C, Straznicky P. Numerical modelling of low-velocity impact damage in fibre-metal-laminates. 23rd ICAS Congress, Congress of International Council of the Aeronautical Sciences, Toronto; 2002.
[36] Kreculj D. Stress analysis in an unidirectional carbon/epoxy composite material. FME Trans 2008;36:127−32.
[37] Serena THN. Modeling damage in composites using the element-failure method. Doctor Thesis, National University of Singapore; 2005.
[38] Shi Y, Swait T, Soutis C. Modelling damage evolution in composite laminates subjected to low velocity impact. Compos Struct 2012;94(9):2902−13.
[39] Farooq U, Gregory K. Global and local buckling simulation of fibrous composite panels after low velocity impact of variable shape impactors. Eur J Sci Res 2009;25(3):384−95.
[40] Ghelli D. Some issues concerning the dynamic response and damage of composite laminates subjected to low velocity impact. Doctor Thesis, The University of Bologna; 2009.
[41] Monaco F, Fenza AD, Petrone G, Fabbtricatore M, Abdi F, Ricci F. Low velocity impact analysis on an unidirectional laminate composite. In: International Conference on Mechanics of Nano, Micro and Macro Composite Structures, Politecnico di Torino; 2012.
[42] Roy S, Larrosa C, Chang F. Developing an Interface with ABAQUS for Analysis of Impact Damage in Laminated Composites. Stanford University; 2009.
[43] Batra RC, Gopinath G, Zheng JQ. Damage and failure in low energy impact of fiber-reinforced polymeric composite laminates. Compos Struct 2012;94:540−7.
[44] Kreculj D, Rasuo B. The Problem of Impact on Aircraft Constructions from Composite Laminates, Technics, LXIV, No. 6, Belgrade, (in Serbian); 2009. M1−M8.
[45] Projectile Impact on a Carbon Fiber Reinforced Plate, Abaqus Technology Brief TB-06-CRP-1, DSS Simulia; 2007.

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