Bird Strike Simulations on Composite Aircraft Structures

Sebastian Heimbs

EADS, Innovation Works, 81663 Munich, Germany

Abstract: Composite materials are increasingly being used for aeronautic primary structures such as wing components or fuselage panels. However, their major drawback is their vulnerability against transversal impact loads, which may lead to internal delaminations or intralaminar fiber/matrix failure. Such loads may arise from numerous impact scenarios, with bird strikes being one of the most relevant load cases. The focus of the current study is on the numerical modeling and simulation of high velocity impact loads from soft body projectiles on composite structures with ABAQUS/explicit. At first, the impact on flat composite plates is studied in experiment and simulation, which allows for the validation of the modeling methods. Some of these plates have been preloaded in tension or compression in order to investigate the influence on the mechanical behavior. It could be shown that the preloading of the plate may have a significant influence on the structural response. As a second example, the bird impact on a composite wing leading edge is treated. Adequate modeling methods for the composite material (stacked shell model), delamination failure (cohesive elements), preloading (implicit-explicit coupling) and soft body impactor modeling (coupled Eulerian-Lagrangian approach) are assessed in this paper. The final simulation results correlate well with experimental test data.

Keywords: Aircraft, Composites, Coupled Analysis, Damage, Delamination, Impact, Bird Strike, Cohesive Elements, Coupled Eulerian-Lagrangian, Preload, Implicit-Explicit Coupling.

1. Introduction

Bird strike is a major threat to aircraft structures, as a collision with a bird during flight can lead to serious structural damage. Although exterior aircraft structures are exposed to various threats of foreign object damage like hail, runway debris or tire rubber impact, about 90% of all incidences today are reported to be caused by bird strike (Meguid et al., 2008). All forward facing components are concerned, i.e. the engine fan blades and inlet, the windshield, window frame, radome and forward fuselage skin as well as the leading edges of the wings and empennage (Figure 1). Consequently, the aviation authorities require that all forward facing components need to prove a certain level of bird strike resistance in certification tests before they are allowed for operational use. For wing leading edges the certification criteria require that even in case of penetration of the leading edge skin no critical damage may be introduced to the front spar elements or the wing tank, so that a continued safe flight and landing after impact are assured. This has to be proven for 4 lb (1.8 kg) birds impacting the wing and 8 lb (3.6 kg) birds impacting the empennage leading edge at operational speed. Nowadays, more and more of such aircraft structures that are exposed to the risk of bird strikes are made of composite materials.

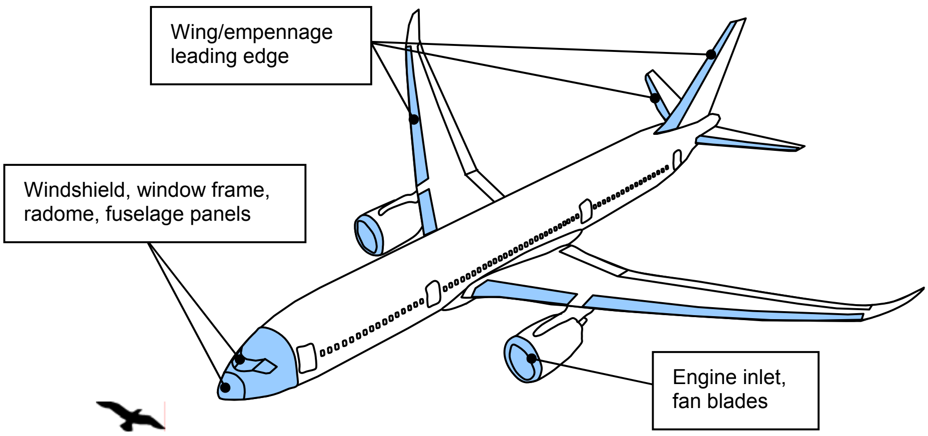


Figure 1. Illustration of aircraft components exposed to the risk of bird strike.

In past years it was common practice for bird-proof design of aircraft components to be built and tested, then redesigned and tested again (Nizampatnam, 2007). One example of this procedure is documented for the development of the bird-proof Dash 8 wing leading edge (John, 1991). Without doubt, this is not only a very time-consuming, but also cost-consuming practice. Therefore, numerical methods were developed and applied since the late 1970s for the purpose of rapid and improved design optimization, ensuring that the very first full-scale bird strike certification test is successful.

The definition of a suitable bird model is often the main problem in the numerical simulation of bird strike incidents. Starting with relatively simple nonlinear calculations and a pressure load applied to the target structure in the 1970s, complex fluid-structure interactions are treated today with explicit simulation codes and high performance computing. Most interestingly, this evolution from simple to complex and accurate methods did not lead to the establishment of one generally accepted bird impactor modeling approach. Instead, there are still at least three techniques today, which are widely used, each having its own advantages and disadvantages (Lagrangian, Eulerian and meshless particle modeling (SPH)). A comprehensive overview of these bird strike modeling methods can be found in (Heimbs, 2011).

The focus of the current paper is on the application of the coupled Eulerian-Lagrangian (CEL) modeling method in Abaqus/Explicit 6.10 for bird strike simulations on composite aircraft structures. After an explanation of the bird impactor and composite material modeling methods, two example load cases are treated. At first, the impact on a flat composite plate is studied numerically and experimentally, which allows for the validation of the modeling methods. Some of these plates have been preloaded in tension or compression in order to investigate the influence on the mechanical behavior. As a second example, the bird impact on a composite wing leading edge is treated.

2. Bird impactor modeling

For bird strike certification tests on aircraft components real birds have to be used. However, real birds with their irregular shape have the disadvantage of large scatter between individual tests. Therefore, artificial birds or substitute birds are typically used for pre-certification impact tests and simulations, leading to advantages in convenience, cost and reproducibility. Typical artificial birds are made from gelatin and have a simplified geometry such as a cylinder with hemispherical ends.

At the velocities of interest, the bird behaves as a soft body and flows in a fluid-like manner over the target structure, with the high deformations of the spreading material being a major challenge for computational simulations. In the current version 6.10 of Abaqus/Explicit, two different soft body impactor modeling methods are available: the Lagrangian and the Eulerian approach. Meshless particle methods like SPH are not yet included in the current version.

The Lagrangian modeling method is the standard approach for most structural finite element analyses with the nodes of the Lagrangian mesh being associated to the material and therefore following the material under motion and deformation (Figure 2a). The major problem of Lagrangian bird impactor models is the severe mesh deformation. Large distortions of the elements may lead to inaccurate results, severe hourglassing, reduced time steps and even error termination, which has to be prevented with adequate element erosion criteria. Although this modeling method is still used today, it is widely accepted that the Lagrangian approach remains an impractical way to model fluid splashing phenomena like bird strikes (Georgiadis at al., 2008).

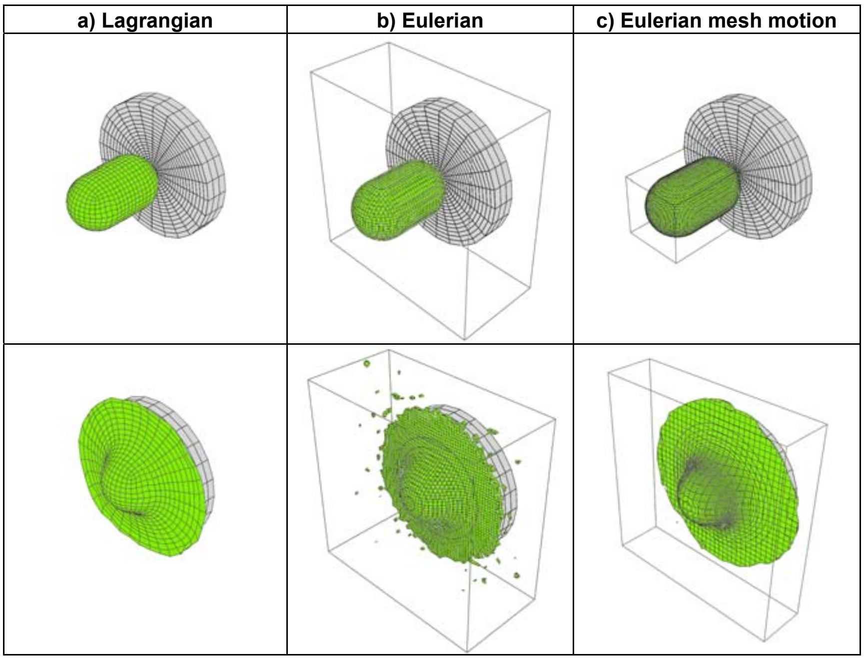


Figure 2. Soft body impactor modeling methods in Abaqus/Explicit 6.10.

A promising alternative is the Eulerian modeling technique, where the mesh remains fixed in space and the material flows through the mesh (Figure 2b). Because the mesh does not move, mesh deformations do not occur and the explicit time step is not influenced. Stability problems due to excessive element deformation do not occur. Since in a bird strike simulation typically only the impactor is modeled as a fluid-like body with Eulerian elements and the target as a solid structure with Lagrangian elements, a coupled Eulerian-Lagrangian approach is used for this fluid-structure interaction problem, which is available in Abaqus/Explicit since version 6.8. Because the mesh in the classical Eulerian technique is fixed in space, the computational domain should cover not only the region where the material currently exists, but also additional void space to represent the region where material may exist at a later time of interest. Thus, the computational domain for structural analyses with the classical Eulerian technique is relatively large, leading to high computational cost due to the high number of elements and the cost-intensive calculation of element volume fractions and interactions. Typically, the element size of the Eulerian mesh has to be defined very small in order to achieve accurate results.

An increase of efficiency is the 'Eulerian mesh motion' option in Abaqus/Explicit (Figure 2c). Here, in contrast to the classical Eulerian approach, the surrounding Eulerian box is not fixed in space but can move and stretch if needed. The initial number of elements for the Eulerian domain can significantly be reduced, leading to computational time savings. However, due to the wide spreading of the bird material the lateral expansion of the Eulerian box is significant and the size of the Eulerian elements is increased considerably. As stated before, the accuracy of the results is strongly mesh dependent and requires fine meshes. Therefore, the accuracy of the model with mesh motion may be reduced for severe impactor deformations. For this reason, the classical CEL approach was used in the present study.

The next step in the bird modeling procedure is the definition of an adequate material model for the impactor. Generally speaking, real birds and artificial gelatin birds are mostly composed of water. Therefore, a water-like hydrodynamic response can be considered as a valid approximation for a constitutive model for bird strike analyses. An equation of state (EOS) describes the pressure-volume relationship with parameters of water at room temperature. The Mie-Grüneisen EOS (u_s-u_p approach) in Abaqus/Explicit was adopted for this purpose in the current study.

A common technique to validate the bird impactor model is to use experimental bird strike test data on instrumented plates and to compare the pressure-time history with the numerical results (Figure 3). A large set of publicly accessible experimental bird impact test data was generated in the late 1970's (Wilbeck, 1978), although the quality of the curves and especially the initial peak pressure is limited due to the limitations of the instrumentation equipment at that time.

Another important aspect for the fluid-structure interaction in the bird impact simulation is the contact algorithm, which prevents penetrations and calculates reaction forces. The contact algorithm has to cope with large deformations and splitting of the projectile, sliding of the bird material over the target surface and the creation of multiple contact interfaces due to possible fracture and penetration of the structure (Lammen and Van Houten, 2008). During the flowing of the bird, significant oscillations in the contact force can occur in a penalty contact algorithm that are often dependent in their frequency and peaks on the penalty stiffness scale factor, which has to be selected with care for this contact pair with highly different stiffnesses (Ryabov et al., 2007). Friction is another aspect, whereas the study in (Shmotin et al., 2009) advises that best results compared to experimental results can be obtained with zero friction.

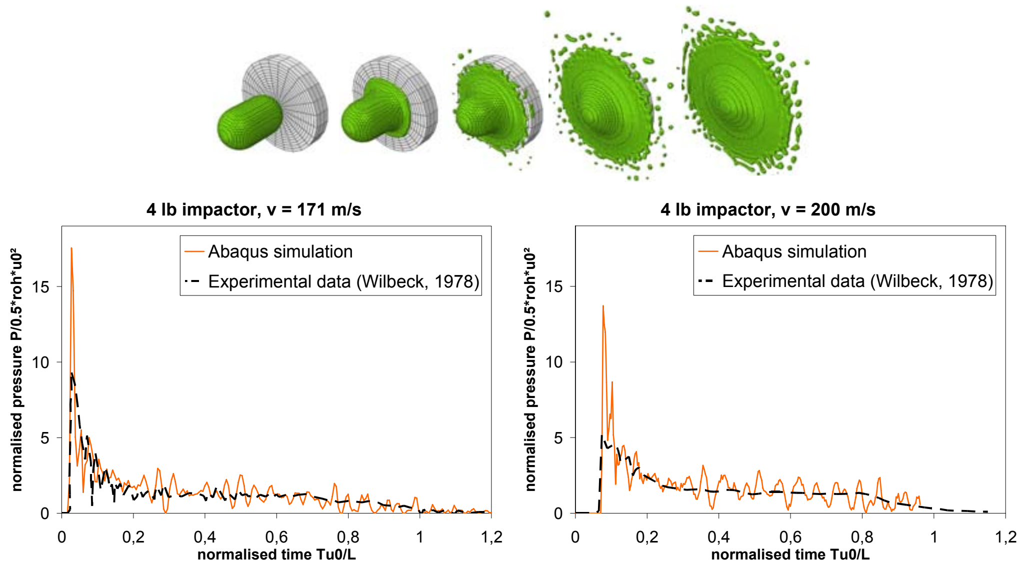


Figure 3. Eulerian bird impactor validation using impact test data on instrumented plates, v = 171 m/s and 200 m/s.

3. Composite material modeling

Since nowadays most aircraft structures subjected to impact loads are made of fiber-reinforced composite materials, the correct constitutive modeling covering all possible impact-induced failure modes is of great importance for reliable simulation results. This involves both intralaminar fiber/matrix damage and interlaminar damage as the separation of individual plies (delaminations).

The standard material model for intralaminar damage in Abaqus/Explicit is based on the Hashin failure criteria for damage initiation and fracture energies for damage evolution. More accurate models, typically implemented as user-defined materials, are often based on continuum damage mechanics and take into account the stiffness degradation and nonlinearities resulting from increasing damage caused by micro cracks under load (Lubineau and Ladeveze, 2008). However, the current study only covers the standard Hashin-based composite material model. Coupon tests have been conducted to obtain the required parameters under different load conditions. For high velocity impact loads the strain rate effect of the target material can also play a significant role, which is to be characterized in dynamic tests. Composite materials are known to show increased stiffness or strength properties under highly dynamic loads (Heimbs et al., 2007). However, as none of the currently available composite material models includes strain rate effects, this phenomenon had to be neglected here.

Delamination damage, which is typically observed under low and high velocity impact loads on laminated composites and which can significantly reduce the global stiffness and residual strength, needs to be included in the model, too. The composite plies are typically modeled with several shell elements across the thickness of the laminate, and the possibility of delaminations is included by cohesive interfaces between these shell elements (stacked shell modeling approach). These interfaces can either be based on a contact definition with cohesive behavior or on cohesive elements. In direct comparison, the cohesive contact has proven to be much more expensive than the cohesive elements. Therefore, in the current study cohesive elements were used. The selection of number of cohesive interfaces needs to be a compromise between accuracy and efficiency. It is often not possible and desired to include a cohesive interface between each individual ply, because the computational cost would be significant and the interfaces may have a negative effect on the global bending stiffness of the composite laminate, which needs to be verified. It is common practice to include one to five cohesive interfaces in a laminate and combine the plies in-between to sub-laminates. The mechanical model of the interface is based on the cohesive zone model with a bilinear traction-separation law. The necessary parameters are typically obtained by double-cantilever beam and end-notched flexure tests, where the critical energy release rates required for the delamination propagation are identified. Simulations of these tests are a good possibility for validation of the delamination model.

4. Bird impact on composite plates with and without preload

As a first generic example load case the bird impact on a flat composite plate is treated. This study, which was performed both experimentally and numerically, was intended to assess the quality of the numerical simulations with a limited amount of complexity. Furthermore, the effect of in-plane compressive or tensile preloads of the plate was investigated.

The 1.625 mm thick target plates were made of T800S/M21 carbon composite material and had a free surface of 300 mm x 200 mm. Both longitudinal ends of the plate were clamped and additional supports on the edges of both free surfaces were introduced that fixate the plate’s translational degree of freedom in the plate’s thickness direction. The composite plate was modeled with three layers of SC8R shell elements with two layers of COH3D8 cohesive elements in-between. The Hashin failure criteria were used for the ply modeling.

The high velocity impact tests were performed at the DLR gas gun test facility in Stuttgart using hard body (steel sphere and glass sphere) as well as soft body impactors (gelatin bird). This paper focuses on the soft body impact with a 32 g gelatin bird with the geometry of a cylinder with one hemispherical end and a length of 50 mm and a diameter of 30 mm. The impact velocities in this study were selected to be 100 m/s, 150 m/s and 200 m/s. A fixed Eulerian mesh domain was defined with the dimensions 220 mm x 200 mm x 100 mm. A biased mesh size was used with 2 mm elements in the impact centre and 6 mm elements at the outer border. This was useful as small elements are necessary in the impact centre for an accurate calculation but the total number of elements should be as small as possible for computational efficiency reasons. A total number of 364.900 Eulerian elements was used for these simulations.

Since in reality it is rather unlikely that the impacted surface of an aircraft structure during flight is unloaded, the effect of preloads on the impact behavior is of great interest (Garcia-Castillo et al., 2006, Mikkor et al., 2006). Uniaxial tensile and compressive prestrain of 0.1% and 0.25% was applied to the composite plate before impact and the influence on the impact performance was investigated. In the numerical simulation, there are different possibilities how to model the preloading before impact. In most studies in the literature the preloading was also performed within the explicit calculation step (Heimbs et al., 2009, Pickett et al., 2009). If oscillations can be avoided, this approach is working well, but it is relatively expensive. Typically half of the computational cost is ascribed to the preloading, half to the impact simulation. A much more elegant approach, which is straight-forward in Abaqus, is the implicit-explicit coupling. The preloading is performed during an implicit calculation step in Abaqus/Standard, which takes only a few minutes, and then the model and stress state are transferred to a calculation with Abaqus/Explicit for the impact loading.

The bird impact of the 32 g gelatin projectile with velocities up to 200 m/s on the unloaded plate led to no penetration but severe internal damage. While ultrasonic C-scans were used to assess the state of damage in the test plates, the intralaminar and interlaminar damage variables (DAMAGEMT, SDEG) were evaluated in the simulation model (Figure 4).

The tensile preloading for the lower impact velocities of 100 m/s and 150 m/s led to less bending deformation of the plate compared to the unloaded case. Consequently, the delamination damage is slightly smaller. The intralaminar damage is a little higher with an increased number of eroded elements in the top element layer. However, although these results seem to be consistent, the results evaluation of the highest impact velocity of 200 m/s shows a different picture.

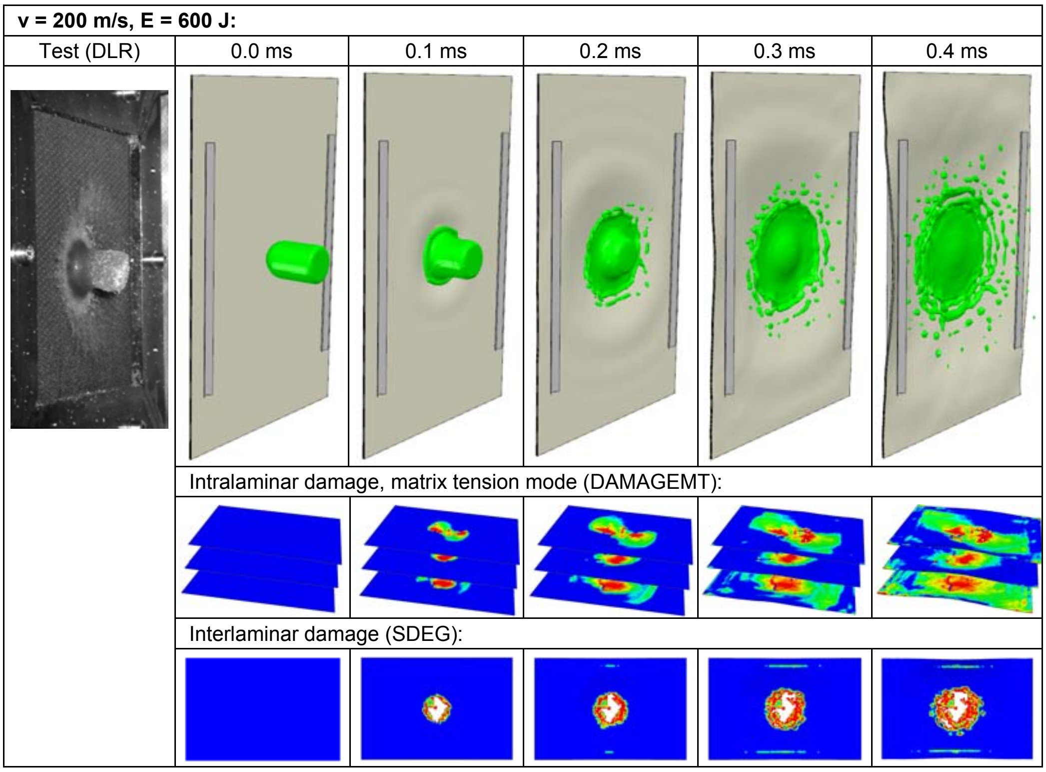


Figure 4. Bird impact simulation results on unloaded composite plate (v = 200 m/s).

In this case, the plate deflection with tensile prestrain is even higher than without preload. Still, it can be seen that the extent of intralaminar damage is higher than in the unloaded case. But also the delamination damage is higher and many more cohesive elements have been eroded (Figure 5). This is because there is so much intralaminar damage resulting from this high impact energy, supported by the tensile prestrain, that the large-scale degradation of the material leads to higher bending deformation and therefore increased delamination damage. A further increase of impact velocity leads to total failure and penetration of the plate. Consequently, the ballistic limit of the plate, defined as the velocity when impactor penetration occurs, is lower for the tensile preloaded plate. At an impact velocity of 225 m/s the tensile preloaded plate fails due to large cracks and global loss of integrity, while the unloaded plate still maintains its structural integrity.

In case of compressive preload, plate buckling becomes an issue due to the small thickness of the composite plate. Different buckling modes occurred depending on the level of compressive prestrain, which can lead to an initial deflection of the plate centre towards or away from the impactor before impact. In this study, the deflection was always selected to be away from the impactor. The assessment of the impact simulation results showed that the global deflection of the preloaded is higher than for the unloaded plate, which is explained both by the initial buckling deformation and the compressive preloading. This higher bending deformation leads to slightly higher delamination damage, which was visible for all impact velocities. The intralaminar damage on the other hand seems to be more localized with higher local damage and more eroded elements compared to the unloaded plate, but a smaller total area of damaged material (Figure 5). The influence of the compressive preload is therefore considerable, leading to more delamination and more localized failure. As a consequence, the ballistic limit of the compressively preloaded plate subjected to bird impact is again reduced. For the impact velocity of 225 m/s the unloaded composite plate can still resist the impact load, while the plate with 0.25% compressive prestrain fails and penetration occurs (Figure 6).

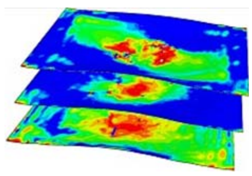
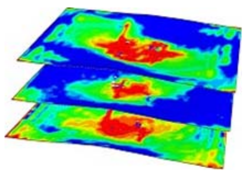
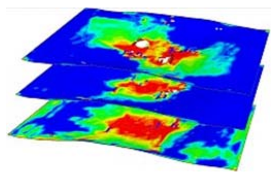
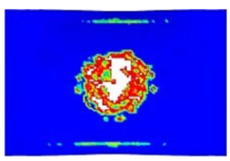
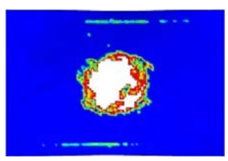
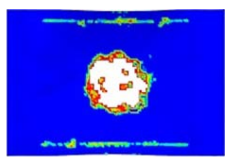
v = 200 m/s, E = 600 J:		
No preload	Tensile preload ε = 0.25 %	Compressive preload ε = -0.25%
Intralaminar damage, matrix tension mode (DAMAGEMT):		
		
Interlaminar damage (SDEG):		
		

Figure 5. Influence of tensile and compressive preload on soft body impact damage (v = 200 m/s, t = 0.4 ms).

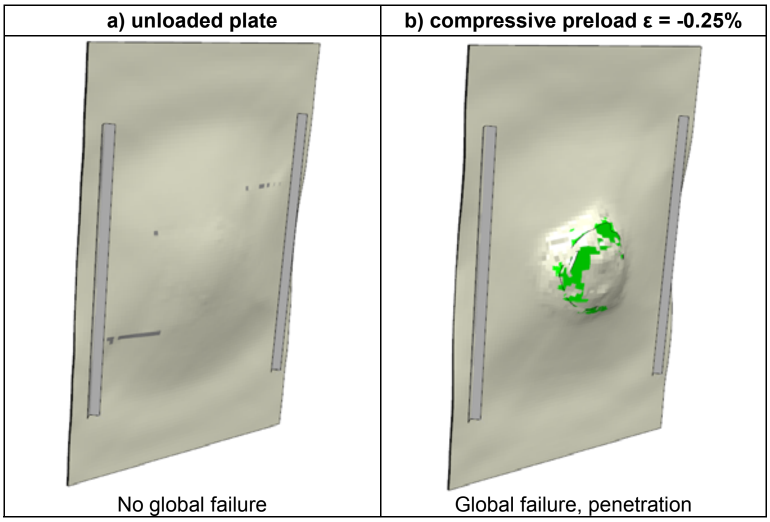


Figure 6. Impact simulation results for v=225 m/s (backside view, t = 0.3 ms).

5. Bird impact on composite wing leading edge

As a second example the bird strike simulation on a composite wing leading edge slat with Abaqus/Explicit is presented. The leading edge structure consists of a composite skin, five composite ribs and a metallic back plate, connected by rivets and adhesive bonding. Further details on the design of the wing leading edge can be found in (Roth, 2006) and (Keck et al., 2009).

The artificial bird is a 4 lb gelatin impactor with a cylindrical geometry with two hemispherical ends and the dimensions 208 mm x 118 mm. The impact velocity is 185 m/s with an angle of 34° to the slat surface. These boundary conditions match to the experimental conditions of full-scale bird impact tests on this leading edge that could be used for model validation.

The composite material was modeled with shell elements and the Hashin failure criteria. The metallic parts were modeled as elastic-plastic materials with defined yield curves and fracture strains. For all bonding connections in the model contact definitions with cohesive behavior based on a traction-separation law were used. In this case, damage is controlled by a quadratic traction criterion with defined failure stresses in normal and shear direction for the bonding surfaces. Beam-type connector elements have been used to model the rivet connections with force-based failure criteria.

The bird impactor was modeled as a Eulerian part based on the Mie-Grüneisen EOS with water-like properties. A general contact with a frictionless tangential behavior was defined for the fluid-structure interaction in the CEL model. A Eulerian mesh size of 6 mm was chosen. With this configuration the final model had 735.000 elements, mainly Eulerian elements, and took 22 h CPU time (on 1 CPU) for a simulation time of 10 ms.

The top view of the bird strike simulation on the composite wing leading edge structure is shown in Figure 7, the cross-sectional view in Figure 8. It can be seen that one part of the impactor penetrates through the skin into the structure and damages two ribs, while another part of the impactor splashes away from the outer surface. A correct representation of such impactor splitting phenomena is essential for reliable bird strike simulations to cover realistic loads of the secondary impact of the penetrating impactor material.

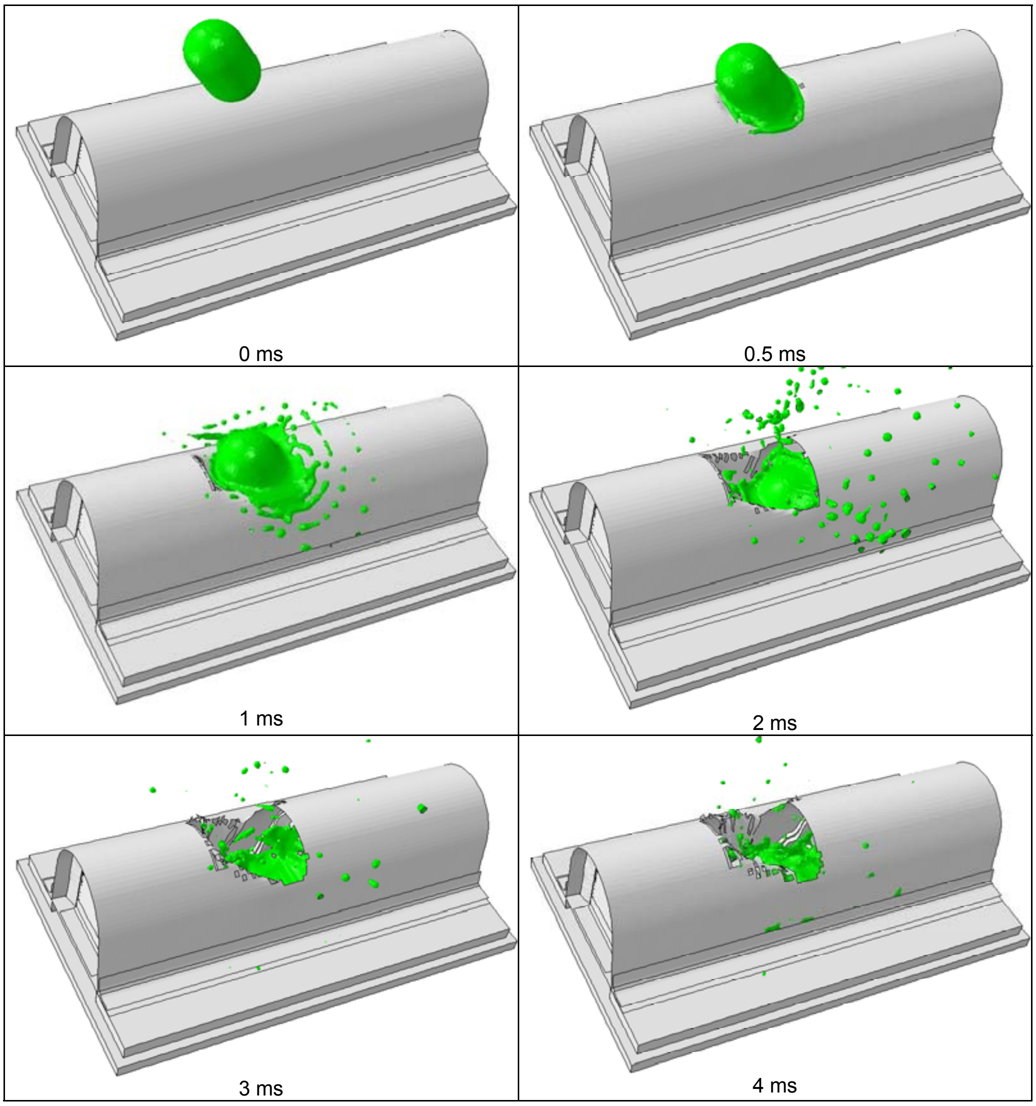


Figure 7. Bird strike simulation on composite wing leading edge (top view).

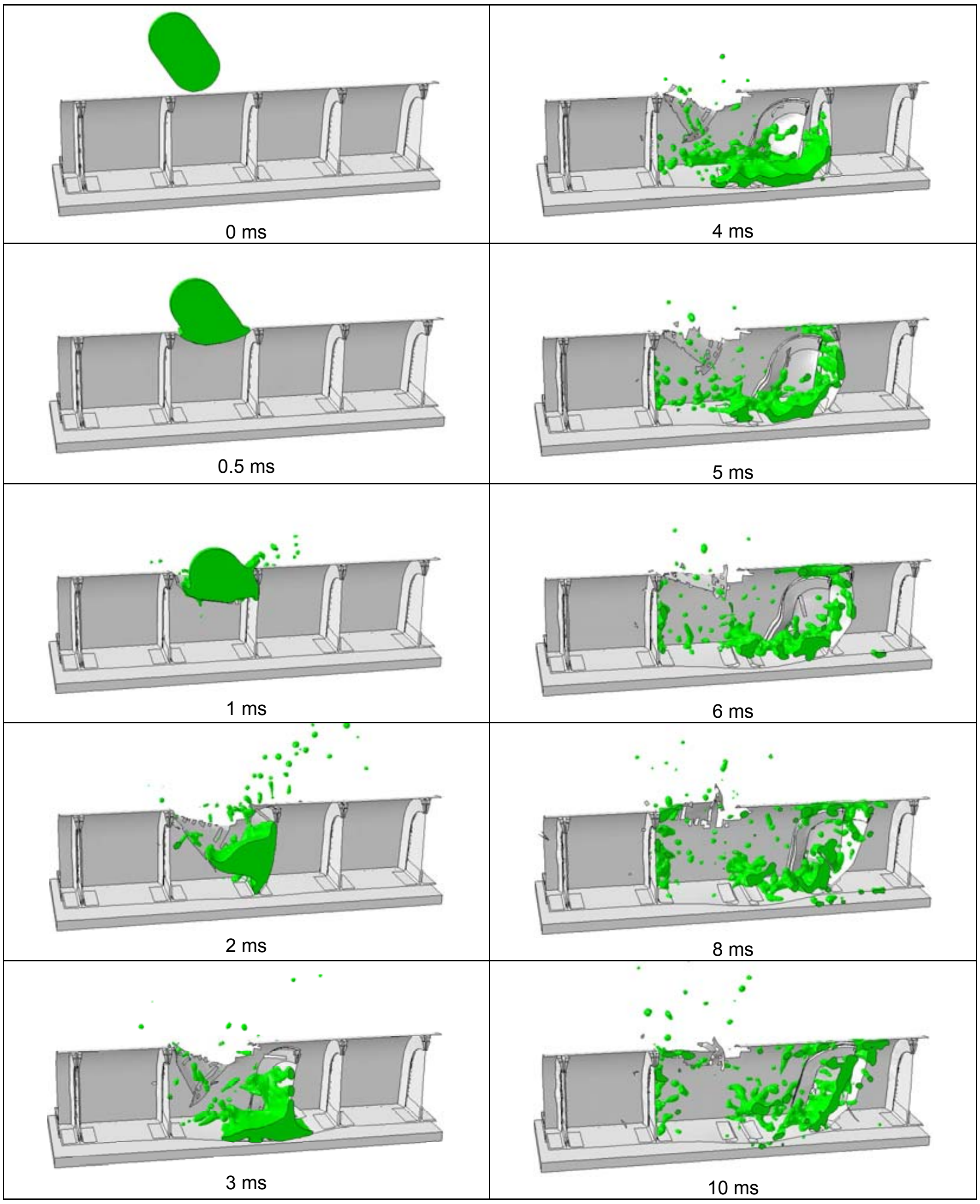


Figure 8. Bird strike simulation on composite wing leading edge (cross-sectional view).

For comparison with experimental impact test data, on the one hand, the qualitative deformations and damage during and after the test were adopted (Figure 9). On the other hand, the residual deformation of the metallic back plate was assessed, which is a good measure of the residual energy of the impactor material after skin penetration. Both comparisons are very satisfying, showing the potential of such bird strike simulations with the CEL modeling option.

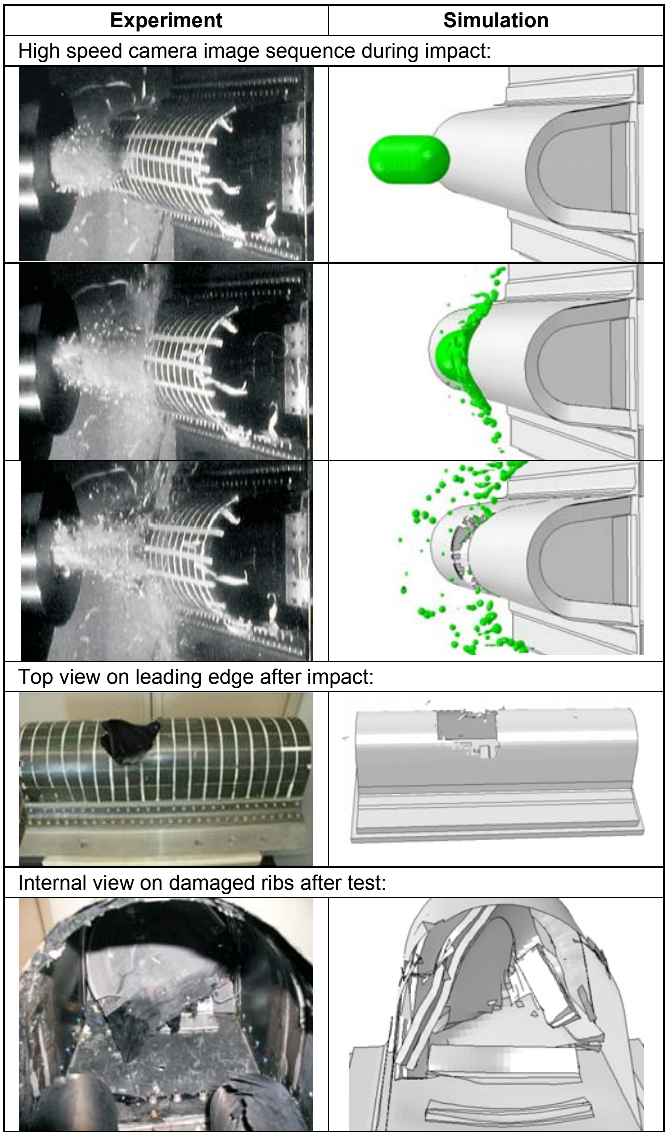


Figure 9. Comparison of test and simulation results.

6. Conclusions

In aircraft engineering there is a strong interest in reliable numerical methods for structural design under vulnerability aspects to reduce testing expenses and development time. One major load case is bird strike on aircraft components that are nowadays typically made of composite materials. This paper assessed the current bird impact simulation methods in Abaqus/Explicit 6.10. The CEL simulation approach is much more appropriate compared to the Lagrangian bird impactor modeling since no problems with excessive element distortion occur. The composite material modeling of the target structure requires the inclusion of intralaminar and interlaminar failure modes. This is typically achieved by a stacked shell modeling technique with cohesive elements for the delamination interfaces. The two example load cases, i.e. bird impact on a flat composite plate and bird impact on a composite wing leading edge, showed promising results that were achieved with these modeling methods and that are close to experimental test data. The influence of preload on the impact behavior of the composite structure could also be assessed, which increased the internal damage and reduced the ballistic limit.

Further ongoing work in order to increase the predictability and reliability of bird impact simulations on composite structures aims at accurate composite damage models for explicit calculations and the standardization of a substitute bird impactor.

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