Bird Strike Analysis for Impact-Resistant Design of Aircraft Wing Krueger Flap

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***Abstract**: Bird strike is a severe high velocity impact load case for all forward-facing aircraft components and a major design driver due to the high energies and the strict safety requirements involved. This paper summarises an experimental and numerical study to design a bird strike-proof lightweight metallic Krueger flap as a high-lift device concept for a laminar wing leading edge of a single aisle short range aircraft. The whole design process was based on numerical optimisations for static load cases in combination with high velocity bird impact simulations, with the focus on accurate modelling of the fluid-like bird projectile, the plasticity of the aluminium material and the failure behaviour of the structural hinges and fastened joints. Finally, a full-scale Krueger flap prototype was manufactured and tested under bird impact loading, validating the numerical predictions and impact resistance.*

***Keywords**: Bird strike, impact simulation, aircraft Krueger flap, gas gun test.*

1. Introduction

Much research effort in aeronautics is currently dedicated to achieve a laminar flow wing for transport aircraft, which significantly reduces air drag and hence fuel consumption. Laminar flow requires the avoidance of any unevenness of the wing surface that could cause flow turbulences. Since aircraft wings need high-lift devices to increase lift during low speeds of flight, extendible slats are the most common leading edge high-lift devices, which involve a flow-disturbing step at their trailing edge (Fig. 1a). Therefore, the more appropriate choice for a leading edge device targeting at laminar flow is a Krueger flap, which is stowed on the lower side of the wing and enables an undisturbed surface at least on the wing's upper side (Fig. 1b) (Schlipf, 2011; Schlipf, 2013). The basic concept of the Krueger flap was invented by the German aerospace engineer Werner Krueger in 1943 and was adopted in several commercial aircraft (e.g. Airbus A300, A310, Boeing 707, 727, 737 and 747).

The design and sizing process of such a Krueger flap against structural failure with the target of weight minimisation is based on typical flight loads and on particular risk load cases. As a forward-facing component, the risk of bird strike impact is hence relevant both for structural design and for part certification. Indeed, it turned out that bird strike is the design-driving load case that requires structural reinforcements, which would not be necessary for conventional flight loads.

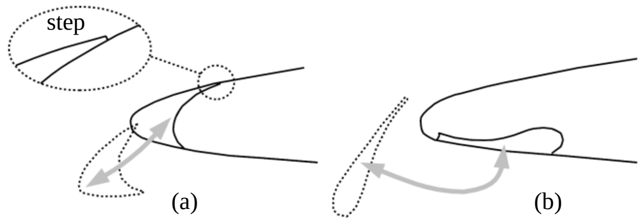

Figure 1. Illustration of (a) conventional slat and (b) Krueger flap as wing leading edge devices.

Bird strike is the major high velocity foreign object impact load case for aircraft with more than 90,000 reported cases between 1990 and 2008 solely in the USA (Dolbeer, 2009). The collision with a bird during flight can lead to serious damage to the aircraft. Consequently, the aviation authorities require that all forward-facing components have to prove a certain level of bird strike resistance before they are allowed for operational use. This can either be done by physical bird strike tests with a gas gun (Bedrich, 1996) or by sufficiently validated finite element (FE) simulations. Numerical methods are increasingly being used today for structural bird strike analyses as an efficient and cost-effective alternative to full-scale tests (Heimbs, 2011a). Bird strike simulation studies of conventional leading edge slats (Machunze, 2008; Heimbs, 2011b) and of trailing edge flaps (Ritt, 2009; Smojver, 2010) can be found in the published literature, but no such published studies seem to exist for Krueger flaps.

This paper presents a numerical and experimental study for the bird strike-proof design of a metallic Krueger flap concept for a laminar wing of a transport aircraft. The focus is on the accurate modelling of the fluid-like bird impactor, the plasticity of the aluminium material and the failure behaviour of the kinematic hinges and fastened joints. Finally, a full-scale Krueger flap prototype was manufactured and tested under bird impact loading for validation.

2. Krueger flap design principles

The Krueger flap in the focus of this study is supposed to be located on an outer position of the wing and was designed as a metallic solution made of aluminium. It basically consists of outer skins (top and bottom skin with leading edge) and an internal reinforcement structure containing spars and ribs (Fig. 2). Metallic bolts and rivets were used to join different parts. The internal structure needed to be designed, on the one hand, to include the necessary system components (e.g. for de-icing) and, on the other hand, to carry the flight loads and bird impact loads. At the same time, the design goal was to reduce the structural weight to a minimum. Hence, especially the optimized selection of sheet thicknesses was the target of the numerical analysis. Since major parts of the structure were supposed to be manufactured by milling, different thicknesses at different positions of the flap can easily be implemented. The thicknesses should be as small as possible to reduce the structural weight, but at the same time as large as necessary to withstand the bird strike impact at various possible impact positions. The criteria for successful bird impact resistance are twofold. Firstly, the kinematic parts and attachments of the flap may not fail or the whole flap or parts of the flap may not break off. In such a case the detached parts of the flap

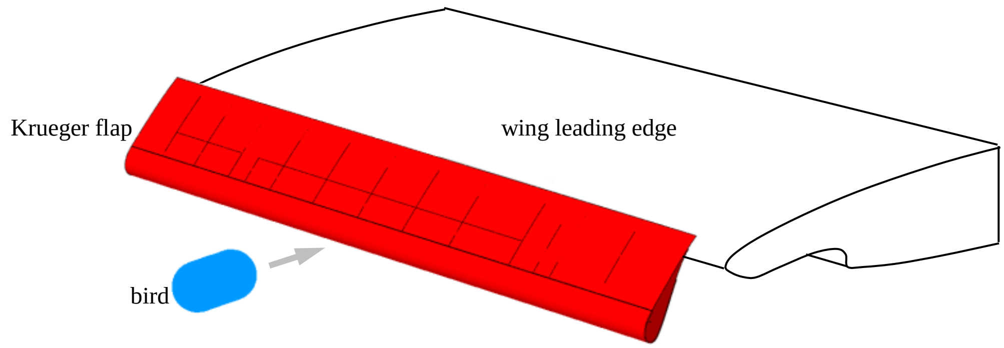

Figure 2. Krueger flap concept treated in this study.

might hit the empennage of the aircraft (vertical and horizontal tail plane) and lead to a critical, uncontrollable flight status. Secondly, the damage tolerance requirements for the damaged structure after impact necessitate carrying so-called ‘get-home loads’, which is a reduced load case for safe landing at the next airport. The get-home load case is typically analyzed in a post-impact simulation run, where – as a conservative approach – all damaged elements are initially removed from the simulation model.

3. Model development for bird strike analysis

The simulations within this study were performed with the commercial FE software Abaqus/Explicit 6.13. The following sections give some brief information on the most important modelling issues, which are the nonlinear material modelling, the modelling of the kinematic hinges and the modelling of the fastened joints, including failure for all those three cases. Finally, the accurate modelling of the soft body projectile for the bird strike simulation is discussed.

3.1 Material modelling

All major parts of the Krueger flap are made of aluminium. The ductility and plastic deformation of this material permits a high energy absorption capability. Material characterisation tests were performed under both quasi-static and high-rate dynamic loading conditions on a servo-hydraulic test machine to fully characterise the nonlinear material behaviour at various loading rates (Fig. 3). The material plasticity and potential failure need to be covered adequately in the simulation model. For this purpose, the yield stress vs. plastic strain was defined using tabular input to represent the experimentally determined yield curve. Ductile damage initiation and damage evolution were also implemented according to the test results. At the final point of failure the element is eroded from the simulation. Strain rate effects were not implemented as the test results and further literature data (Rodríguez-Martínez , 2011) prove that the material behaviour at the velocities of interest is not strain rate-sensitive (Fig. 3).

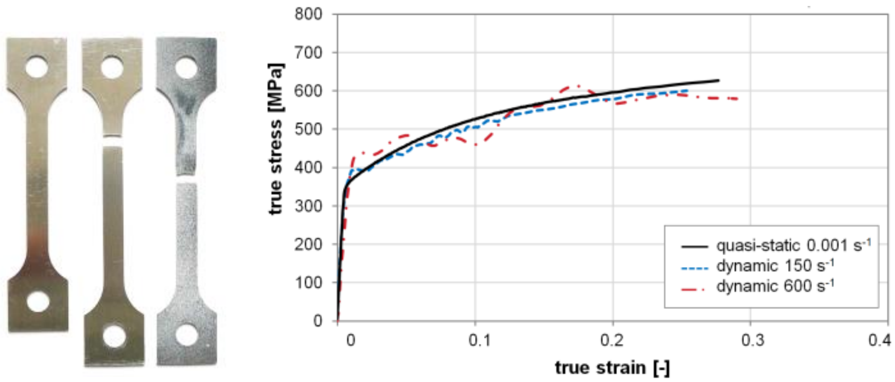

Figure 3. Material characterization of aluminium AA 2024 for constitutive modelling.

3.2 Kinematic hinges

Kinematic hinges exist at different positions of the Krueger flap and enable the rotation during flap extension using either cylindrical or spherical hinges. The simulation model was not only supposed to represent the degrees of freedom for rotation correctly, but also to cover potential failure of the hinges. The most versatile approach to model such hinges in Abaqus is the use of connector elements. They connect specific points and allow for the locking or unlocking of individual translational and rotational degrees of freedom. Failure can either occur due to failure of the bolt inside a hinge or due to failure of the lug of the kinematic part. Lug failure was captured by detailed modelling of the parts with solid elements including material models with failure (Fig. 4). Bolt failure by bending or shear loads was implemented into the connector element by defining maximum loads, after which the element is removed. Even connector stops could be defined easily for the connector elements, representing limits of rotational angles.

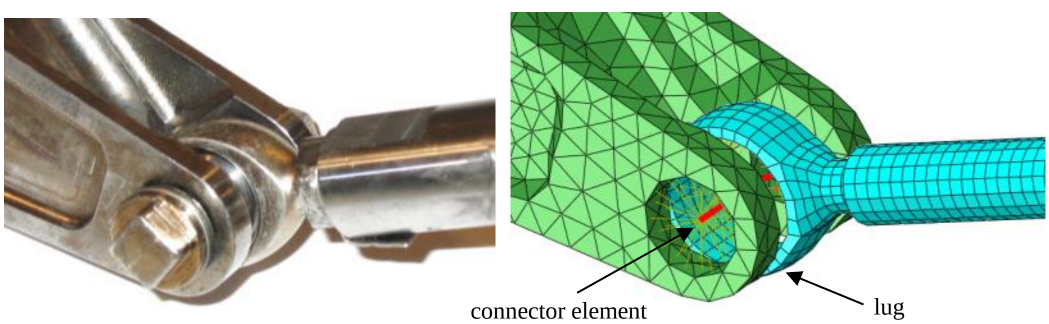

Figure 4. Modelling of kinematic hinges.

3.3 Fastened joints

Fastened joints based on bolts or rivets are mainly loaded in shear or normal tension and exhibit elastic and failure behaviour depending on bolt and sheet material and thickness (Heimbs, 2013a; Heimbs, 2013b). Again, connector elements are the most suitable approach in Abaqus to model such joints connecting two or more parts at node-independent, discrete locations. Elastic, plastic and damage behaviour can be ascribed to the six degrees of freedom in the connector section definition. Elastic translational behaviour for tension and compression was defined based on the equations of Gray and McCarthy (Gray, 2011; Gray 2012), which take into account the stiffness and thickness of the bolt and the joining material. The definition of the connector strength, plasticity and damage behaviour strictly depends on the failure mode, e.g. bearing, net tension, pull through, fastener failure, etc. Therefore, for a general analysis, the prediction of failure mode needs to be performed first based on respective equations for failure loads (e.g. given in the literature (Schwarmann, 2003)) and the identification of the load case with the lowest failure load. In the current study, bearing failure under shear loads and pull-through failure under normal loads are the most relevant failure modes. The calculated failure loads indicate the beginning of plasticity of the connector behaviour, see point A in Fig. 5. A simplified linear approach for the description of the plastic deformation was used here by defining point B by a value of plastic displacement and force. This point indicates the onset of damage (damage initiation). The progression of damage (damage evolution) up to point C is represented by a linear softening behaviour, characterised by a maximum displacement value when the connector element is removed from the calculation. The values for the description of the plastic and damage behaviour (points B and C) were derived from experimental force-displacement curves of joint failure tests in aluminium AA 2024 plates (Langrand, 1999; Birch, 2005).

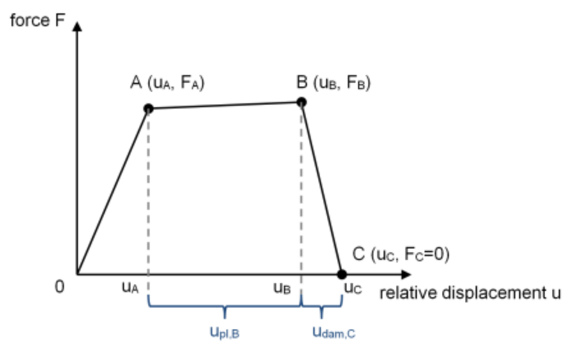

Figure 5. Illustration of elastic, plastic and damage behaviour of fastener element.

3.4 Bird projectile

When the bird hits the Krueger flap at the velocities of interest, it flows in a fluid-like manner over the target structure with the large deformations of the spreading material being a major challenge for FE simulations. Different numerical methods exist to model this fluid behaviour (Heimbs, 2011a). In this study, the smoothed particle hydrodynamics (SPH) approach was used, which is a meshless Lagrangian technique with the fluid being represented by a set of discrete interacting particles that can exhibit large deformations without the numerical problem of mesh distortion.

Since real birds are mostly composed of water, a water-like hydrodynamic response can be considered as a valid approximation for the constitutive modelling of the bird projectile. A Mie-Grüneisen-type equation of state (EOS) of the type us-up with parameters of water at room temperature was used in this study.

For a separate validation of the projectile model independent of the target structure, impact test results of birds being shot against rigid plates are typically used (Liu, 2014) , where the pressure or force vs. time response is compared to ensure an accurate loading and stationary flow behaviour. For this purpose, in-house test data from bird strike tests on rigid plates and rigid flap-like edges were used to verify both the correct load-time history and the correct splitting of the SPH bird model upon impact, which is of high relevance for the impact on the Krueger flap.

4. Bird strike simulation results

Based on these validated sub-models the final bird strike simulation model of the whole Krueger flap including wing leading edge and bird impactor was generated and used for impact simulations and various parameter studies. The impactor was a 4 lb bird with a velocity of 128 m/s. A total time of 15 ms was simulated.

In a first study, the influence of the impact point in terms of horizontal and vertical variation was assessed. Although the impact on the lateral positions close to the left and right edge are challenging in terms of bending moment initiated in the Krueger flap, the impact directly in the middle turned out to be the critical horizontal load case as the forces in the attachment struts and the flap itself were the highest. During the variation of the vertical position, the impact onto the Krueger flap’s front spar appeared to be the critical vertical load case, as the front spar is the major load-carrying member assuring structural integrity and impact damage tolerance. It was decided to use this combination of vertical and horizontal critical load case for the final real bird strike test. A cross-sectional view of this simulation is shown in Fig. 6.

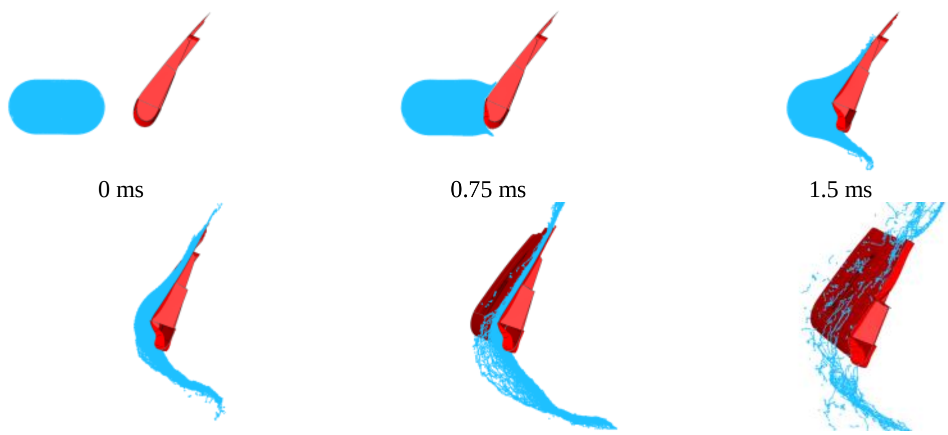

Figure 6. Cross-sectional view of bird strike on Krueger flap.

Nevertheless, the impact simulations on all other positions were used for the sizing of the metallic part thicknesses targeting at compliance with the design goals of impact resistance and residual strength. The thicknesses were optimized in a series of numerical simulations in order to assure static strength (linear static FE analysis), bird impact resistance (explicit FE analysis) and post-impact residual strength (linear static FE analysis with removal of damaged elements) with minimum weight, see Fig. 7.

Although plastic deformation occurs at the flap's leading edge, structural integrity is assured. Neither the kinematic hinges nor the fastened joints exhibit critical failure loads. The final design of the Krueger flap, derived from these simulations, was then used for the prototype manufacturing for a real bird strike test.

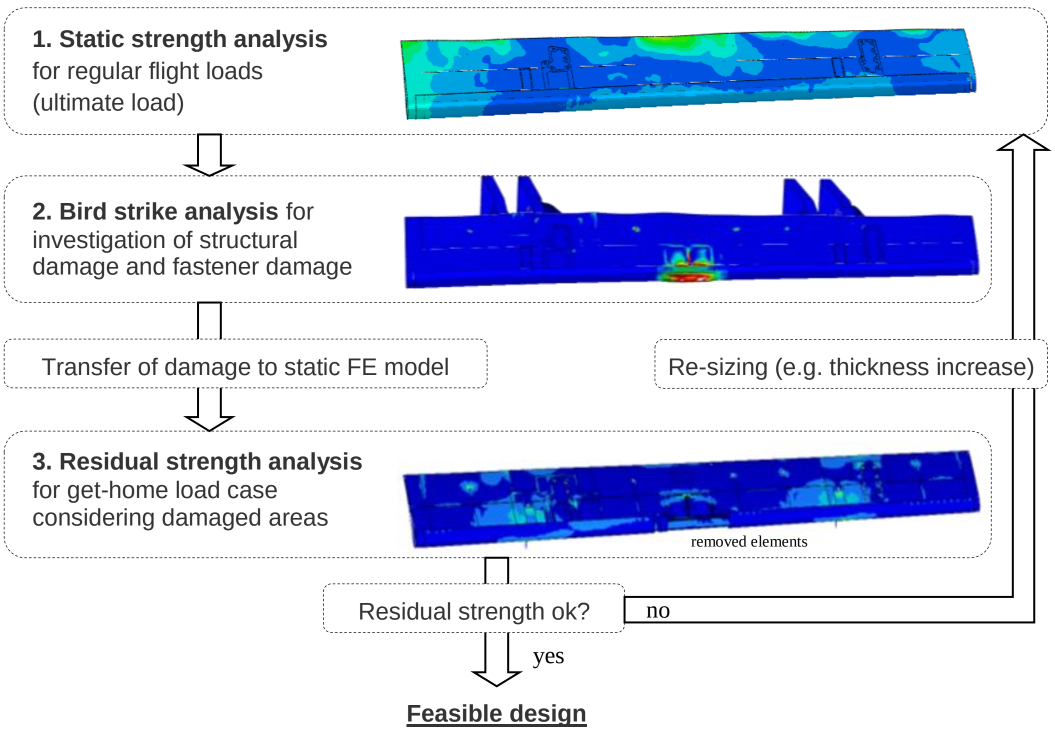

Figure 7. Iteration loop for get-home load verification.

5. Full-scale bird strike testing

For validation of the numerical predictions and of the impact-proof design, a bird strike test was performed at IABG with a full-scale prototype of the metallic Krueger flap. The flap was mounted to generic metallic ribs, which were then attached to a rigid wall with a mass of 10 tons (Fig. 8). The 4 lb bird projectile was accelerated in a gas cannon to an impact velocity of 128 m/s. The target point was in the center of the Krueger flap being the worst case impact scenario.

Neither the Krueger flap nor any attachment parts failed under this impact load and no fastener failure was observed. Moderate plastic deformations of the metallic flap occurred at the location of impact, similar to the pre-test simulation results. The numerically predicted structural deformations, reaction forces at the attachment points and strains on the upper and lower flap surface are in close agreement to the test results, proving the bird strike resistance of the Krueger flap and the accuracy of the numerical pre-test simulations (Fig. 9, Fig. 10).

Figure 8. Full-scale bird strike test set-up with gas cannon and rigid wall.

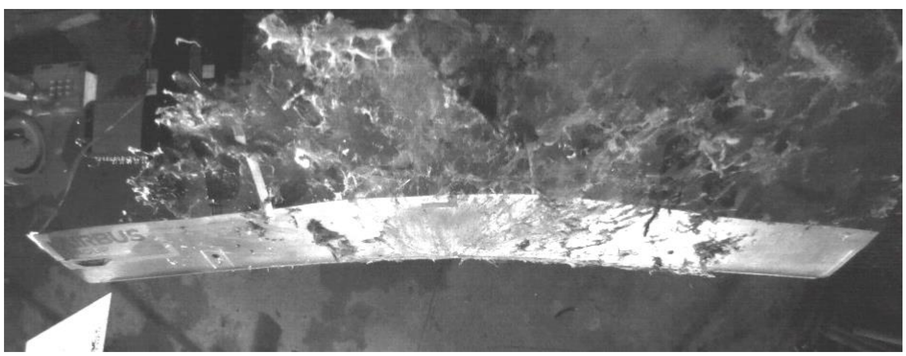

Figure 9. Maximum deflection of Krueger flap under bird impact (from high speed video).

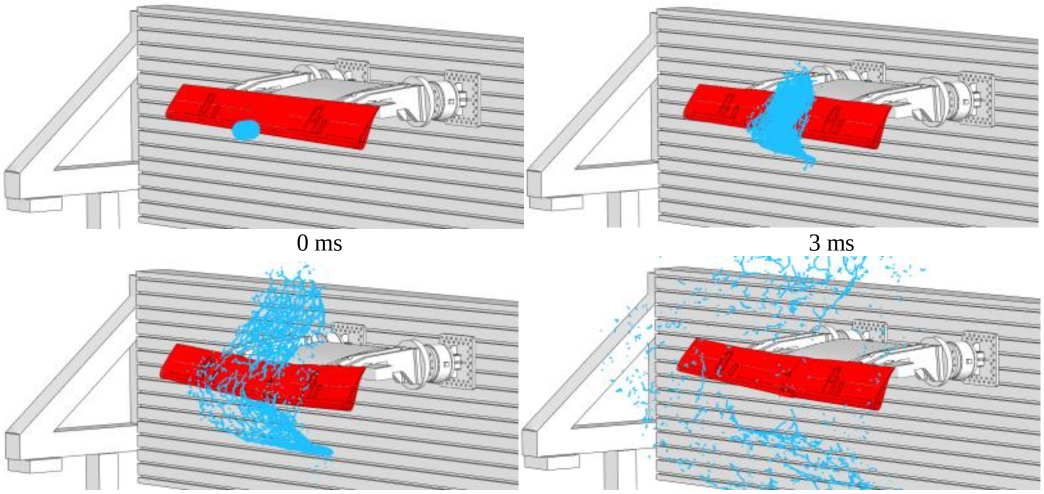

Figure 10. Simulation of bird strike on Krueger flap including realistic test set-up.

6. Conclusion

A procedure was presented to design and size a metallic Krueger flap for a laminar wing application against bird strike loads using advanced numerical methods. The approach was based on step-by-step validation of the modelling methods using experimental data. The major modelling aspects turned out to be the nonlinear material modelling, the kinematic hinges modelling, the fastened joints modelling and the hydrodynamic bird impactor modelling. The final design that was derived from the impact simulations has proven bird strike-resistance in a real full-scale gas cannon impact test.

The whole procedure using numerical methods for the design and sizing significantly increases the efficiency of structural developments compared to conventional approaches that are mainly based on tests. However, further improvements are possible in terms of multi-disciplinary optimization, combining the three simulation steps (static strength analysis, impact analysis and residual strength analysis) for material thickness optimizations in an automatic process to obtain more quickly the final design with less manual interaction.

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