Towards a novel design method for impact on leading edges

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Abstract – Results of a parametric study concerning low velocity impact on leading edge profiles is presented. This work is the first part of a larger program on the development of an engineering design method for impact on Glare. In this first part, experimental tests and numerical simulations on two-dimensional aluminium leading edge profiles were carried out. An extensive parametric study was done using numerical analysis. Selected configurations have been validated using impact tower testing. Impact tests were done with a solid impactor with a circular diameter on leading edges having a width of 20 mm. Profiles with three different thicknesses and three different sizes were tested. Impact velocities were in the range 1 to 8 m/s. The numerical models predicted the deformation of the leading edges accurately. Important impact parameters were identified and relations were established between impact parameters and geometrical properties of the leading edge profiles. The obtained results give important insight in the set up of simulations and experimentation and in the identification of important parameters of leading edge impact.

INTRODUCTION

A substantial part of aircraft structural components has to be designed against impact resistance, like leading edges of vertical and horizontal tailplanes, hatches and moveables. In a preliminary design phase, where the structure to be designed is only roughly known, it is difficult to size the structure against impact. Choices to be made do not only include the lay-out and geometry of the component but also material selection. For metallic components, basic design guidelines for bird impact exist [1]. These guidelines basically consist of empirical formulas derived from experimental results. For components build of composite or Glare materials, however, no such guidelines are available yet. This is mainly due to the complex failure behaviour of these materials. In general, the lay-out and thickness of the components are chosen conservatively based on methods for metallic components. The choice leads to thicker, and hence heavier, structures than necessary. Due to the increased use of composites and Glare, there is a strong need for a methodology which can assist the designer in the pre-design and development phase.

The overall objective of the program is to develop a design methodology for impact analysis of foreign objects on advanced new structures and materials like Glare. The final design method requires input on geometry and material parameters and results in quantities describing the final impact behaviour. This can be in the form of explicit relations, surrogate models or even more complex but standardized finite element models. With the help of such a design method, a reduced design time and more economically designed components result. In addition, this opens possibilities for cost-effective optimization of components.

Various types of impactors can be considered of which birds, debris and hail are the most important ones. The size of the current program does not permit to include all impactors and structural components. Therefore, the driving scenario in the current program is chosen to be bird impact on Glare leading edges.

The approach followed here is to develop a design and analysis framework for automated analysis. A generic, fully parametric CAD leading edge component is designed and analysed in an automated way. Once a generic component has been designed and validated, the CAD and finite element model are re-used and changes are re-analysed many times with minimal designer/analyser effort. The resulting simulations form a “cloud of points” which is used to derive an empirical method for the component of interest. With this approach not only the geometry or material changes can be studied, but also the lay-out of the component. In order to verify the numerical simulations, comparison with data from impact tests is crucial. Therefore, experimental testing plays an important role in the whole program.

The current paper presents the chosen design approach. First the experimental procedure is outlined. Two-dimensional leading edges were manufactured and impact tests were performed using a impact tower. A test matrix was set up with profiles of different geometry, thickness and impact velocity. Impact force and displacement were measured. All experiments were numerically analysed. Some preliminary results on the comparison of experiments and simulations are presented. Based on the outcome of the comparison, conclusions for further research are drawn.

DEVELOPMENT APPROACH

Several steps have been identified in the development of a reliable numerical simulation model of the leading edge. This ensures that all the important effects of structure and impactor are covered. The steps range in complexity from studying low speed impact on simple two-dimensional aluminium leading edge profiles to high speed soft body impact on a full three-dimensional Glare leading edge structure. In detail, the following steps are defined:

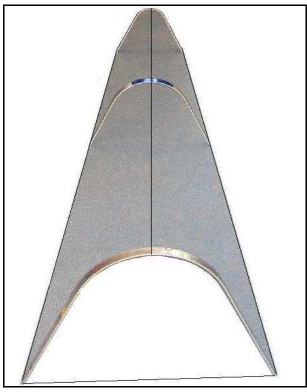
1. Impact on aluminium leading edge profiles (2D) with a solid impactor at low speed. The numerical simulations are validated with impact tower experiments. This relatively simple 2D structure is used for studying the basic deformation mechanisms. Analytical relations can be derived [2,3] to support the definition of the explicit relations.
2. Impact on Glare leading edge profiles (2D) with a solid impactor at low speed, both experimentally and numerically. In addition to step 1, here the effect of Glare material properties and failure mechanisms are also studied. Material properties of Glare are obtained from tensile testing.
3. Impact on Glare leading edges (3D), with a solid impactor at low speed. Numerical modelling and simulation are verified with limited experimental testing. Going from 2D to 3D structures different failure mechanisms will occur.
4. Impact on Glare leading edges (3D), with a solid impactor at high speed. High strain rate data for Glare is needed for an accurate prediction of the impact behaviour. Limited testing is needed to verify the numerical simulations.
5. Impact on Glare leading edges (3D), including aluminium ribs, with a bird-like material at high velocity. Verification of the simulation procedure is done with existing bird impact tests on Glare leading edges [4,5].

During all steps an automatic analysis procedure for fast re-analysis of the impact behaviour is being developed. In each step, more complexity is added to the simulation model and parameters are optimized. The effects of structural thickness, material and impact properties on the structural behaviour are studied. In the current paper the first experimental and numerical results of step 1 are presented.

EXPERIMENTAL PROCEDURE

An extensive test program was set up in which two-dimensional leading edge profiles of different size and thickness were manufactured and impacted using an impact tower. The leading edge profiles were made of aluminium 2024-T3. The geometry of the profiles corresponds to the geometry of the leading edge of a vertical tailplane typically found on large commercial airplanes. A leading edge has usually a tapered form, getting smaller from tail root to tip. Therefore, at three different sections in the leading edge (Figure 1) the geometry and dimensions were taken. The smallest profile measures 20 by 15 cm (base width by height), the middle profile 35 by 22 cm and the large profile 46 by 28 cm. Three nominal thicknesses were used: 1.6, 2.0 and 3.2 mm. These are typical thicknesses found in leading edges. All profiles have a section width of 20 mm and can therefore be considered as two-dimensional structures.

The profiles were made out of flat aluminium plates and manually rolled in their final shape. Although this is a rather crude manufacturing process, only slight geometric differences were found between similar sized profiles. After rolling of the profiles, internal stresses were not removed.



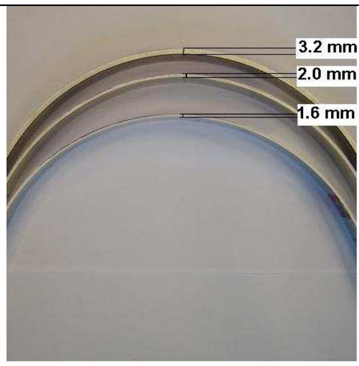


Figure 1 On the left, three different sized two-dimensional profiles are shown. They are chosen at the root, the middle and the tip of the leading edge. Typical length of the leading edge is 6 meters. On the right, three different thicknesses are shown. These are typical thicknesses found in leading edges.

The material properties were obtained from tensile tests on specimens cut out of the three flat aluminium plates. Five tensile tests were done for each thickness. Results from three different thicknesses did not significantly differ so the results for all three were averaged. The following (average) properties for the three thicknesses were obtained: modulus of elasticity 68 GPa, yield stress 304 MPa, tensile stress 445 MPa and failure strain 18%. The measured engineering stress-strain curves were converted to true stress-strain curves for use in the numerical simulations. No high strain rate data was needed because the impact velocity in the first series of tests was sufficient low.

The impact experiments were carried out using an impact tower, model Dynatup 8250. The impact mass was kept constant during all experiments. The head of the impactor has a circular diameter of 10 mm. The total impact mass is 3.2 kg.

A data acquisition system measured the impact force and displacement at the impact point as a function of time. Before and after the test the position of the impact point was measured separately with a measurement device. The end displacement, i.e. the difference in position of the impact point before and after the impact, was used as a typical property for comparison with the numerical simulations. The impact velocity was measured both digitally and from the drop height.

The test matrix with experiments is shown in Table 1. In the first set of experiments on the aluminium profiles (numbered AL1 to AL9) all three geometries with three different thicknesses were tested. The impact speed was 3.5 m/s which corresponds to an impact energy of about 20 Joule. At least two tests at the same condition were carried out in order to check the repeatability of the tests. The presented end displacement is the average value of all tests. In the second set of tests, the middle sized profiles with thickness 2.0 and 3.2 mm were impacted with velocities ranging from 1.0 to 8.0 m/s.

The maximum force and measured end displacement for each test condition is shown in Table 1. The results are average values. In two tests (AL15 and AL19) the maximum deflection of the profile was limited by an arrester plate situated under the impact tower. The measured end displacement in these cases is therefore not considered to be valid.

NUMERICAL SIMULATIONS

The geometry and mesh of the profile and the impactor are generated with MSC/Patran. In generating the geometry of the profile, it is assumed that the curved part of the profile is a perfect circular arch. In practice this may not be exactly the case since no mould was used and therefore similar sized profiles may differ a little from each other. Otherwise it would require an exact measurement and modelling of each separate profile. However, before the profiles were tested, their exact geometry was recorded. If the results would indicate that a more accurate modelling is required, this would still be possible.

			Experimental results			Numerical results		
Result ID#	Profile thickness (mm)	Profile size	Impact speed (m/s)	Max. Force (N)	Measured end displacement (mm)	Result ID#	Max. Force (N)	End displace-ment (mm)
AL1	1.6	Small	3.5	427	42	PAMAL1	250	41
AL2	2.0	Small	3.5	700	20	PAMAL2	700	21
AL3	3.2	Small	3.5	2226	6	PAMAL3	1570	7
AL4	1.6	Middle	3.5	150	90	PAMAL4	125	78
AL5	2.0	Middle	3.5	272	46	PAMAL5	190	50
AL6	3.2	Middle	3.5	791	12	PAMAL6	600	14
AL7	1.6	Large	2.5	85	78	PAMAL7	128	50
AL8	2.0	Large	3.5	165	74	PAMAL8	250	76
AL9	3.2	Large	3.5	528	16	PAMAL9	467	13
AL10	2.0	Middle	1.0	210	2	PAMAL10	148	2
AL11	2.0	Middle	2.1	251	15	PAMAL11	242	10
AL12	2.0	Middle	2.8	258	27	PAMAL12	304	22
AL14	2.0	Middle	4.0	275	98	PAMAL14	308	62
AL15	2.0	Middle	4.8	280	119 [a]	PAMAL15	355	NA [b]
AL17	3.2	Middle	5.8	904	55	PAMAL17	675	57
AL18	3.2	Middle	6.6	894	86	PAMAL18	695	85
AL19	3.2	Middle	8.0	748	217 [a]	PAMAL19	759	NA [b]

[a] maximum displacement during impact was limited by impact tower arrester plate.
[b] NA = not analyzed.

Table 1 Experimental and numerical results

The numerical simulations are carried out with the explicit finite element code PAM-CRASH [6]. The profiles are modelled with four-node thin shell elements. Material type 103 is used for modelling the material of the profile. It corresponds to elastic-plastic isotropic thin shell materials. This material model uses a plasticity algorithm that includes transverse shear effects, thus exactly satisfying Hill's criterion and precisely updating the element thickness during plastic deformation. The elastic-plastic behaviour was obtained from tensile tests and input as pairs of plastic tangent modulus and the effective plastic stress. For the three thicknesses tested, different true stress-strain curves were used. No strain rate data was included in the material model as the impact speeds are sufficient low to justify this approach.

The number of integration points through the thickness was varied from three (default) to five in order to investigate the effect on the results. No substantial effect on results and analysis time was seen, so it was decided to use the default value of three. A variation of mesh size was carried out. It appeared that four elements over the width of the profile gave sufficient accurate results. This corresponds to an element size of 5 by 5 mm. The ends of the profile are fixed just as they are in the experiments, i.e. both translations and rotations are suppressed.

The shape of the impactor is modelled as close as possible, especially the part which comes in contact with the profile. The impactor is modelled with 10-node tetrahedral elements. Material type 99 (null material) was chosen. The impactor is considered as a rigid body. Internal forces are not calculated in this case. However, realistic mass density of 7850 kg/m^3 and material properties are defined since they are needed for the determination of the contact stiffness. An additional mass of 3.0 kg was added to the centre of gravity (COG) of the impactor to reflect the exact weight of the impactor, which is 3.2

kg. The boundary conditions of the impactor are applied to its COG and it is allowed only to displace vertically, i.e. no rotations are allowed. This reflects the condition in the impact tower.

Contact type 34 between impactor and structure is defined. This is a non-symmetric node-to-segment contact with edge treatment. The profile, having a coarser mesh than the impactor, is chosen as the master surface. Nodes of the impactor are chosen as the slave. The coarser mesh of the profile reduces the potential of master nodes penetrating the slave surface and also reduces the contact computations. A small amount of friction was added to the contact definition. During several impact simulations it appeared that the profile would slide away from the impactor if no friction was defined. A fixed contact thickness of 2 mm was used in all simulations. Definition of self-contact is not necessary if the profile does not fail because no parts of the profile will contact each other during the impact duration. However, after the profile fails parts can come into contact with each other. The first goal here is, however, to simulate the impact behaviour up to the point of failure. To reduce computation time, only a part of the profile is selected to come into contact with the impactor.

The results of the numerical simulations are presented in Table 1. The same set of input control parameters were used for all simulations. In this stage no optimization of parameters was carried out to find the best match between experiments and numerical simulations.

DISCUSSION OF RESULTS

An important issue in experimental testing is that the results are repeatable. This means that the outcome of multiple tests on similar profiles must not differ too much from each other. In Figure 2 an example of the measured force-displacement curves for two tests (22 and 23) on identical profiles is shown. The force-displacement curves are filtered with a moving average method to remove the noise from the measurement data. As can be seen the results of the two tests are almost identical. For most of the other tests, repeatability was good to very good. In Table 1 the results for the maximum forces and end displacements are averaged results of two or three tests.

In Figure 3 the measured end displacement as function of the profile thickness for the three different profiles is shown. Impact velocity in all cases is 3.5 m/s. It can be seen that the thinnest profiles have the largest end displacement. This is obvious as the stiffness of these profiles is lower. For thicker profiles the difference in end displacement gets less. The relation between profile thickness and end displacement is not linear.

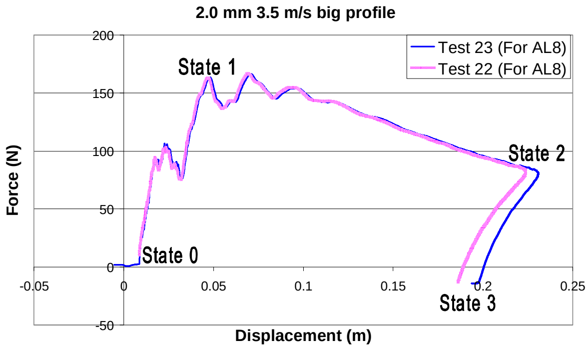


Figure 2 Repeatability of force-displacement curves for two impact tests on identical profiles.

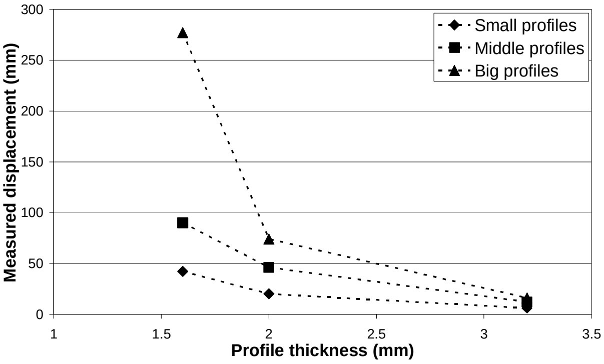


Figure 3 Relations between profile thickness and measured end-displacement for three different sized profiles. The remaining end displacement increases for larger profiles with similar thickness. With thick profiles, end displacement depends less on the profile size.

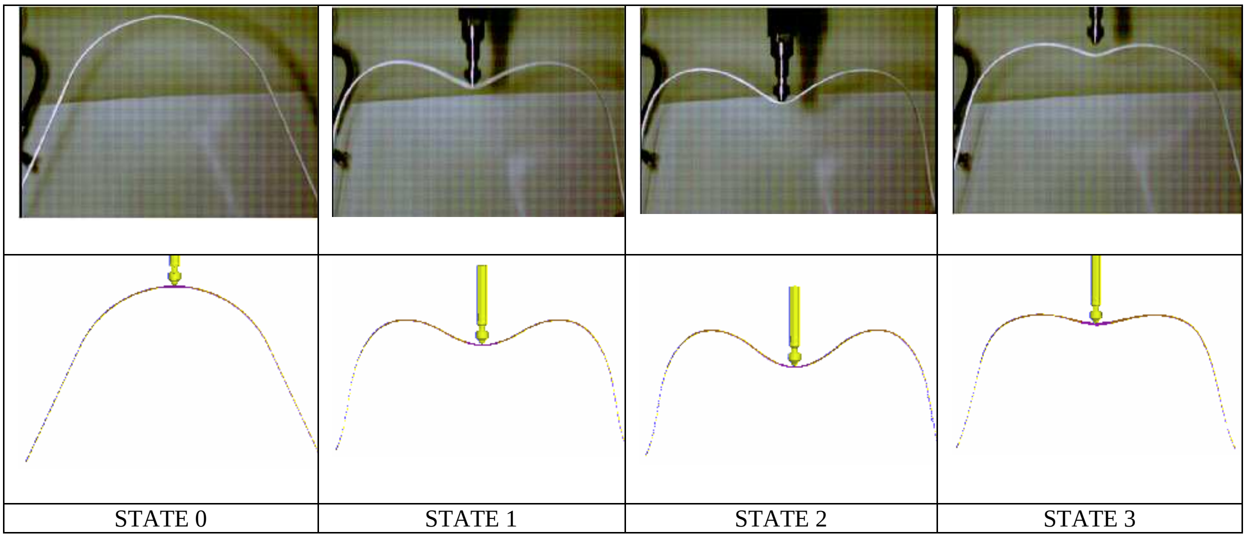


Figure 4 High-speed camera pictures (top) and simulation results (bottom) at different states.

The difference in maximum impact force between experiment and simulation is larger. To a large extend this can be explained by the selection of the maximum force value. A procedure to improve the selection has to be derived yet. The overall trend is that the smaller the profiles are, the larger the maximum force becomes.

In Figure 4, four states are shown during an impact event. On the top row snap-shots of a high-speed camera are shown. The bottom row depicts the results of the numerical simulation at the same time. State 0 is the moment just before the impact (see also Figure 2), state 1 is when the maximum force is reached, state 2 is where the profile reaches the maximum displacement and state 3 shows the resulting displacement of the profile after the spring back. The frames are taken by a high-speed camera with 500 frames per second. The numerical simulation shows closely the deformed states.

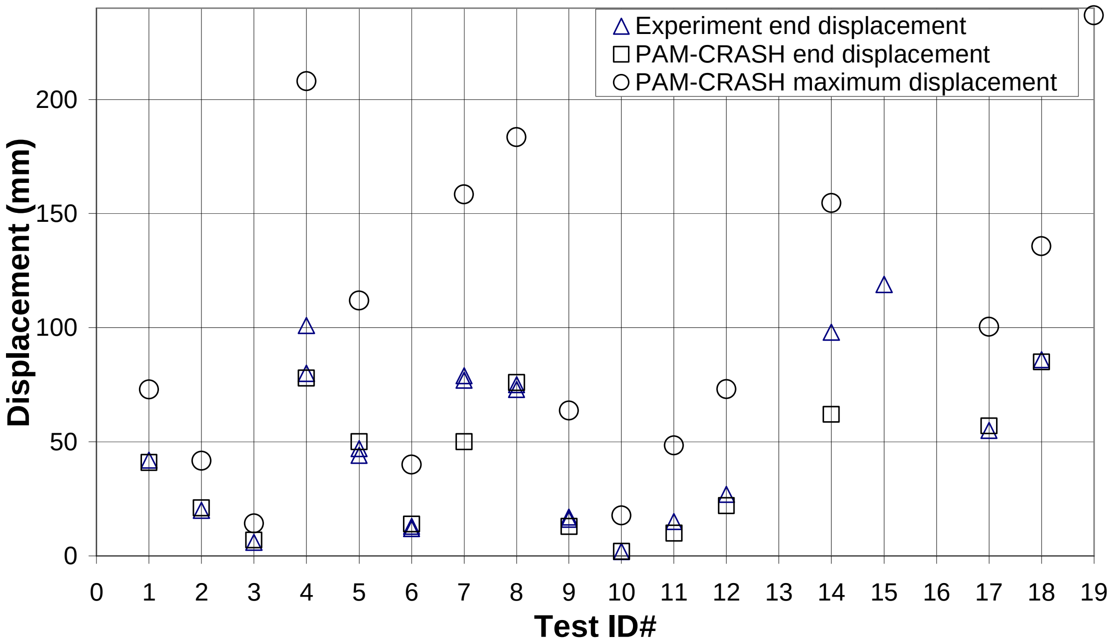


Figure 5 Comparison of displacements from experiments and numerical simulations. The measured and simulated end displacements are close to each other. The maximum displacement shows a similar trend as the end displacement. Prediction of one displacement from the other is therefore possible.

Figure 5 shows the displacements found in both the experiments and simulations. Besides the measured and analysed end displacement, also the maximum displacement found in the simulation is plotted. In some cases there is a larger difference in end displacement. The reason for this discrepancy is currently under investigation.

CONCLUSIONS

The first part of a program for the development of a novel design tool for bird impact on Glare leading edges is presented. In this first part, an extensive experimental and numerical parametric impact study was conducted on two-dimensional aluminium leading edge profiles under low velocity impact. The impact mechanisms and parameters steering the impact behaviour of the leading edge profiles were studied. The obtained results give more insight in the basic impact behaviour of two-dimensional leading edge profiles.

The experiments show that low velocity impact testing on aluminium leading edge profiles is repeatable. The numerical simulations match in most cases the experimental results. The combination of experimental testing and numerical analysis is necessary to verify and validate the final finite element model of the complete leading edge. The explicit relations between impact parameters and impact responses have to be established yet, but trends are clearly identified in this stage of the program.

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