PRELIMINARY INVESTIGATION ON THE CONSEQUENCE OF A BULLET IMPACT ON HELICOPTER COMPONENTS

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ABSTRACT

Requirements for military helicopter certification call for a level of tolerance to bullet impacts. Recent studies have shown that also small-calibre guns can cause a helicopter crash and therefore have to be considered as an actual menace for flight safety. Since experimental tests are expensive and time consuming, reliable and computationally efficient numerical models for predicting damages due to ballistic impacts are fundamental to improve the damage resistance and then safety of military helicopters. A method for creating reliable numerical models to investigate the consequences of a bullet impact onto aircraft subcomponents critical for flight safety is introduced here. A campaign of tests was initially carried out to collect data for validating a numerical model and evaluating its reliability. Simulations of bullet impacts were then performed and efforts provided to enhance the efficiency and the straightforwardness of the numerical model so that it could be suitable for industrial applications. The results of the simulations were compared with the experimental data and a good agreement was observed. In view of this, it was recognised that the numerical approach is time- and cost-effective, able to provide accurate results and therefore a useful design tool.

1. INTRODUCTION

Requirements for military helicopter homologation call for a level of tolerance to bullet impacts [1].
Recent studies have shown that, often, even small-calibre guns cause a helicopter downing or crash and therefore may represent a serious threat for flight safety.
Since full-scale tests are time-consuming, difficult to perform and expensive, reliable and computationally efficient numerical models that allow to predict bullets impacts damages can be a useful design tool to improve damage resistance and then the safety of the military helicopters.
The research work introduced in this paper, in particular, aims at validating numerical models for the prediction of the consequences of a small-calibre bullet impact onto aircraft subcomponents which are critical for flight safety such as non-redundant and unprotected items like the most of the rotor's components.
In particular, since numerical models have to be accurate and time-efficient before being integrated into industrial practice, the attention focused on a procedure for developing numerical models that satisfies these criteria.
A campaign of tests was initially carried out to collect data for validating the numerical model and evaluating its reliability.
A test device was built and used to throw small-calibre brass projectiles toward flat plates of two different thicknesses made with an aluminium alloy typical in aircraft constructions.
Simulations of the bullet impacts were then performed and efforts were provided for enhancing the efficiency and the straightforwardness of the numerical model focusing, in particular, on FE mesh and material modelling.
Various combinations of material models and failure criteria were investigated. Data from literature and specific static tests were used as a guide to find the parameters which represent the best trade-off between accuracy of the results and required computational efforts.
In an effort to further validate the numerical model, an additional impact scenario, the blunt projectile impacts, was also simulated and the results compared with experimental data obtained from bibliographic sources [1]. The findings obtained in this part of the research provided the necessary background to develop a numerical model to draw the limit curve for the impact of bullets onto aluminium alloy plates.

2. TEST FACILITY

Impact tests using small calibre-brass projectiles were carried out to collect data for validating a numerical model and evaluating its reliability.

2.1. Projectile launcher

A device to carry out high-speed impact tests using small-size blunt bodies or projectiles was designed, and built at the Laboratory for the Safety in Transport (LAST), Politecnico di Milano.

The device consists of four parts: a fourteen-litres air reservoir (or tank), a nozzle, a dam valve and a six-metre launch tube.
The air reservoir can be filled with compressed air at a maximum pressure of 8 bar.
The dam valve is a 0.05 mm (rectified thickness) nickel plated brass (Ni Cu-Zn) sheet. To open the valve, a radio-controlled device was used that breaks the valve and release the compressed air: a simple, but quick, accurate and efficient (large outflow) system.
The reservoir is then connected by means of a convergent-divergent nozzle to the launch tube – i.e. an aluminium barrel (length 6 m and inner diameter of 40 mm).
The projectile is inserted in the barrel close to the nozzle before the launch.
When the inner diameter of the launch tube is usually larger than the cross-dimension of the projectile used in the test, PVC sabots are used to accelerate and guide the projectile. The sabot is then arrested at the end of the barrel by means of a device (a crash-tube absorber) able to dissipate the energy of the sabot without altering the trajectory of the projectile.
Sandbags are placed behind the target to arrest the bullet and allow its recovery for a post-test examination.

2.2. Impact velocity

The impact velocity of the projectile was initially controlled by modifying the pressure of the air in the reservoir.
However, due to the effects of the friction between the sabot and the barrel this approach is not accurate for low pressures and hence for low impact velocities.
In view of this, an alternative approach to control the impact velocity was adopted: the pressure was kept constant at 8 bar and the sabot ballasted.
Calibration tests were carried out and the following constant energy estimation was obtained:

$$v = \sqrt{\frac{\overline{E} \cdot 2}{m}} = 58.8 \cdot \sqrt{\frac{1}{m}} \tag{1}$$

where $\overline{E}$ [J] is the average kinetic energy for the performed tests, m [kg] the mass of the projectile and the ballasted sabot and the v [m/s] the velocity. This formula yields an accurate estimation until the choked condition in the nozzle is reached (i.e. around v = 200 m/s). Thus, a correction is required for high speed launches.

2.3. Data acquired

When tests on flat panels are carried out a massive 600x500 mm aluminium frame mounted on steel columns is used.
Between the frame and the columns are installed three of four mono-axial load cells (full scale 20 kN) to measure the force transferred to the constrains.
On the frame three mono-axial piezoelectric accelerometers (full scale 250 g) are also installed to estimate the inertial forces thus improving the estimation of the load transferred from the projectile to the target.
In the tests a total of twelve strain gauges can be installed on the target plate to acquire the complete strain in various points of the target.
For data acquisition, a 14 bits A/D converter with a maximum of 64 channels and a maximum sampling frequency of 2.2 MSamples/s was used.

Figure 1. The projectile launcher used in the bullet impact tests.

Figure 2. The sabot used in the bullet impact tests and a bullet.

2.4. High speed camera

The tests are recorded with a Phantom high-speed camera that allows a maximum frame rate of 100'000 frames/s and a maximum resolution of 1024x1024.
In order to keep the exposure time low, around the test area are installed lights able to clearly illuminate without relevantly warming up the target.
The trajectory and the velocity of the projectiles during the test are evaluated by post-processing the high-speed recordings with a code for automatic tracking. A technique that proved to be more reliable and accurate than the measurements of the photo-cells speed trap and allowed measuring the post-impact velocity of the projectiles and their trajectory (in the horizontal plane) without the need for further measurement devices.

3. BULLET IMPACT TESTS

Bullet impact tests were performed on thin, 2 mm, and thick, 6 mm, aluminium 400x400 mm flat plates.
An 8 mm (0.326 in) calibre, sharp pointed brass bullets the geometry of which is representative of common military ammunitions, were used as projectiles

3.1. Tests on thick plates

Several tests were performed using the maximum speed achievable with the test facility (210 m/s) in order to evaluate test repeatability and to acquire data for validating the numerical model.
However, due to the limited velocity achievable the bullet was not able to penetrate the thick plates.
During the tests, the measures from the load cells, from the accelerometers and from the strain gauges were acquired and the high speed video recorded.
In
Figure 3 a sequence of frames from the high-speed movie is shown.
The projectile, after impacting the plate, looses the most of its kinetic energy and ricochet. After the test, it shows evident damages while the plate presents only small graze and scratch in the impact area.
In
Figure 4 it is shown a cut section of the plates were. The depth of the impact crater was measured to be used as reference for evaluating the reliability of numerical models.

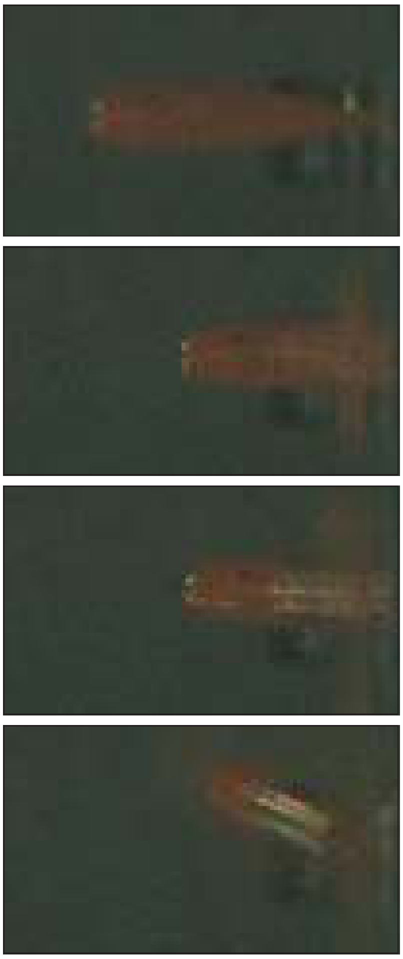
T = 0 μs
T = 56 μs
T = 111 μs
T = 500 μs

Figure 3. Impact sequence of the test on the thick target plates.

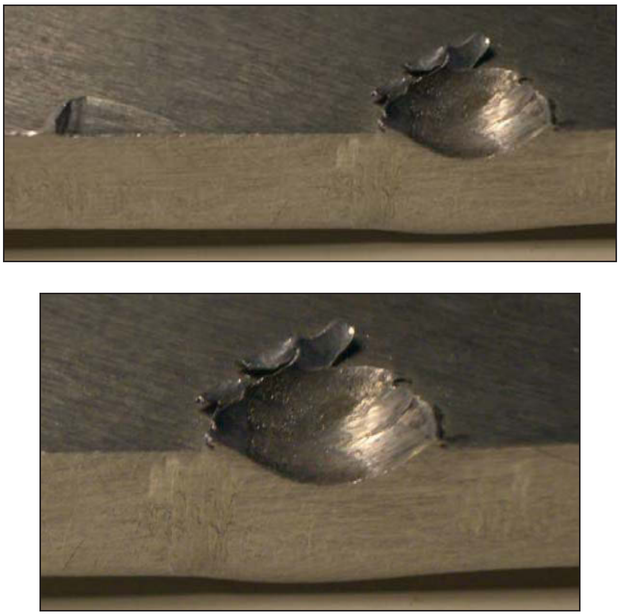

Figure 4. A cut section of the thick plate after the test.

3.2. Tests on thin plates

Several tests of impact on thin plates were performed with impact velocities ranging from 127 m/s to 209 m/s. In the most of these tests, the projectile perforated the plates.
After the impact, the projectile showed no relevant deformations, whilst the plates presented a failure characterised by a petaling (Figure 5) with a level of axial-symmetry dependent on the incidence of the projectile at the moment of the impact.
During the tests, the projectile velocity before and after the impact was calculated post-processing the high speed video recording.
In addition, the measures from the load cells and from the accelerometers were acquired as a further reference – although these measurements are not usual for ballistic test of this kind.

FRONT

BACK

Figure 5. Views of the thin target plate after the impact.

4. IMPACT OF BLUNT BODIES

Due to the lack of own experimental data during the first steps of the research, the development of the numerical model was initially carried out using data from literature sources [2].

Two impact scenarios were considered: the impact onto a thick aluminium plate, 0.25 in; and the impact onto a thin aluminium plates, 0.125 in.
The same numerical model was used for both cases.

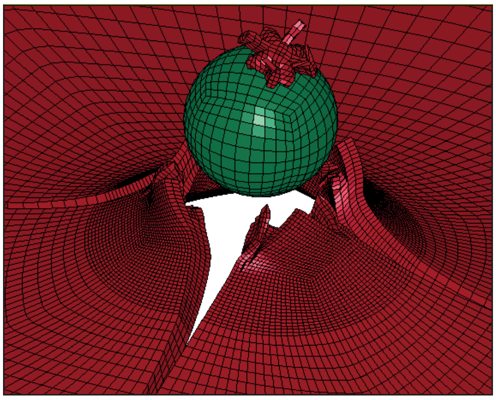

Figure 6. Simulation of the impact of a blunt body against a thin plate.

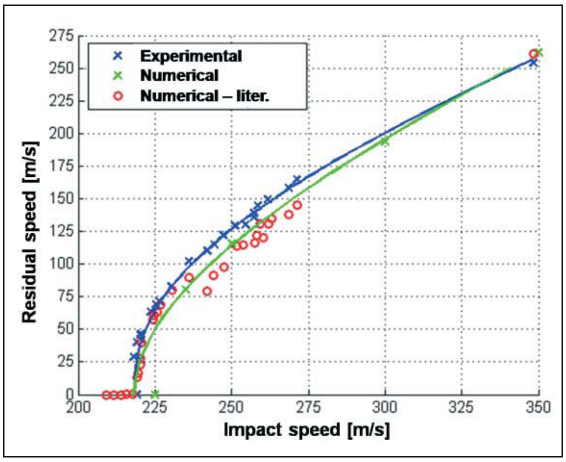

Figure 7. Residual velocity of a blunt body after the impact onto a thin plate.

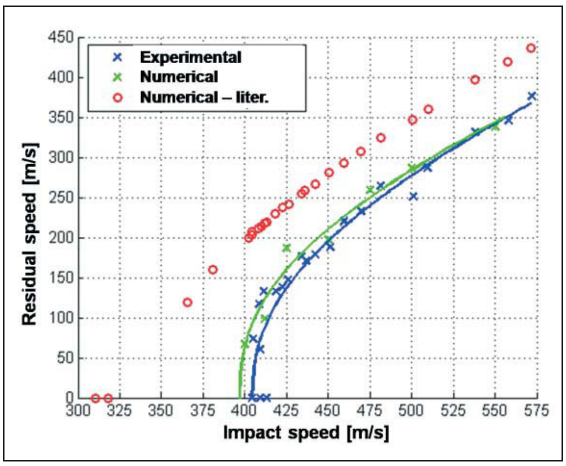

Figure 8. Residual velocity of a blunt body after the impact onto a thick plate.

The residual velocities calculated with the numerical method were compared with the results of the experimental tests.
The correlation yielded excellent results both for the thin (Figure 7) and for the thick plates (Figure 8), confirming the reliability of the model developed. Thus, the same modelling technique was applied to the impact of sharp pointed projectiles.

5. IMPACT OF SHAPED PROJECTILES

Moving from the good results obtained for the blunt body, the same approach was adopted to develop, tune and validate a numerical model able to reproduce the impact of a small-calibre projectile onto aluminium alloy plate.
The experimental impact tests previously carried on on plates characterised by two different thicknesses was simulated
The same model set-up was applied to different cases to test the performances of the method under different conditions.

Simulations were carried out using LS-Dyna (version 9.71), a widely diffused nonlinear explicit FE code [9]. The approach adopted however was such that it could be readily extendible to the use of other explicit codes.

5.1. Numerical model

The Lagrangian approach was adopted to model the event. This approach is typical of the explicit FE codes and therefore, adopting this approach, it would be easier to guarantee the generality and portability of the model.
In addition, according to recent research works [3], the Lagrangian approach allows obtaining better numerical-experimental correlation than other approaches such as the Eulerian and the ALE approaches or the mesh-less SPH and EFG approaches.
All the components, including the projectile, the target plates and the supporting frame, were modelled with eight-node constant-stress solid elements and a viscous hourglass control was defined to prevent zero-energy modes.
In an effort to reduce the CPU time without compromising elements regularity, discontinuous meshes characterised by different level of refinement were created and joined together using *tied* contact interfaces.
When dealing with discontinuous meshes it is important to avoid cracks formation and propagation in proximity of and through the discontinuity to guarantee the correct evolution of the event and hence capture the exact failure mechanism of the structure.
In addition, high refinement ratios (i.e. the ratio between the characteristic lengths of the two meshes tied together) should be avoided because they degrade the accuracy of the contact algorithm and hence of the solution. When high refinements are desired, several discontinuity surfaces should be used.
With regard to the contact interface between discontinuous meshes, the penalty formulation was preferred to the constraint formulation [9] because the latter caused an abnormal behaviour of the elements that lay along the interface. The slave surface was defined with a node set. The coincident nodes lying on the interface were exclude from this set and then merged to save computation time and to improve the overall behaviour of the model. The master surface was defined with a set of segments.
Contact interfaces were defined to create two refinement areas in the target-plates (Figure 9): a 1:2 refinement ratio was used. As a result, the element typical dimension was 13 mm on the outside part of the plates and 0.16 mm in the impact area: 83% of the overall elements were in the plate impact area.
Under these conditions, after preliminary simulations it was observed that the stresses were reasonably continuous across the interface and the stress waves were not significantly affected by the discontinuities.

In Figure 9, the numerical model used for the bullet impact simulations is shown. The different parts of the model are apparent: the support frame (dark grey), the target (light grey) and the projectile (orange).

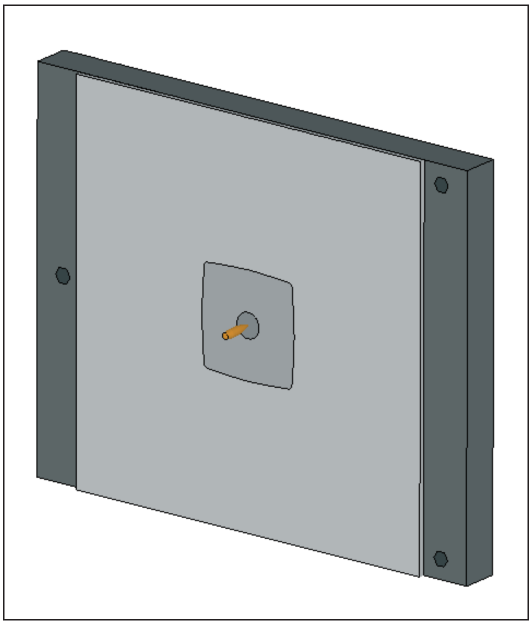

Figure 9. Projectile impact numerical model.

Although the problem presented symmetry planes (one or two depending on the impact incidence of the projectile), symmetries were not exploited because the failure modes were characterized by a non-symmetrical pattern – especially in case of petaling caused by the impact of a projectile with a nonzero incidence.
A piecewise linear plasticity material model was adopted for the projectile. For the inner part of the target-plates, a Johnson-Cook material model with the Grüneisen's equation of state was used; for the rest of the plates, whilst a simplified Johnson-Cook model (without equation of state) was used to limit the calculation time [4].
Both for the projectile and the target-plates, a failure criterion based on minimum pressure (the failure was only under tensile loads) and maximum strain to prevent the calculation time from increasing too much was defined.
Since no plastic deformations were expected for the support frame, an elastic material model was adopted.
The parameters that characterize the strain-rate dependency of the materials were from literature ([5], [6], [7] and [8]) sources and tuned with data from specific tensile tests carried out with the materials of the projectile and the target.
The contact interaction between the projectile end the target plate was defined with a contact based on penalty method able to keep into count the change in the geometry of the contact surfaces due to elements erosion [9]. The same contact algorithm was also used to define the self-interaction of the projectile defined to prevent the penetration of bullets fragments in the bullet body after the failure.
The target plate was constrained to the support frame with tied-contact interfaces whilst no attempts were made to model the bolts.
The support frame was then constrained to the ground with three linear spring elements to reproduce the stiffness of the load cells used during the test to measure the impact forces.

5.2. Impacts on thick plates

Simulations of impacts on thick plates were performed assuming an impact velocity 210 m/s.
The results obtained were then compared with experimental data.
The depth of the crater obtained with the numerical simulation matched exactly experimental results.
The measurements of the strain gauges were compared with the stresses obtained numerically. The correlation (Figure 11) was good with the exception of the first peak partly due to the low sampling frequency used during the test.
Also, the constraint forces measured by the load cells were compared with those numerically obtained.

Numerical results showed a strong dependency on the stiffness of the springs used to model the constraints. However, instead of "tuning" the stiffness of the spring elements, it was preferred not to make comparisons in terms of constraint force.

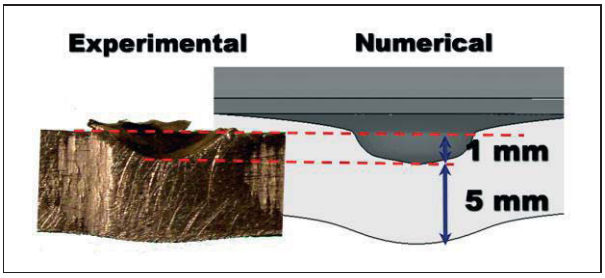

Figure 10. Numerical-experimental comparison in terms of crater depth.

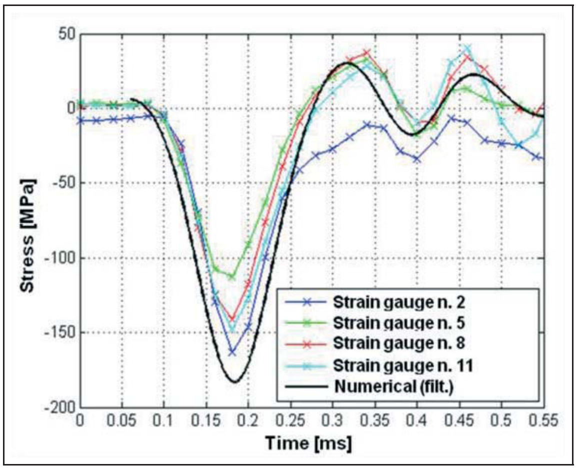

Figure 11: comparison between calculated and measured stresses.

5.3. Impacts on thin plates

Simulations of impacts on thin plates were performed considering various impact velocities of the projectile.
The same numerical model as for the thick plates was used, but a smaller number of elements in the thickness was defined to maintain the same through-thickness characteristic length of the elements. An erosion criterion based on the shear strain was introduced to limit element distortion and hence to avoid large calculation time.
Since the projectile was able to perforate the target plates, the comparison with the experimental data was made in terms of residual velocity – i.e. the velocity of the projectile after having passed the target.
The residual velocity is one of the most commonly used correlation parameters because it provides a global estimation of the event and of the energy transferred from the projectile to the target.

In addition, it allows a comparison in terms of parameters fundamental for the assessment of the structures vulnerability like the ballistic limit – i.e. the velocity required to a given projectile to penetrate an assigned target structure.
From the comparison between numerical results and experimental data (shown in Figure 12) emerged an excellent agreement. Only negligible discrepancies were observed due to the actual incidence of the projectile before the impact which was not considered in the numerical model.

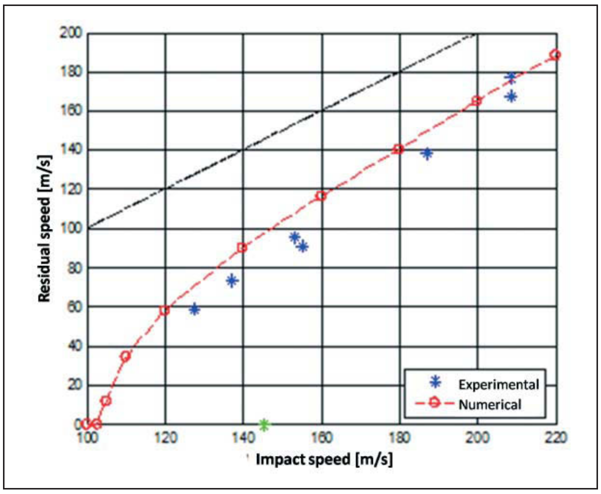

Figure 12. Impact speed vs. residual speed for impacts on thin plates.

5.4. Discussion

Experimental tests were carried out and a method to create reliable numerical model was developed.
Several efforts were provided to make the method more attractive for industrial application as attested by the use of discontinue meshes and tied-type contact interfaces to reduce the calculation time or the use of material data from literature sources to limit the experimental tests to determine material parameters.
In view of the results obtained it was concluded that the method proved to be sufficiently accurate for predicting the effect of a bullet impact on metallic plates.

6. APPLICATIONS

Once developed the procedure to create reliable numerical model for investigating the consequences of a bullet impact, the impact on a complex helicopter component was considered to validate the method. A component fundamental for flight was selected (Figure 13).
Since under normal flight conditions, the component is subjected to relevant loads which might affect the result of the impact, the effect of the pre-loading was taken into account.
The impact point was chosen in the part of the component most exposed to the danger of hostile ground fire.
The numerical simulation of the impact was first performed using a model created accordingly to the developed method. Only a small tuning of the model was necessary to adapt the procedure to the more complex problem. In addition, a pre-stress analysis was necessary to consider the flight loads.
Then full-scale tests were carried out and the data collected compared with the results of the simulations in order to evaluate the feasibility of the method as a numerical tool to predict damages caused by a ballistic impact.
Finally, a new simulation with the actual impact scenario of the test (e.g. projectile incidence, impact velocity) was performed to further evaluate the accuracy referring to the experimental data.

Figure 13. Helicopter component under investigation.

6.1. Numerical simulation

A numerical model of the component was created accordingly with the developed method.

Due to the geometrical complexity of the component, it was difficult to produce a good quality mesh with eight-node solid elements (hexahedral elements) and therefore four-node solid elements (tetrahedral elements) were used.
On the other hand, standard four-node solid elements are known to provide poor accuracy solutions when used for simulations of events that, such as that under investigation, are characterised by large deformation and inelastic behaviour of the materials.
In view of this, the impact area which is geometrically regular (Figure 14) was isolated and modelled with eight-node solid elements whilst the rest of the component, which is characterised by a complicate shape but remains in the linear field, was modelled using four-node solid elements with quadratic shape function and full integration [9].
In LS-Dyna it is possible to define ten-node tetrahedral elements. The solver automatically converts four-node to ten-node tetrahedral element by adding the mid-nodes when the calculation starts. However, this operation creates new segments thus preventing using the tied contact algorithm.
In addition, ten-nodes tetrahedral elements were considered not to be essential because preliminary simulations carried out to assess the accuracy of the tetrahedral element showed that four-nodes tetrahedral elements give satisfactory results.
Discontinuous meshes were used not only for refinement purposes but also to simplify and speed-up the creation of the model.
The two meshes are connected, as previously described, with a tied-type contact.

In Figure 14 the FE mesh of the component under investigation is shown: the green part is modelled with eight-node solid elements; the blue part with four-node solid elements.

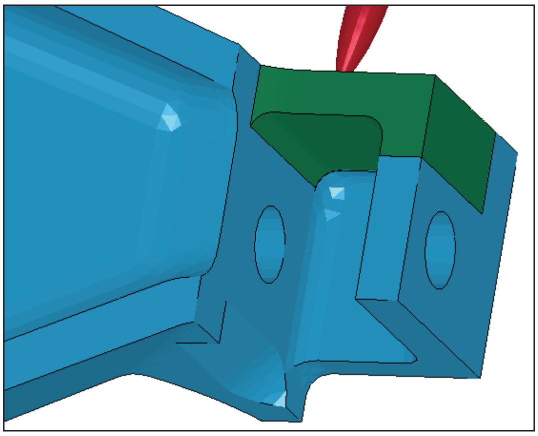

Figure 14. FE models of the helicopter component and projectile.

Accordingly to the method developed so far, the Johnson-Cook material model with a Grüneisen's equation of state was used for the impact area while a simplified Johnson-Cook model was used for the rest of the component.
For the projectile, the same model created for the impacts on plates was used.
Before running the simulation, a pre-stress was applied to the component with the dynamic relaxation method. The calculated pre-stresses were then validated with a linear stress calculation performed with MSC Nastran. Finally, a first impact simulation was run using the estimated impact parameters.

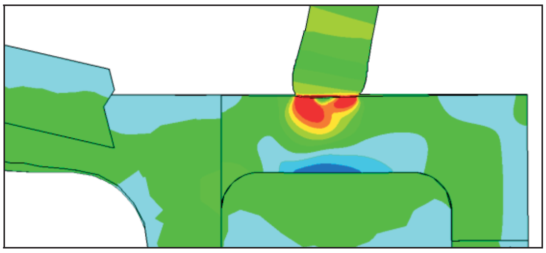

Figure 15. Section cut of the component during the impact.

6.2. Experimental test

After the simulation, an experimental test was performed with the test facility previously described. The helicopter component was constrained to two steel columns and the pre-loads were applied.
The impact location used in the simulation was found on the actual target with the help of a laser pointing system.
The test was performed using the maximum projectile velocity. An impact velocity of 210 m/s and a ricochet velocity of 30 m/s were estimated using the post-processing software for high-speed movies.
From the high-speed movie was also inferred that the projectile had an angle of 4.5° with respect to the trajectory at the moment of the impact.
Since the helicopter component was slightly deformed because of the pre-loads, the trajectory was not perpendicular to the target but had an angle of 8.5°.
Due to the nonzero incidence of the bullet, after impacting the target, it started rotating (Figure 16-3). Unfortunately, the impact speed and the bullet toughness were not sufficient to cause relevant damages to the component and the crater's depth was too small to be a reliable reference for evaluating the accuracy of the numerical solution.

T = 0 μs

T = 61 μs

T = 111 μs

Figure 16. Impact sequence of test onto the helicopter component.

6.3. Further assessment of the numerical model

After the test, the actual impact scenario was used to improve the numerical model and a further simulation of the event was run.
In particular, the actual impact location, the impact velocity and inclination of the projectile were updated.
Since the aim of this simulation was to assess the numerical method, tuning neither of the model nor of the simulation parameters were made at this stage of the research.
As a result, even if it was not possible to make quantitative correlations, from a qualitative standpoint numerical results and experimental evidence were definitively comparable.

6.4. Discussion

The creation of the numerical model and the simulations were time inexpensive. Small efforts were needed to tune and debug the numerical simulation (the main difficulty being pre-load calculation and the assessment of the tetrahedral performance).

Even if it was not possible to make quantitative comparison, the qualitative description of the event was encouraging and suggested that the method is feasible although further researches are necessary.

7. CONCLUSIONS

For the safety of operative military helicopter it is important to be able to design bullet-proof structures. Since full-scale experimental tests are expensive and time consuming numerical methods able to exploit the potentialities of the numerical approach are fundamental. Accordingly, in this paper is introduced a method to investigate the ballistic resistance of a structure.
Experimental tests were performed throwing brass projectiles toward aluminium plates. The velocity of the projectile before and after the impact was measured post-processing videos recorded with a high-speed camera. Load transducers and strain gauges were used to provide global and local measure of the strength of the impact.
Simulations of the bullet impacts were performed using the finite elements code LSTC/LS-Dyna.
Discontinuous meshes and tied contacts were used to reduce the number of elements and hence to enhance the computational efficiency of the numerical model. Various material models and failure criteria were investigated referring to data from literature and tests specifically carried out.
In an effort to further develop the methodology the impact of a blunt projectile was considered. A numerical model was developed and validated against experimental data collected from bibliographic sources.
As an application of the method, the impact of a projectile on a helicopter component was studies.
First, a numerical model was created and simulation performed accordingly. Then, an experimental test was performed and the data collected compared with the numerical solution. A good agreement was observed and therefore the numerical approach was recognized to be able to provide accurate results in a rather time-efficient and costless way.
Further works will focus on tests with higher impact velocity and tougher bullets.

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