HELICOPTER FUEL TANK CRASHWHORTINESS: NUMERICAL APPROACH FOR THE DESIGN

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Abstract: The ground impact of a helicopter in emergency represents a threat for flight safety and, therefore, crashworthiness is the main concern in the design of a helicopter tank.

Up to few years ago, research made to improve tank crashworthiness consisted mainly of experimental tests. These tests are both expensive and difficult to perform. Accordingly, numerical tools that support the development of safer structures are needed. Several efforts have been provided and, nowadays, explicit codes based on Finite Element (FE) Method are successfully used to analyse crash events. The use of these codes, once the FE model reliability is demonstrated by numerical-experimental correlation, allows reducing the number of tests to be performed to achieve the airworthiness certification. Specifically, design modification can be certified without repeating experimental tests.

In this work, the impact with the ground of a filled tank of a medium weight helicopter has been numerically studied. In particular, the compliance to the Civil Requirements of a helicopter fuel system equipped with the auxiliary fuel tank kit was demonstrated by means of a non-linear explicit FE code.

Initially, a numerical model has been developed and validated referring to the experimental data collected during the certification impact test of the main fuel tank, without auxiliary tanks, equivalent to the real helicopter fuel bay.

Subsequently, the validated model has been used to predict the impact behaviour of the fuel tank structure when the helicopter was equipped with the auxiliary fuel tank kit.

The simulation allowed achieving the certification of the helicopter fuel system.

1 INTRODUCTION

As statistics show [1], tank crashworthiness is fundamental for accident survivability. The collapse of the fuel system, as a consequence of the impact with the ground of a helicopter in emergency, is the main cause of death among the occupants. Therefore, the design of fuel systems undergoes severe crashworthiness requirements ([2], [3], [4]). Post-crash fire prevention is the most important objective. The basic requirement is the fuel containment: fuel tanks must be designed to withstand a survivable crash landing without structural damage that would leak fuel to an ignition source. In particular, the strength to prescribed ultimate inertial load factors must be proved and drop tests must be performed to achieve the certification. Furthermore, bladder attachment points, where tearing may be unavoidable, should be breakable and self-sealing joints should be installed. Fuel lines must be ductile and designed to buckle before they could puncture the bladder. Ignition sources, such as engines, heaters and electrical lines, must be as far as practicable from the fuel system.

When certifying a fuel tank, the substantiation of drop test requirements is customarily the most demanding: drop tests are both expensive and difficult to perform. Accordingly, numerical tools able to speed up the crashworthy design process are crucial [5]. Nowadays, explicit codes based on Finite Element (FE) Method [6] are successfully used to analyse numerous crash events not economically feasible with crash testing. Thought experimental tests are still fundamental, the numerical approach, once the FE model reliability is demonstrated by numerical-experimental correlation, allows reducing the number of tests to be performed to achieve the airworthiness certification. Specifically, design modification can be certified without repeating experimental tests.

In this work, the impact with the ground of a filled tank of a medium weight helicopter has been numerically studied. In particular, the compliance to the Civil Requirements [2] of a helicopter fuel system equipped with the auxiliary fuel tank kit was demonstrated by means of a non-linear explicit FE code, ABAQUS/Explicit ([7], [8]).

Initially, the numerical model has been developed and validated referring to the experimental data collected during the certification impact test of a filled tank, without auxiliary tanks, equivalent to a real helicopter fuel bay. The drop test was simulated using a FE model that reproduced the test article in details. Riveted joints were modelled using a specific contact algorithm and the dynamic characteristics of the materials were considered. The mechanical behaviour of the water, used instead of fuel during the test, was reproduced exploiting user subroutines in order to accurately reproduce the sloshing of the fluid inside the tank. Subsequently, the validated model has been used to predict the impact behaviour of the fuel tank structure when the helicopter was equipped with the auxiliary fuel tank kit.

2 EXPERIMENTAL DROP TEST

A drop test was performed in order to achieve the certification of the main fuel tank of a medium weight helicopter. As already mentioned, data collected during this test was used to develop and validate a FE model of the filled tank.

2.1 Specimen description
The test article included two 800 litres symmetrical fuel tanks and the surrounding structure representative of the actual installation (Figure 1). In particular, the entire helicopter segment containing the bladders was included in the test.

The bladder is made of an external fabric with a high tear resistance and an internal anti abrasion rubber film. The structure is mainly made of sandwich panels with aluminium alloy skins and honeycomb core.
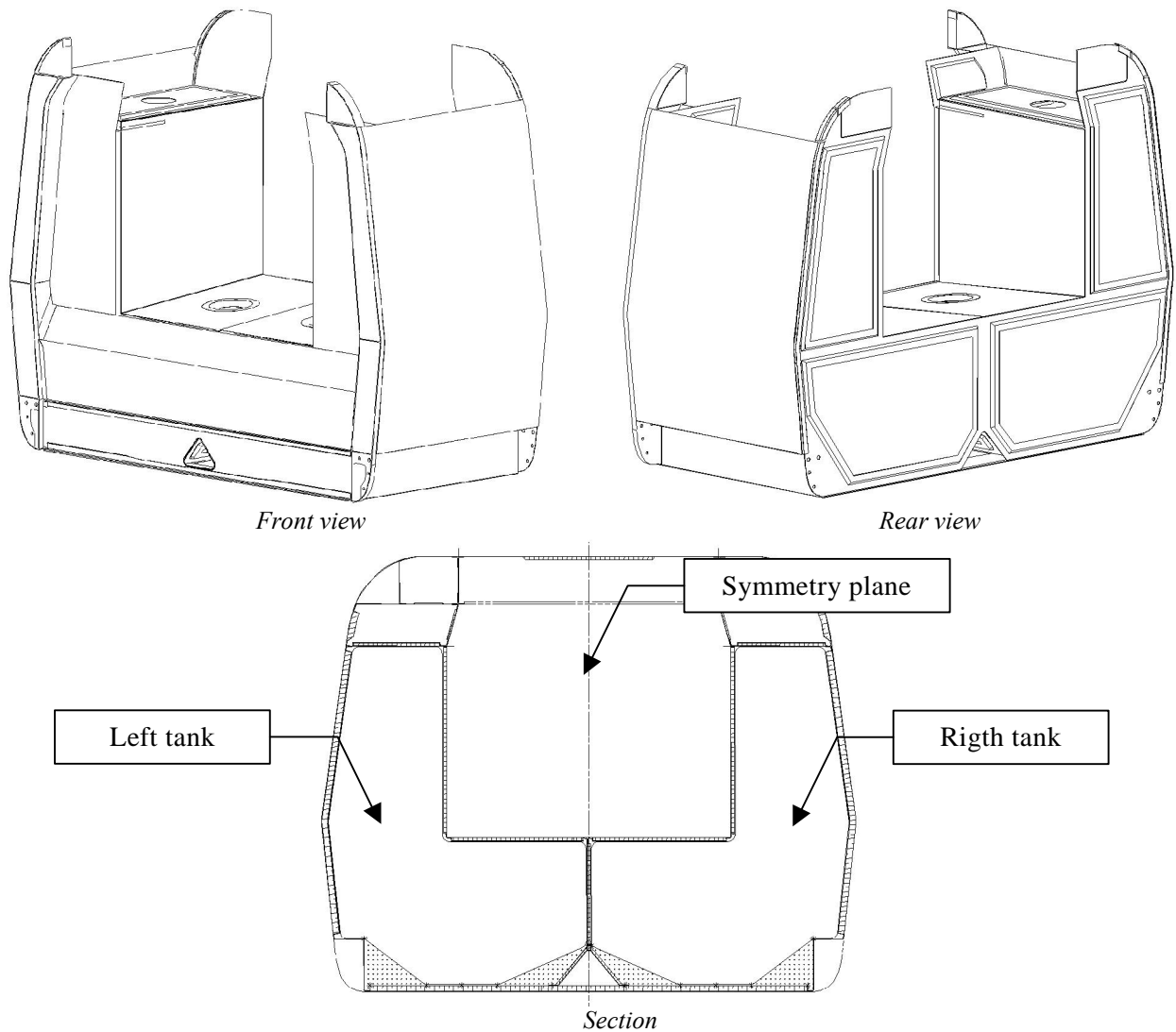
Front view   *Rear view*

Symmetry plane

Left tank

Rigth tank

Section

Figure 1: Standard fuel tank

2.2 Test features

The drop test was performed according to the Civil Requirements ([2], Par. 29.952a,). The tank was filled with 1280 litres of water, used instead of fuel during the test, corresponding to 80% of the full capacity and dropped from a height of 15.25 m (50 ft).

A lifting system was manufactured in order to support the test article. The platform consisted of a metallic frame and a non-deforming floor (Figure 2).

High-speed video cameras were used to verify the specimen behaviour during the test and to verify the impact angles - lateral marks on the structure were compared with the horizontal ground reference.

2.3 Test results

The analysis of the high-speed movies demonstrated that the structure has been dropped in horizontal position (within the prescribed limits of ± 10).

The structure was deformed during the impact, but the deformations did not cause any damage to the bladder. In particular, failure of rivet lines and sandwich panels did not produce puncturing or grabbing of the bladder. Accordingly, no leakage has been observed immedi-

ately after the crash impact and during the following 30 minutes. Post crash images of the specimen are shown in Figure 4.
These results allowed achieving the certification of the helicopter main fuel system.
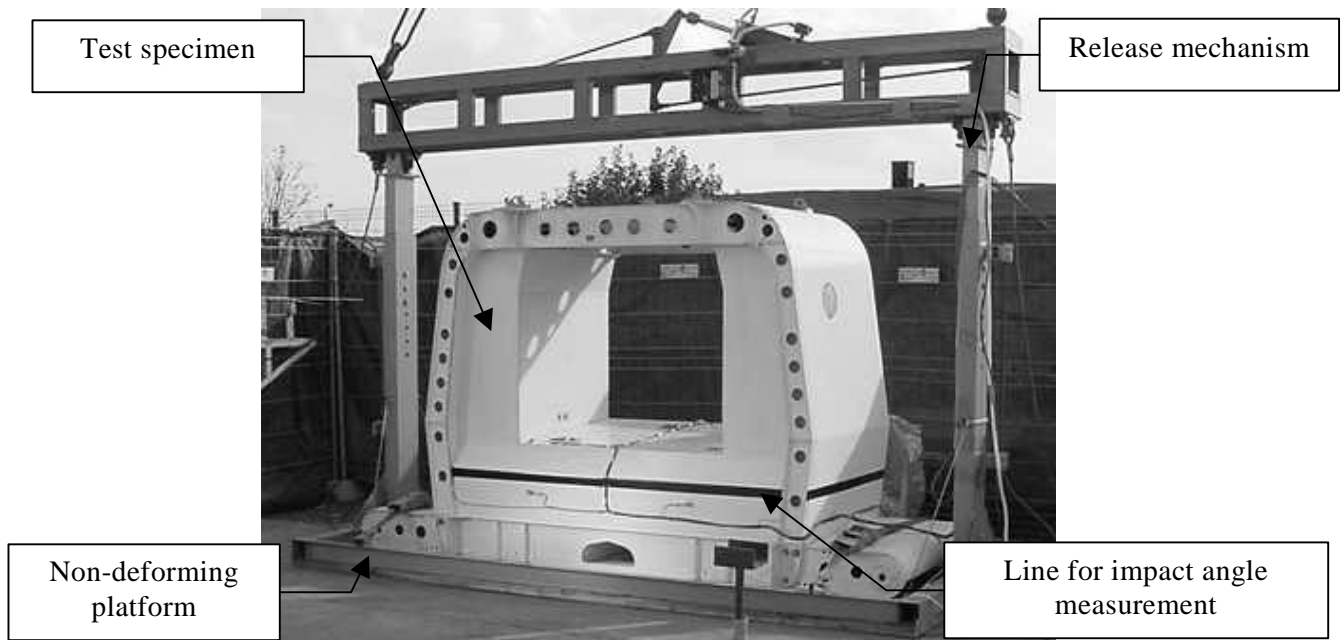

Figure 2: Test specimen and lifting system

3   FINITE ELEMENT MODEL VALIDATION

Referring to the experimental data collected during the drop test, a finite element model of the fuel tank was developed and validated. The ground impact simulation was performed by ABAQUS/Explicit, an explicit numerical code, suitable to study highly non-linear phenomena such as crash event ([7], [8]).

3.1   FE model description

In order to save computational efforts, only half structure of the test specimen was modelled in details. In fact, the entire fuel tank has a symmetry plane (see Figure 1), and the analysis of the high-speed movies demonstrated that the impact angle could be considered negligible. Sandwich panels were modelled by means of shell elements (metallic skins) and 8-node solid elements (honeycomb core). Stiffeners and connecting elements were modelled by shell elements. The characteristic length of the elements was a compromise between the need to properly reproduce the large deformations of the tank structure and the need to reduce the CPU-time.
Metallic parts behaviour was reproduced using isotropic elastic-plastic constitutive laws, while orthotropic constitutive laws were used to model honeycomb behaviour. Hardening due to strain rate effects was taken into account.
Riveted joints were modelled using a specific contact algorithm, the *contact pair algorithm* used with the spot-weld option ([7], [8]). A failure law was introduced defining shear and axial ultimate loads of rivets, which had been obtained during specific research works previously conducted.
The bladder was modelled with shell elements and the mechanical behaviour of its material was reproduced with an elastic constitutive law. The mechanical properties were obtained with specific experimental tests.

In order to reproduce the actual crash test condition, the tank was filled to 80% of its maximum capacity. The water inside the tank, used instead of fuel during the test, was modelled with 8-node solid elements. Particular attention was paid to the choice of the water material model. Indeed, the post crash structure deformation is strongly affected by the sloshing of the water inside the tank. In particular, the mechanical behaviour of the water was reproduced exploiting an ABAQUS/Explicit user subroutines "VUMAT": a material model characterised by the absence of deviatoric stresses featured with the customary Polynomial Equation of State [11] was implemented.

The interaction between water, bladder, tank structure and ground was defined using the *general contact algorithm* ([7], [8]).

Initial and boundary conditions were accurately reproduced. An impact velocity of 17.3 m/s (corresponding to a 15.25 m drop height) was considered and symmetrical boundary conditions were applied to nodes located on the symmetry plane.

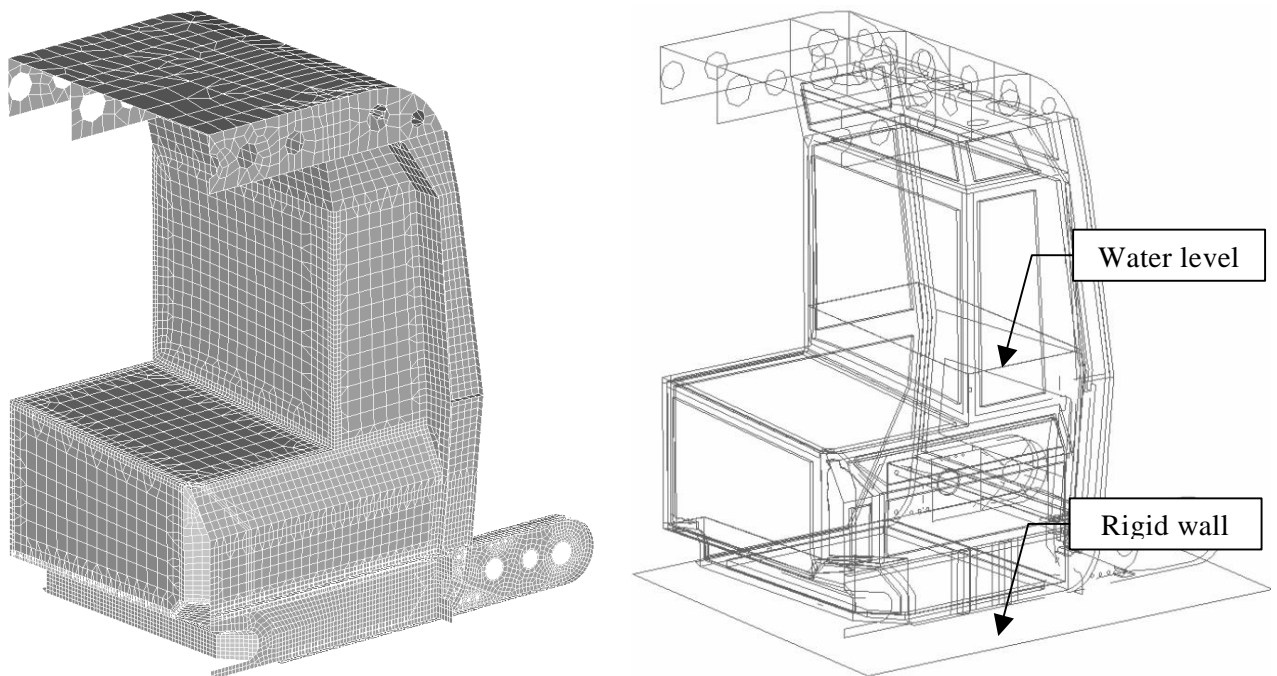An overview of the model is shown in Figure 3.

Figure 3: Test specimen FE model

3.2 Numerical-experimental correlation

The validation of the model was based on the comparison between experimental data and numerical results. Overall deformations, local structural damages and fasteners failure were considered to evaluate the capability of the model to represent the specimen behaviour during the drop test.

A qualitative comparison between numerical results and experimental data showed that the FE model was able to reproduce the general crash behaviour of the specimen. Furthermore, local deformations and fasteners failure were correctly represented.

In particular, permanent deformations of the upper panel and rivet failure, caused by the water sloshing, can be observed in accordance with the drop test (Figure 4a). Moreover, the FE simulation accurately represented the failure of the rivet line connecting the rear panel, the lateral panel and the angle (Figure 4b).

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As a consequence, the model was deemed reliable and it could be used to evaluate other structural configurations. In particular, this model was used to evaluate the behaviour of the structure when the auxiliary fuel tank was installed.
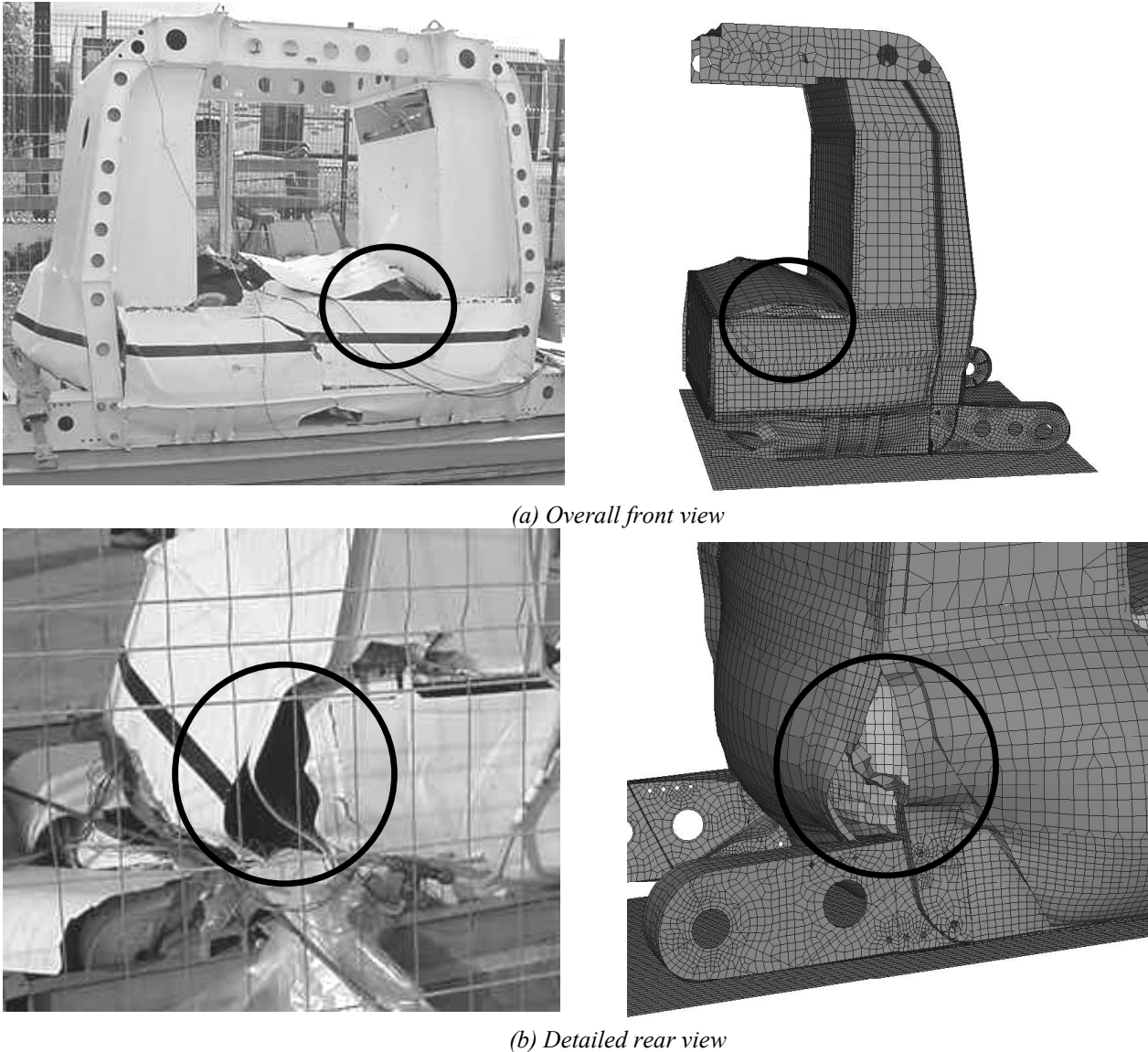

(a) Overall front view

(b) Detailed rear view

Figure 4: Standard fuel tank. Experimental - numerical correlation.

4   NUMERICAL DROP TEST

The validated fuel tank FE model was used to achieve the certification of the fuel tank system when the helicopter was equipped with the auxiliary fuel tank kit. Accordingly, the numerical simulation of the drop test was performed according to the Civil Requirements ([2] Par. 29.952a).

4.1 Auxiliary fuel tank description
The considered helicopter can be equipped with a single 500 litres auxiliary fuel tank to further increase the operation range. The auxiliary fuel tank is installed in the bay located between the right and left main tanks and it is linked to them through two flanges (Figure 5a). The auxiliary tank installation is made of three honeycomb-cored panels connected to the sur-

rounding panels of the main tank (Figure 5b). The auxiliary fuel tank bladder is made of the same material used to manufacture the main tank ones.
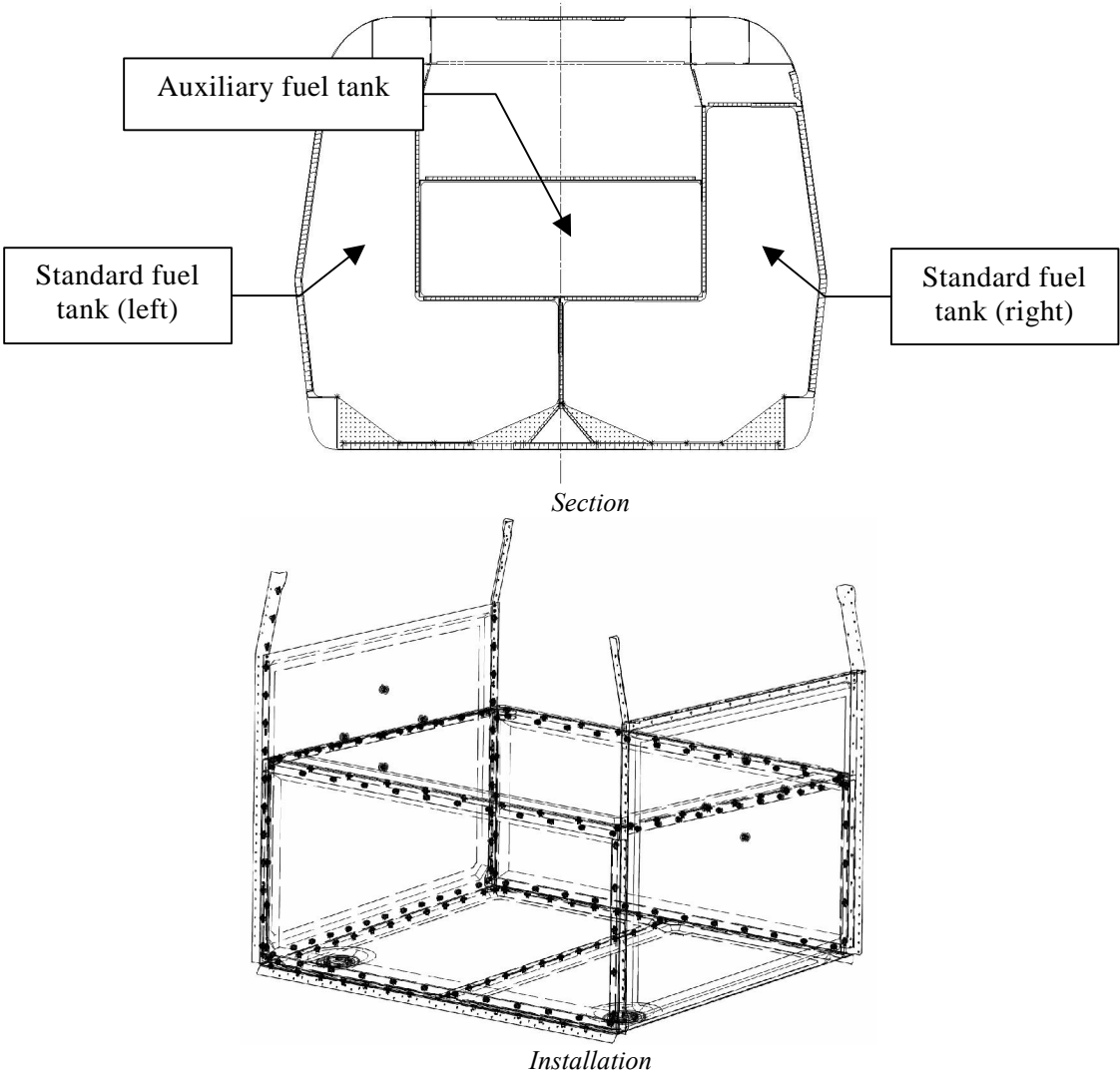
Auxiliary fuel tank

Standard fuel tank (left)

Standard fuel tank (right)

Section

Installation

Figure 5: Auxiliary fuel tank

4.2 FE model description

The FE model developed and validated in the first part of this work was used for the main fuel tank. The auxiliary tank FE model, including riveted joints, contacts and constitutive laws, was realised following the guidelines used for the main tank (Par. 3.1). The entire tank – standard and auxiliary - was filled to 80% of its maximum total capacity.

Initial and boundary conditions were equal to the ones defined for the main tank drop test and, consequently, compliant with the Civil Requirements [2].
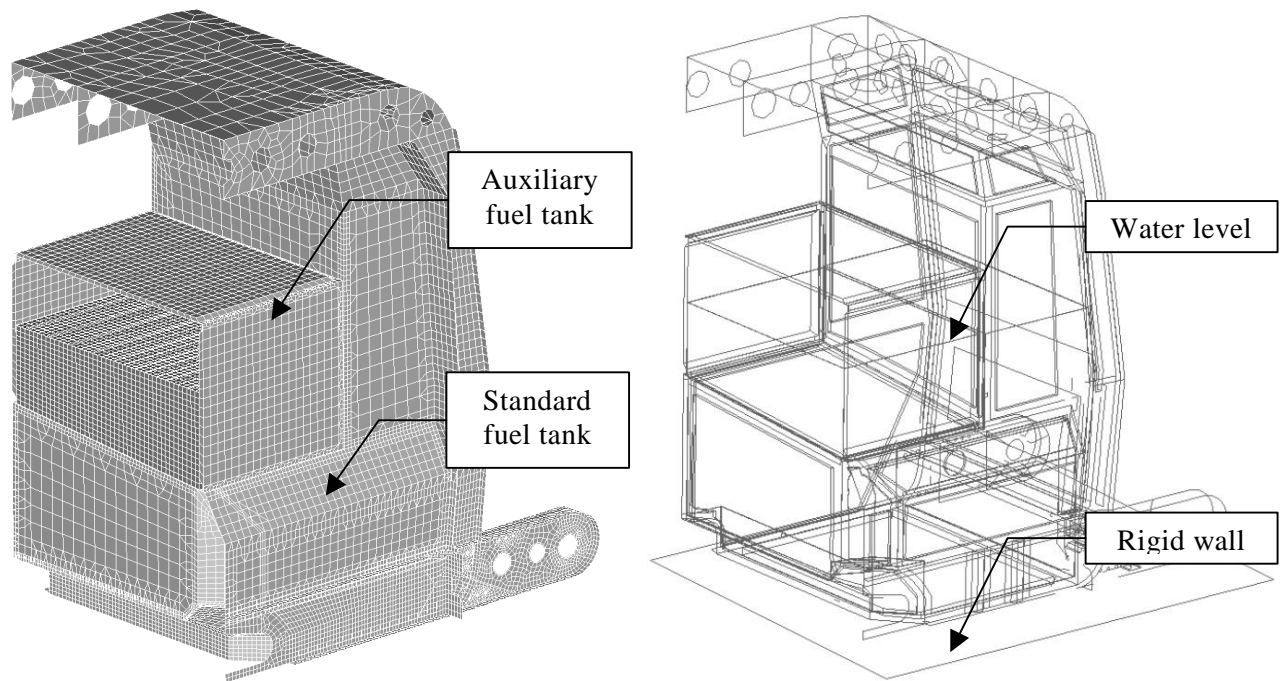
Auxiliary fuel tank

Standard fuel tank

Water level

Rigid wall

Figure 6: FE model for numerical drop test

4.3 Results

The numerical results showed that the general crash behaviour of the fuel tank bay did not differ significantly from drop test results, obtained without installing the auxiliary fuel tank, though the structure underwent bigger deformations due to the higher amount of energy.

In particular, some regions, not affected by permanent deformations in the experimental drop test, resulted deformed in the simulation (Figure 7a). Rivet failures occurred in the same locations in which they were observed after the test, though in this case more rivets failed (Figure 7b). Nevertheless, panels' displacements and deformations due to rivet failure were similar to the ones observed in the test. Contact between the main fuel tank bladders and the failed structure occurred in the same areas. Potential cutting edges were in the same locations and comparable to the ones that did not cause puncturing in the test. Thus, no puncturing and, consequently, no leakage from the main tank bladders were envisaged after the drop test of the main and auxiliary tanks.

Furthermore, failures were observed along the fasteners lines connecting the auxiliary tank panels to the main tank structure. However, these panels did not breakaway totally from the structure and they were able to retain the bladder.

The above results allowed achieving the certification of the fuel system equipped with the auxiliary fuel tank kit.
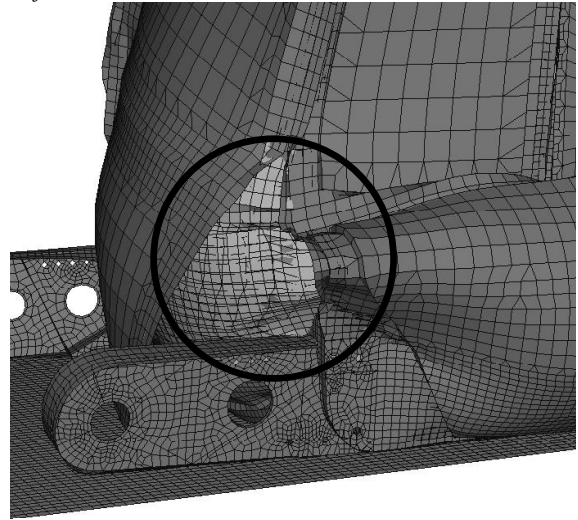
Main tank drop test results *Main and auxiliary tanks simulation results*

(a) Overall front view

Main tank drop test results *Main and auxiliary tanks simulation results*

(b) Detailed rear view

Figure 7: Numerical drop test results

5   CONCLUSIONS

Tank crashworthiness is primary for accident survivability. The fuel system failure, as a consequence of the impact with the ground of a helicopter in emergency, is the main cause of death among the occupants and, therefore, the design of the fuel system undergoes severe rules: drop tests are required to achieve the certification. These tests are both expensive and difficult to perform. Accordingly, in this work an alternative approach to the problem was presented: experimental tests were replaced by numerical simulations carried out using a non-linear Finite Element code, specifically ABAQUS/Explicit.
In particular, the impact with the ground of a filled tank of a medium weight helicopter has been numerically studied.
Initially, the numerical model has been developed and validated referring to the experimental data collected during the certification impact test of the standard fuel tank, without auxiliary tanks. The experimental-numerical correlation showed that the FE model was able to reproduce the drop test and, consequently, that the numerical analysis was a reliable tool. Subsequently, the FE model has been used to predict the impact behaviour of the fuel tank structure when the helicopter was equipped with the auxiliary fuel tank kit. The results showed that the deformations were of the same kind occurred in the test without the auxiliary fuel tank, where no puncturing, cutting and consequently leakage occurred. Accordingly, it was assumed that no leakage would have occurred as well. The obtained results allowed achieving the certification of the fuel system equipped with the auxiliary fuel tank kit.

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