A crashworthiness optimisation procedure for the design of full-composite fuselage section

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Abstract. Crashworthiness of composites is a key-point in the design of new aeronautical structures. Special attention has been addressed in the last years to the energy absorption mechanisms of dedicated components in order to limit the structural damages and to preserve the occupants’ safety. Remarkable progress has been made in this field. Despite this, to further improve the design of crashworthy composite structures, components modification, sensitivity analysis, design of experiments and optimisation procedures are needed. In this work, crashworthiness improvements, related to a simplified finite element model of a full-composite fuselage section subjected to a vertical drop-test, have been introduced. The genesis of the model has been described together with its main features and details and a high-speed vertical fall has been simulated, paying attention to velocity and payload. In addition, sensitivity analyses of some components and a discussion on the main crashworthiness characteristics have been carried out. Finally, the parent fuselage section and its simplified model have been compared under both energy and deformation points of view, showing a good results agreement.

1. Introduction

Over the years, composite materials have found a wider and wider diffusion in aeronautical structures due to their advantages in terms of lightness and specific stiffness. However, the failure behaviour remains complex and difficult to predict. Specifically, destructive tests for the assessment of airframes crashworthiness are mandatory to better understand composites failure mechanisms and to improve occupants’ safety. However, such tests are often not reproducible because of the high costs. As in the other field [1,2], numerical models represent a very effective tool in the aerospace sector to reduce time and costs of design phases investigations [3-5]. Following the building block approach, subsequent improvements in failure behaviour can be executed by using already validated and time-saving numerical models so that various scenarios can be explored, e.g. by performing sensitivity analyses or optimising procedures.

In this area, several studies have been carried out. Since ‘90s, Mateus et al. conducted sensitivity analysis and optimal design for static and dynamic behaviour of thin laminated composite structures by varying geometry and fibre orientation [6]. Later, Fernlund et al. discussed a sensitivity analysis (thickness changes) of a composite front spar for wing in autoclave process, showing that their numerical model can provide good predictions of process induced deformations [7]. In the following decade, Fish
and Ghouali proposed a multiscale sensitivity analysis approach for inelastic periodic composites revealing its advantage in terms of accuracy and computation efficiency [8]. Kaminski implemented a finite element method (FEM) for sensitivity analysis in homogenization of composite materials having linear elastic behaviour [9]. Belingardi and Vadori investigated the influence of the laminate thickness on the composite plate’s behaviour under low velocity impact due to a standard drop dart test [10]. Khosravi and Sedaghati considered thickness of layers and fibre orientation angles as variables to get an optimum design of composite laminates by means of FEM. They developed an efficient optimality criterion without performing a sensitivity analysis [11]. During last years, Akoussan et al. carried out a sensitivity analysis of the damping properties of viscoelastic composite plates according to their layers’ thicknesses [12]. De Sousa et al. worked on the optimal design of multi-layered composite laminates and on a topological sensitivity analysis in anisotropic elasto-statics, able to obtain the optimal topology of composite laminated structures [13]. Then, Gao et al. developed a methodology for a composite fuselage frame crashworthiness design including a sensitivity analysis. They managed to enhance the structure’s crashworthiness keeping computational costs low [14]. Meanwhile, within a work on the crashworthiness of fabric composite corrugated beam, Ren et al. carried out a parameter sensitivity study in order to probe effects of pure numerical parameters on failure responses [15]. Mandal et al. proposed a model for stochastic sensitivity analysis of laminated composite bolted joints with respect to geometric and material properties [16]. Moreover, Huang and Zhang investigated the crashworthiness of metal/composite hybrid tubes under bending collapse. The validated model was further employed to survey the effects of structural parameters such as the partial wrapping, wrapping angle and ply thickness on the crashworthiness, managing to improve tubes’ performances [17]. In another work, Huang et al. applied a sensitivity analysis to braided composites with respect to the braiding angle, fibre volume fraction and braided structure to predict their vibration behaviour [18]. Lastly, Liu et al. accomplished a parametric study of holed composite tubes to probe the holes’ effect on crashworthiness performance [19].

Generally, accurate and validated FE models are employed for sensitivity analyses in order to investigate how geometrical and material parameters affect composite structures’ behaviour and their crashworthiness performances. Nevertheless, only simple or isolated specimens/parts are subject of researches. Moreover, it is worthwhile to mention that most of the aforementioned authors underlined the importance and the need of high CPU performances to execute analyses, proving that light numerical models are essential to save computational time and costs.

In this work, a light highly detailed FE model of a full-composite fuselage section has been described and, following energetic considerations, the most appropriate load case has been selected in order to carry out sensitivity analyses for geometric parameters of several model’s components. The article is structured as follows: first of all, an introductory overview concerning the main model’s features is presented; then, the choice of the load case is illustrated and, finally, the results of a preliminary sensitivity analysis are shown.

2. The fuselage section
A regional aircraft fuselage section, fully made of composite materials, was subjected to a vertical drop test onto a concrete surface at CIRA (Italian Aerospace Research Centre) facilities, figure 1, in order to investigate its impact structural behavior with a focus on the crashworthiness response [20].
For this purpose, the test article included accelerometers arranged along the structure, an aluminium seats row and two test dummies, properly positioned. The structure’s components, such as nine frames, ribs, spars and struts, were designed following the building block approach. Details and results are available in literature [20].

3. The parent numerical model
Starting from the experiment, a highly detailed FE model was developed in order to replicate the test event in Ls-Dyna environment [21]. The aim was to reach an experimental-numerical correlation and to define a starting point for future certification by analysis purposes. An overview of the developed FE model with its details is illustrated in figure 2:
Due to model complexity, shell elements with an average dimension of 10 mm were adopted for a total of 2426312 elements and 2031764 nodes. Thermoplastic and thermosetting composite materials were modelled including the Chang-Chang failure criteria, according to Ls-Dyna material library (MAT054). At the end, the model total mass was 929.8 kg.

Spot-weld contact were set up to join the experimental bolted components while surface-to-surface and single-surface contacts were defined to avoid penetrations where eventually occurred after failures. However, bolts acting as connection between floor beams and struts were modelled by using solid elements.

In order to simulate the load case, the impact surface was modelled as rigid one, the experimentally detected impact angles were applied and the 9.143 m/s impact velocity was imposed to the whole model, beyond the gravity acceleration. Ls-Dyna code was used to perform the dynamic analysis which took roughly 140 hours to run out, simulating a 300 ms event.

Comparing experimental and numerical results, it is possible to note in figure 3 and figure 4 the good correlations in terms of deformation and failures as well as the accelerations trend, so that the model can be defined as validated and therefore usable for further researches. Full results and other details are available for consultation [22].
4. The simplified model
The aforementioned validated numerical model can be exploited to develop a more crashworthy FE fuselage section so that a new concept of fuselage may be designed in future. To do that, sensitivity analyses and structure optimizations are necessary but, first of all, as mentioned in Section 1, a less time-consuming FE model is needful. So, a simplified model has been extracted from the parent model, as reported in figure 5. Just two frames have been isolated, where the seats row is placed.

![Figure 5. Genesis of the simplified model.](image)

The entire payload, consisting in seats, two dummies (on the left) and the balancing mass (on the right) have been shifted in two concentrated masses, rigidly connected to the underlying rails (figure 5).

After the cut, skew mesh around edges has been adjusted and the previous impact angles have been set to zero, approaching the model toward the rigid surface.

Continuing the simplification, solid bolts have been substituted with 1-D rigid elements (figure 6).
Then, symmetry constraints have been applied along the forward and back edges to take into account the effect of the removed parts of the structure (figure 7).

Lastly, the material behaviour regarding upper composites components have been converted in pure elastic one, without failure criterion (figure 8).

In the end, the simplified model results to be characterised by 330321 elements and 315654 nodes and a total mass equal to 240.8 kg. The only structural mass is equal to 111.6 kg, while the added concentrated mass is equal to 129.2 kg, as better explained in the following.
5. Load case

As aforementioned, the issue of load case has to be faced when dealing with a simplified model. As a matter of fact, it is no longer possible to apply the original loading conditions, belonging to the parent model, since the simplified one reduced dimensions. For this reason, in order to get a reasonable comparison between the two models, i.e., the parent and the simplified ones, the internal energy has been considered. In particular, the parent model’s parts within the green area displayed in figure 9, consisting in six frames (named “subsection” from here on, ss) have been taken as reference.

The expected load case can be obtained dividing the subsection’s maximum internal energy by three for the purpose to fit for the two frames simplified model (simp). Then, this value ($IE_{\text{max,ss}}/3$) must be equal to the starting kinetic energy of the simplified model ($KE_{0,\text{simp}}$):

$$IE_{\text{max,ss}}/3 = KE_{0,\text{simp}} = 8868.4\, \text{J}$$  \hfill (1)

In this way, two parameters play a key-role to define the load case: the payload mass ($m_{\text{load}}$), relating to the concentrated masses, and the impact velocity ($V_0$). The payload mass assigned for the simplified payload can be evaluated dividing the subsection’s payload by three (table 1):

$$m_{\text{load,simp}} = m_{\text{load,ss}}/3 = 387.7/3 = 129.2\, \text{kg}$$  \hfill (2)

Since the structural mass of the simplified FE model is equal to 111.6 kg, the total simulated mass ($m_{\text{tot, simp}}$) results to be 240.8 kg, as indicated in Section 4.

Consequently, it is easy to calculate the impact velocity to apply in the simplified model:

$$V_{0,\text{simp}} = \left(2 \cdot KE_{0,\text{simp}} \cdot m_{\text{tot, simp}}^{-1}\right)^{1/2} = 8.582\, \text{m/s}$$  \hfill (3)

Table 1 summarizes the parameters involved in the calculations.
Table 1. Models and their load cases.

| Frames | \( m_{\text{tot}} \) (kg) | \( m_{\text{load}} \) (kg) | \( V_0 \) (ms\(^{-1}\)) |
|--------|--------------------------|-------------------------|----------------------|
| Parent | 9                        | 929.8                   | 387.7                | 9.143 |
| Subsection | 6                    | 777.9                   |                      |      |
| Simplified | 2                   | 240.8                   | 129.2                | 8.582 |

The FE analysis has required about 6 hours to simulate a 100 ms drop test event, resulting in a great time-saving. Comparing numerical outcomes, figure 10 shows that in the transient interval (roughly 0-50 ms) the simplified curve is fitting to the subsection’s curve. After that, steady state values are different due to their different dimensions, indeed the subsection has got more components available to absorb the impact energy. Even respect to resultant displacement, internal energy trends are very similar (figure 11).

![Figure 10. Internal energy versus time.](image1)

![Figure 11. Internal energy versus total displacement.](image2)

This good outcome is confirmed by the deformation/failures achieved in the two analysed models, figure 12, where subfloor’s components are more damaged by the crash in the case of the simplified model.

![Figure 12. Comparison at 50 ms between subsection (a) and simplified (b) models.](image3)
6. Preliminary sensitivity test

Finally, the developed simplified model with its valid load case has been used to perform multi-run sensitivity tests. A preliminary sensitivity test will be herein shown to identify the most critical components and parameters so that they can be subsequently used for focused sensitivity analyses and structural optimizations.

In this work, it has been decided to focus on the composite components of the cargo zone, whose numerical material behaviours contain failure criteria. Such investigation has consisted in a ±50% variation of the laminates’ thicknesses, for both the thermosetting and thermoplastic ones. The table 2 lists all the involved components, shown in figure 13 and figure 14.

Table 2. Model’s parts employed for the sensitivity test with their features.

| Laminate thickness (mm) | +50% (mm) | -50% (mm) | material |
|-------------------------|-----------|-----------|----------|
| Stringers               | 1.032     | 1.548     | 0.516    | thermosetting |
| Skin5                   | 1.806     | 2.709     | 0.903    | thermosetting |
| Skin6                   | 1.29      | 1.935     | 0.645    | thermosetting |
| Slabs_frames            | 4.464     | 6.696     | 2.232    | thermosetting |
| Sector_4_frames         | 4.464     | 6.696     | 2.232    | thermosetting |
| Sector_5_frames         | 4.464     | 6.696     | 2.232    | thermosetting |
| Sector_6_frames         | 4.464     | 6.696     | 2.232    | thermosetting |
| Beams_fLOOR             | 2         | 3         | 1        | thermoplastic |
| Ribs_subfloor           | 2         | 3         | 1        | thermoplastic |
| Beams_subfloor_1        | 2         | 3         | 1        | thermoplastic |
| Spar_subf_central       | 2         | 3         | 1        | thermoplastic |
| Beams_subfloor_2        | 2         | 3         | 1        | thermoplastic |
| Spars_subf_lateral_1    | 2         | 3         | 1        | thermoplastic |
| Spars_subf_lateral_2    | 2         | 3         | 1        | thermoplastic |
| Beam_subf_central       | 2         | 3         | 1        | thermoplastic |

Figure 13. Thermosetting components involved in the sensitivity test.
Considering components settled in two groups (thermosetting and thermoplastic), four runs have been performed, one for each thickness variation (table 3).

**Table 3. Simulations performed.**

| Run | thermosetting | thermoplastic |
|-----|---------------|---------------|
| 1   | +50%          | nominal       |
| 2   | -50%          | nominal       |
| 3   | nominal       | +50%          |
| 4   | nominal       | -50%          |

Results of the first two runs (thermosetting group) are shown in figure 15. Run 1 points out the grown of internal energy due to stiffness increasing concerning parts illustrated in figure 13. Conversely, Run 2 demonstrates how the structure weakening does not allow to absorb impact energy.
Figure 15. Model’s internal energy for Run 1 and Run 2.

Going more in detail, figure 16 and figure 17 show the internal energy contribution of each component to probe which ones are more influential for the overall result.

Figure 16. IE of each component for Run 1.

Looking at figure 16, the largest internal energy contribution is provided by skin. During the initial phase of crash, also frames give a fair contribution. Whereas going on simulation, beams floor’s internal energy increases while subfloor spars and beams are near-zero effective.

In figure 17 for Run 2, the order of magnitude of energy is much lower and only frames provide barely relevant contributions when crash evolves.
Concerning thermoplastic components (figure 18), growing their thicknesses of fifty percent, Run 3, no significant changes for model’s internal energy have been detected as evidence of a previous optimization work. On the opposite, a reduction of the thicknesses, Run 4, leads to a decreasing of internal energy.

Focusing on each component concerning Run 3 (figure 19), skin and stringers are the most involved ones, followed by frames and floor beams having intermediate values, while the other ones are less influencing.
Figure 20 concerning Run 4 shows how skin, stringers and frames are the most relevant components from an energetic point of view, despite values are globally lower than Run 3.

7. Conclusions
Sensitivity analyses and optimization procedures are demonstrated to be effective to improve crashworthiness of composite structures. A FE model was developed to simulate a drop test event of a full-composite fuselage section including mannequins and sensors for crashworthiness purposes. The experimental-numerical correlation makes possible to develop a new FE model having a more crashworthy behaviour and design a new fuselage in future. So, a simplified model has be generated which fits with multi-run procedures from a time-consuming view point. A discussion of the most suitable load case has been done comparing internal energies and deformations with a subsection of the parent model. By changing thicknesses of composite components, a preliminary sensitivity analysis has been carried out on the simplified FE model in order to detect the most sensible parts. These will be the focus of authors’ future works. Taking internal energy as reference, composite components having failure criteria have been settled in two group and a ±50% thickness change have been applied to each group per time resulting in four runs.
Results have shown that the most influential components are skin and frames, leading in every run. So, it is worth to focus on them for next tests.

As further developments, more sensitivity tests are necessary such as acting on part’s thicknesses and composite features. In this way, design of experiments can be performed to get an improved FE fuselage section having better crashworthiness performances.

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