

Crashworthiness Behaviour of a Composite Fuselage Section with Cargo Door

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This paper presents the crashworthiness assessment of a composite fuselage section with a cargo door by means of the Finite Element (FE) software ABAQUS/Explicit. In crashworthiness research, no analysis, either experimental or numerical, of a composite fuselage section with a cargo door has ever been carried out. Therefore, the numerical analysis of the vertical drop test of three models of composite fuselage sections, representative of a regional aircraft fuselage, will be performed: a typical fuselage section without cargo door, a section with the cargo door but not the appropriate reinforced structure and a section with the surrounding door structure reinforced as in commercial aircraft sections with such cut-outs. In order to guarantee the integrity of the passengers as well as the structure, the crash kinematics of each model as well as the accelerations experienced by the passengers have been compared and examined in detail. The comparison between the three models allowed to identify the penalty that a duly reinforced cargo door structure induces on the crashworthiness of a composite fuselage.

1. INTRODUCTION

Composite materials have replaced aluminium and steel in the primary structural components of an aircraft mainly due to their beneficial mechanical properties that improve the performance of large civil transport airliners through reduced structural weight. However, in terms of crashworthiness, ability of an aircraft and its internal systems to protect occupants from injury in the event of crash, composites materials present a weakness given their low strain-to-failure behaviour, with negligible plasticity, compared to metals. The limited energy absorption capacity of composite structures may lead to much higher impact forces expected on the occupants as well as the structural integrity may be affected by uncontrolled fuselage fractures that can lead to occupant entrapment, intrusion of fire and smoke, or water in case of ditching [1]. Consequently, the analysis of the crash response of the entire composite fuselage cross-section and its crashworthy design improvement has been an important source of study within the crashworthiness research. As a result, composite fuselage designs capable of absorbing sufficient kinetic energy to provide a good level of safety are those in which a controlled crash kinematics, consisting of a cascading failure mechanism that starts at the lower part of the fuselage and progressively advances by triggering the failure of the upper components, is achieved [2]. The reason for this is that, with the right geometry and layout, carbon fibre reinforced plastic (CFRP) structures can achieve better specific energy absorption than aluminium or steel, particularly when a progressive failure mode is achieved in the composite component under compressive loads [3].

Airworthiness rules concerning crashworthiness, which historically have been based on the capabilities of traditional aluminium aircraft structures [4], seek to introduce regulations for the crashworthiness of composites structures as reflected in the publication of special conditions for the B787, A350 and Learjet 200 [5]; [6]; [7]. This has been possible due to the numerous studies, both experimental and numerical, carried out on the different components (frames, struts or sine wave beams), as well as full fuselage sections of transport aircraft structures made of composites. In particular, due to the high costs of full-scale structures crash tests, reason why there are few vertical drop test analysis on composite structures available in the literature, and the improvement of numerical modelling techniques, especially the development of accuracy of Finite Element software, has enabled to reliably analyse the crashworthiness of composite structures saving resources as well as money. This is beneficial towards Certification by Analysis for showing compliance to the crashworthiness rules by using numerical models validated by correlation with experimental results [8].

However, most of the crashworthiness research has been conducted on the typical symmetrical fuselage section. Of all the analyses of a whole fuselage section performed, whether made of metals or composites, only three of these studies were focused on a metallic non-typical fuselage section, that is to say, sections with cargo-door, Main Landing Gear (MLG) bay, Nose Landing Gear (NLG) bay, wing-box or tail cone. As stated in [2], crashworthiness of composite transport fuselage structures can be enhanced by considering non-typical fuselage sections in the design process in order to improve the response of the overall fuselage structure. Among the non-typical sections, the cargo door is usually present twice along the fuselage in commercial aircraft structures, which implies a major variation in the structure underneath the passenger crossbeam, area responsible for absorbing the impact kinetic energy, resulting in a non-symmetrical fuselage cross-section. This paper aimed to evaluate the variation in crashworthiness properties of a composite fuselage section due to the presence of a cargo door. For this purpose, the dynamic response of a cargo-door composite fuselage section in an impact event was modelled, by means of finite element method using ABAQUS/Explicit, and compared with that of a conventional composite fuselage.

2. GEOMETRY AND NUMERICAL MODEL

The cargo door cut-out in the lower deck of a transport aircraft requires skin reinforcement and an increment in frames dimensions applied in the cargo-door area along with auxiliary elements such as sills or intercostal in order to ensure that this area withstands the loading condition to which it is subjected. The design method of the cargo-door structure is based on the load case under normal flight or aircraft operating conditions and in no case has the crashworthiness properties of this section been taken into account.

Therefore, to understand to what extent the presence of the cargo door affects the dynamic response of the composite fuselage structure, three six-frame composite fuselage barrels were modelled, analysed and compared. The first model corresponds to a typical fuselage section without any cut-out (Figure 1–A). The second will be a model with the same geometry, dimensions and component layout as the first, but with the presence of a cut-out corresponding to a cargo door (Figure 1–B). Finally, in the third model, the cargo door surrounding structure will be modelled with the components and reinforcements that such structure usually has in commercial aircraft ([9]; [10]). In order to simplify the process, it was assumed that the sizes of the frames surrounding the opening are increased by a factor of $\times 1.5$ as well as upper and lower main sill and intercostals were added to the cargo door surrounding structure (Figure 1–C). The developed numerical models of the three different fuselages contained all the important structural features of a transport aircraft: outer skin, frames, stringers, beams of cargo and

passenger floors and struts. In all three cases, the considered fuselage has a radius of 2000mm and a length of 3250mm and consists of 6 frames, with a pitch of 590mm, and 24 stringers. The struts that connect the frames to the passenger crossbeam are based on the fuselage shown in [11] and [12]. The geometry and components present in the sub-cargo floor area, the main responsible for kinetic energy absorption, are based on the sub-cargo structure employed in [8] and [12].

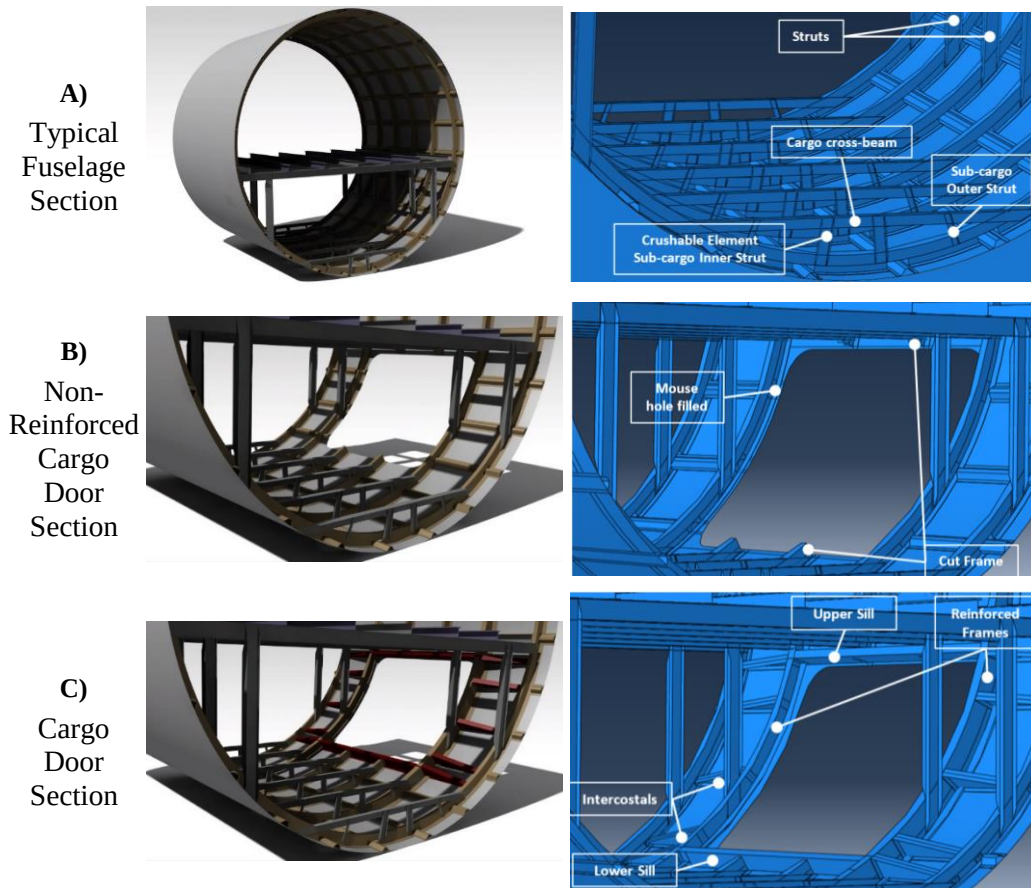


Figure 1 Geometry, components and cargo-door surrounding structure of the three composite fuselage sections

In order to be able to approximately measure the accelerations that passengers would experience, six conventional airline coach-class passenger seats and a total of eighteen passengers were introduced (Figure 2). The three-passenger seat, whose geometry and materials are described in [13], was modelled by means of beam elements. Passengers were introduced in the form of point masses/inertias of 77 kg [14], equivalent to that of a Hybrid III 50th percentile male dummy, located at what would correspond to the centre of gravity of an occupant sitting in the normal upright position [15] and constrained to the rest of the model through Multi Point Constraint (MPC) type tie.

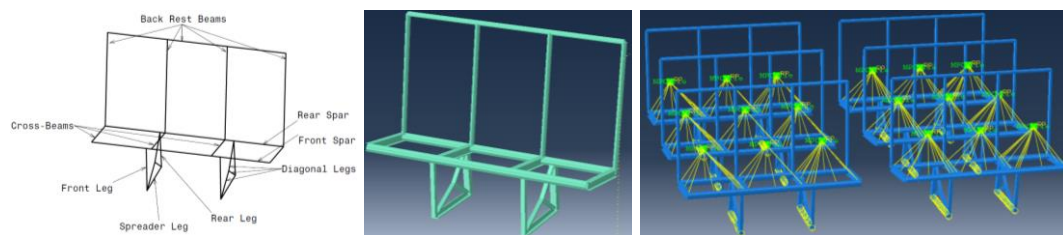


Figure 2 Seat components, seats render view on ABAQUS and Passenger-Seat connection modelling

The structure of the three fuselage sections was entirely made of CFRP, in particular of AS4/3501, a unidirectional CFRP, and of TC1100, a woven fabric thermoplastic. These are the

same materials that were used in the composite fuselage section analysed in the vertical drop test conducted at LISA (Laboratory for Impact testing of Structures in Aerospace field) by the Italian Aerospace Research Centre (CIRA), in July 2017 [16]. Only the passenger floor rails, to which the seats are attached, and the seats were made of metallic materials. Figure 3 shows the materials from which each component is made of.

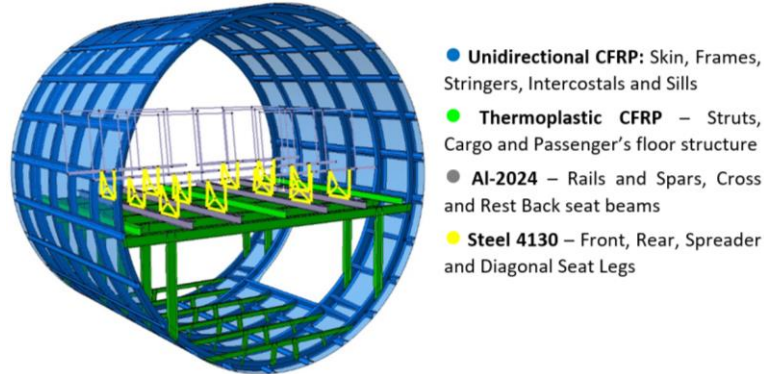


Figure 3 Components of the models plotted by materials

When defining material properties, for composite materials the orthotropic elastic properties of a ply together with the parameters necessary to implement the Hashin's failure criteria, used for predicting the onset and evolution of damage in CFRP structures, were defined. In the case of metals, their elastic-plastic properties were specified. A list of the mechanical properties of the materials is provided in Table 1, Table 2, Table 3 and Table 4.

Table 1 Material properties of AS4/3501 [16]; [17]

AS4/3501 – Unidirectional CFRP Thermosetting Matrix							
Density				$2 \times 10^{-9} \text{ ton/mm}^3$			
Ply Thickness				0.125 mm			
E_1 / MPa	144,400	G_{13} / MPa	7,000	Y^T / MPa	60	G_{1T}^c / N/mm	91.6
E_2 / MPa	10,000	G_{23} / MPa	5,760	Y^C / MPa	400	G_{1C}^c / N/mm	79.9
ν_{12}	0.3	X^T / MPa	2,200	S^L / MPa	180	G_{2T}^c / N/mm	0.22
G_{12} / MPa	7,000	X^C / MPa	1,700	S^T / MPa	180	G_{2T}^c / N/mm	1.1

Table 2 Material properties of TC1100 [16]; [18]

TC1100 – Woven CFRP Thermoplastic Matrix							
Density				$2 \times 10^{-9} \text{ ton/mm}^3$			
Ply Thickness				0.25 mm			
E_1 / MPa	134,000	G_{13} / MPa	5,000	Y^T / MPa	2,020	G_{1T}^c / N/mm	6
E_2 / MPa	134,000	G_{23} / MPa	5,000	Y^C / MPa	1,100	G_{1C}^c / N/mm	6
ν_{12}	0.33	X^T / MPa	2,020	S^L / MPa	180	G_{2T}^c / N/mm	6
G_{12} / MPa	5,000	X^C / MPa	1,100	S^T / MPa	180	G_{2T}^c / N/mm	6

Table 3 Material properties of Al-2024 [16]

Al-2024	
Density	$2.78 \times 10^{-9} \text{ ton/mm}^3$
E / MPa	73,100
ν	0.33

Table 4 Material properties of Steel 4130 [20]

Steel 4130	
Density	$7.85 \times 10^{-9} \text{ ton/mm}^3$
E / MPa	205,000
ν	0.3

The geometry of the components were defined in CATIA in the form of surfaces or lines and imported into ABAQUS/CAE. All the physical connections between components were replaced by surface-to-surface tie constraints available in ABAQUS. In the case of the connection between the seats and the rails (surface with a beam), a tie constraint has also been made but in this case of the node-to-surface type. Once the properties of the thickness and layup of each component of the structure have been applied, the resulting weight of each model is as shown in Table 5. The presence of the cargo door cut-out reduces the weight in 13 kg while the added reinforcements increase it in 20 kg.

Table 5 Mass properties of the three models

	“Typical Fuselage Section”	“Non-Reinforced Cargo-Door Section”	“Cargo Door Section”
Mass of the Barrel Structure	281 kg	268 kg	288 kg
Total Mass of the Seats	127 kg		
Total Mass of the Passengers	1386 kg		
Total Mass of the Model	1794 kg	1781 kg	1801 kg

The impact conditions of the three analyses were completely symmetric with zero pitch and roll angles resulting in a perpendicular impact between the ground and the fuselage section. All the structural components of the fuselage section have been modelled using conventional shell elements (4-nodes) (S4R) due to they are suitable for modelling structures in which the thickness dimension is significantly smaller than the rest of dimensions as well as they have displacement and rotational degrees of freedom, which allows to capture the bending. In the analysis of the crash impact of a fuselage section, which allows capturing the bending of the components during the impact. Seats were modeled through beam elements [19]. The ground against which the models impact was modelled as a rigid surface (elements type R3D4, a 4-node 3-D bilinear rigid quadrilateral) of 3.5 m long and 4.5 m wide. The three vertical drop tests were performed under the conditions of maximum vertical velocity at which a level of occupant safety and survivability equivalent to that of previously certified transport aircraft of similar size must be demonstrated (severe condition stipulated for the Airbus A350 and Boeing B787 [5]; [6]). Therefore, a velocity of 9.14 m/s (30 ft/s) in the $-Z$ direction was applied to each node of the model. Moreover, a gravity acceleration of 9810 mm/s^2 in the $-Z$ direction was applied to the whole model. A frictionless “General contact (Explicit)” with a “Hard” pressure-overclosure relation is defined for the contact between all the surfaces including a component with itself. In addition, a “Surface-to-surface contact (Explicit)” is established between the skin and the rigid plate with the balanced master-slave contact pair formulation, a friction coefficient of 0.3 [21] and a “Hard” pressure-overclosure relation. The element size was chosen in such a way as to result in a uniform mesh with mesh quality metric within the accepted limits. All the components had a size of 10mm except the skin and the rigid plane, which had a size of 50 mm, resulting in meshes with about 250,000 – 300,000 number of nodes and elements. The total simulation duration of the three model was 65 ms, requiring around 30 hours the first model and around 50 hours the two with cargo door to perform the numerical simulation by means of 48 CPUs of the HPC.

Following a certification by analysis approach, before elaborating and assessing the models described above, the numerical model of the vertical drop test of a composite fuselage section whose experimental results are known was developed. The validating model was based on the abovementioned vertical drop test of a full-scale composite fuselage section of a regional aircraft conducted at LISA by the CIRA [16] (Figure 4). The FE model representing said drop test, which had similar geometry, materials and impact conditions, was validated by means of comparisons with deformations, failure onset and propagation and accelerations arising from the experimental test.

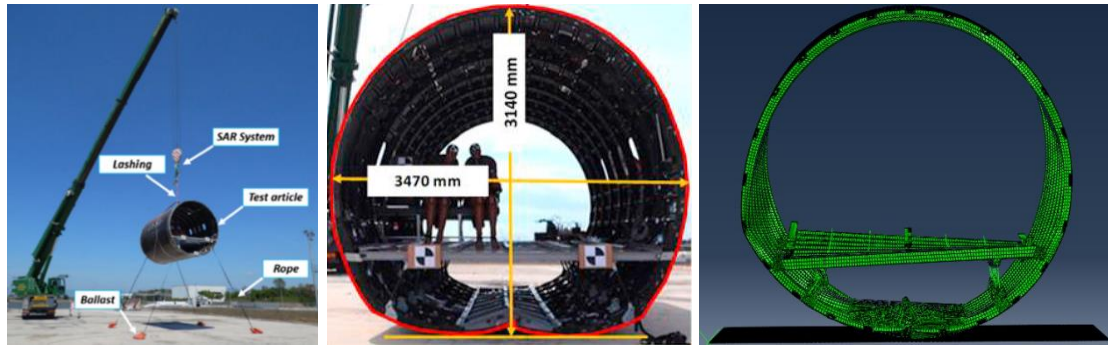


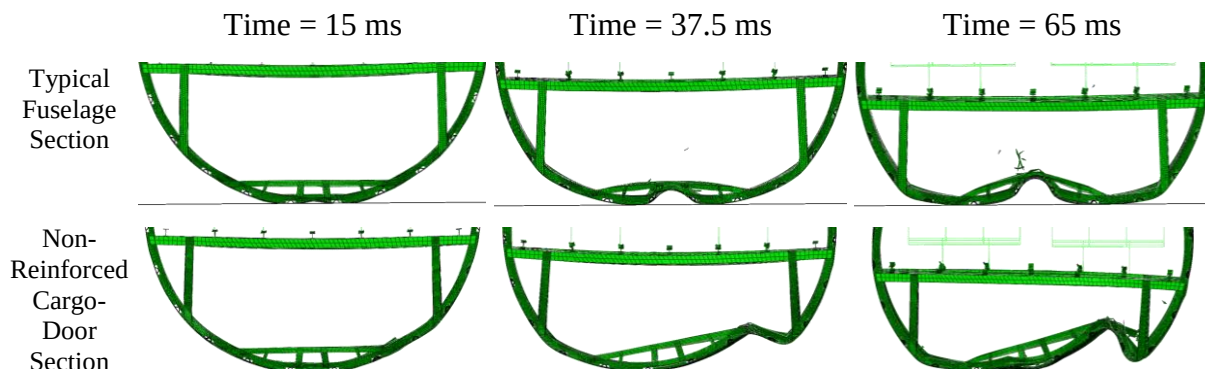
Figure 4 Vertical drop test of full-scale composite fuselage section conducted by CIRA [16] and Validation Model

The results derived from this validation model analysed with ABAQUS/Explicit showed that the model was able to represent in a similar way to the experimental case the behaviour of the sub-cargo structure or the accelerations experimented in the passenger crossbeam. Therefore, it was considered that modelling techniques used in the analysis of the dynamic response of fuselage sections subjected to an impact with a rigid surface are sufficiently reliable to be able to assume that the results obtained in future models are valid.

3. RESULTS

The effect that the presence of the cargo door has on the crashworthiness of a composite fuselage section was assessed comparing first the deformations, damages and failures produced in the structure of the three models during the impact and, subsequently, the kinematic behaviour of the different fuselage in terms of accelerations experienced by the occupants.

Qualitative assessment in terms of failure onset and propagation between the dynamic responses of the three fuselage section can be reported by means of comparisons of how the three models are deformed throughout the analysis. Such deformations will allow to identify the natural crash kinematics, that is, the natural structural behaviour during an impact event for each of the three models. Figure 5 shows the crash sequence of each model throughout the impact.



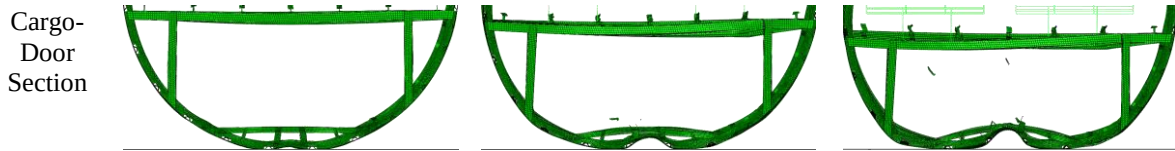


Figure 5 Crash sequence of the three composite fuselage section models

It can be seen that the “Typical Fuselage Section” presents a symmetric Unrolling crash kinematics in which, first, the sub-cargo area starts crushing. Then, the frames also begin to bend at the points of both sides of the fuselage near the struts producing an upward movement of the lower fuselage shell together with the cargo cross beam. In the final state, the sub-cargo area crushing as well as the frame bending continues. On the contrary, the “Non-Reinforced Cargo-Door Section” model results in a completely different behaviour, an asymmetric crash sequence in which only the bending and consequent failure of the frames on the cargo-door side occurs. However, in the case of the “Cargo-Door Section”, the behaviour of the structure is similar to that shown by the “Typical Fuselage Section”, a symmetric crash sequence with an Unrolling crash kinematics. Taking a closer look at the sub-cargo and right side areas of the models structure (Figure 6), the phenomena related to the crash cascading sequence explained above can be noticed in more detail as well as the points at which the frames and the sub-cargo beams bends and fails.

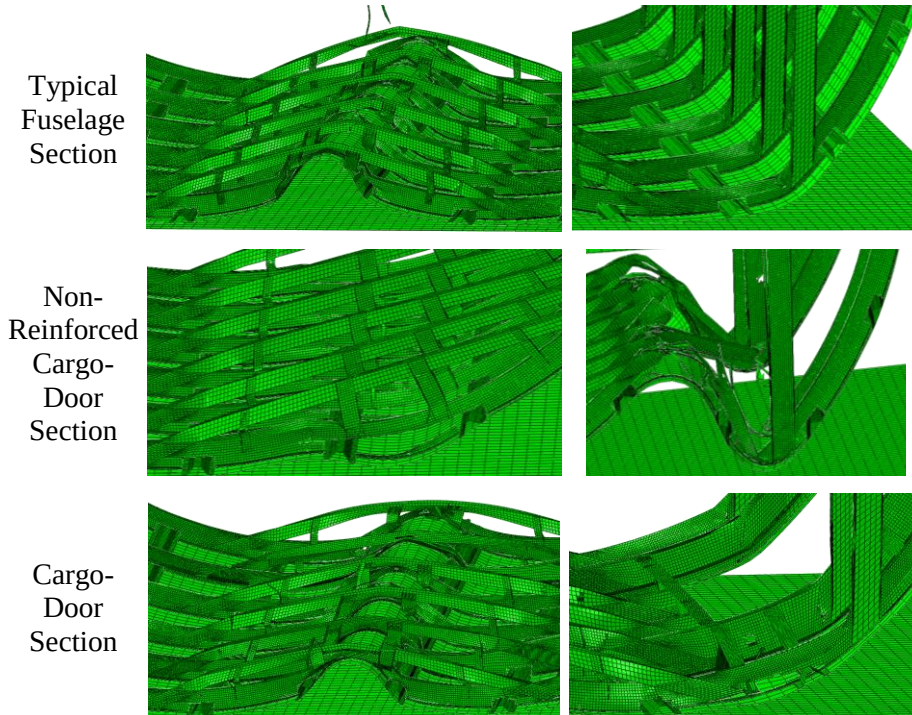


Figure 6 Sub-cargo crushing and frame bending of the three composite fuselage section models

Again, it can be clearly appreciated how the response of the structure of the "Cargo-Door Section" is similar to that of the "Typical Fuselage Section". The main reason may be that, by increasing the thickness and dimensions of the frames ($\times 1.5$) as well as the addition of reinforcement elements, the resulting area surrounding the cargo door is stiffer than the sub-cargo structure. Therefore, this means that the most susceptible failure mode during an impact for the “Cargo-Door Section” model occurs in the sub-cargo area, as opposed to the “Non-Reinforced Cargo-Door Section” where the most susceptible area of failure is the unreinforced frames surrounding the cargo door.

Since the "Typical Fuselage Section" and "Cargo-Door Section" models have similar dynamic responses, the magnitude of the sub-cargo zone deformation was compared (Figure 7). The

magnitude of the sub-cargo zone deformation of the “Typical Fuselage Section” is greater than that of the “Cargo-Door Section”. This will surely imply a different magnitude of the accelerations experienced by the occupants in both models, being, most certainly, higher in the “Cargo-Door Section” model due to its lesser amount of damage. The rotation around the points where the frames next to the struts bends was symmetric in the first case and slightly asymmetric in the second, reflecting the greater structural stiffness that the reinforcements provide on the cargo door side.

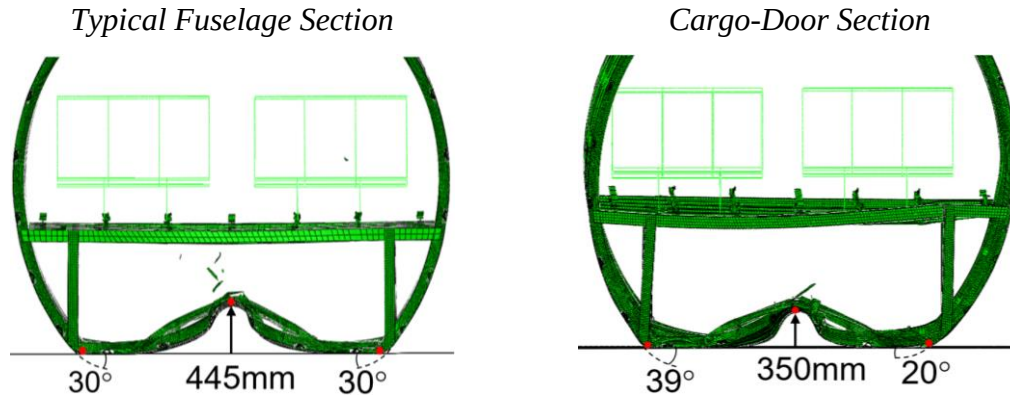


Figure 7 Comparison of the deformations between the “Typical Fuselage Section” and “Cargo-Door Section” models

The final aspect to be analysed in relation to deformations and failure onset and propagation is if the structure is capable of preserving the survivable space without entrapping the passengers after the impact. In none of the three models gave the impression that there will be any sort of penetration into the safe space or that the occupants may be trapped. Nevertheless, as can be observed in Figure 8, in the passenger crossbeam of the “Cargo-Door Section” model, failure of several web elements occurred, probably due to the smaller deformation developed in the cargo area of said model. This can lead to the failure of the passenger crossbeam of said model at a later stage, thus inducing other types of injuries in the occupants apart from the ones related to accelerations. Therefore, this issue has to be taken into account and analyses should be carried out for longer time periods.

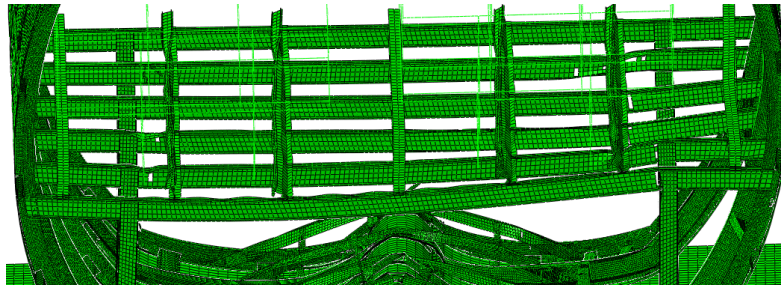


Figure 8 State of the “Cargo Door Section” passenger crossbeam at the end of the impact simulation time

All the acceleration measured on the results of the FE models were filtered with a CFC180 filter, one of the available SAE filtering classes ABAQUS contains. Acceleration signals on the structure, in particular the cargo and the passengers crossbeams, of the three models were analysed and compared finding that the different acceleration peaks, specially the highest ones, coincide with the moment of the crash sequence at which the failure on these components occurs. The impact the cargo door has on the crashworthiness of the sections can be appreciated though comparison of the accelerations experienced by the passengers. The acceleration-time curves with the highest acceleration peaks, measured on the passengers of each model, were transformed into acceleration – pulse duration curves, producing an Eiband chart, which

allowed to analyse the acceleration load level as well as potential passenger injuries [8]. Figure 9 gives the resulting Eiband diagram with the potentially most dangerous acceleration signal of each of the three models.

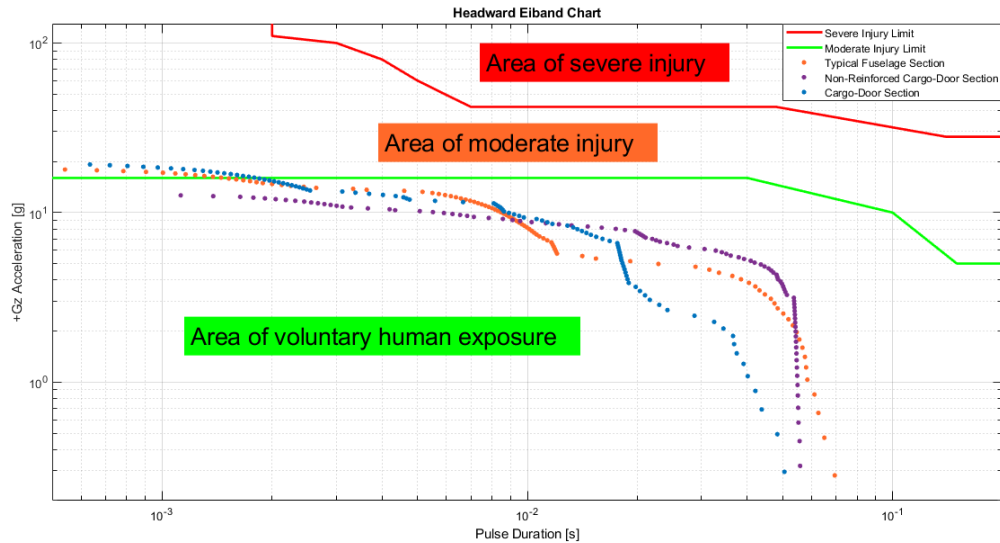


Figure 9 Eiband chart of the critical acceleration curves measured on occupants of each model

According to the eiband chart derived from the results of accelerations measured on the passengers of the three models, it can be seen that the dynamic response during an impact event of the “Non-Reinforced Cargo-Door Section” is the most effective in terms of crashworthiness. The crash kinematics that this model shows, together with its consequent crash cascading sequence, makes this design the one that experiences the lowest acceleration loads of the three, all of which are within the voluntary human exposure level, and the safest for the occupants in case of impact. On the other hand, on the “Cargo-Door Section” model, occupants experience accelerations that may cause damage and which are the highest measured in all three models. Therefore, the fuselage section with the structure properly designed due to the presence of a cargo door would be the most dangerous for passengers, in terms of accelerations, in the case of an impact event.

4. CONCLUSIONS

A numerical assessment of the effect a cargo door has on the crashworthiness of a composite fuselage section was presented in this paper. Three numerical models of a composite barrel were developed and examined, one without any cut-out and two with a cargo door. The results showed that the presence of a cargo door implies a non symmetrical a crash sequence. However, the presence of reinforcements on the surrounding structure of the cargo door force the section to behave similar to a section without any cut-out. The increased stiffness of the structure on the cargo door side due to reinforcements in less deformation of the whole structure, which is detrimental to the absorption of the impact kinetic energy. This is reflected in the accelerations experienced by passengers, being the “Cargo Door Section” the most hazardous fuselage design for the occupants. Therefore, the presence of the cargo door and its surrounding structure duly reinforced is detrimental to the properties of crashworthiness of a composite fuselage section. Finally, it was observed that thanks to the crash sequence it develops, which allows to the structure to deform significantly and thus absorb more energy, the “Non-Reinforced Cargo-Door Section” is the safest design for the occupants just in terms of crashworthiness.

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