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Partial modeling of aircraft fuselage during an emergency crash landing

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Abstract

During an emergency crash landing, the first requirement translates into the ability of an aeronautical structure to ensure a vital space for the occupants during an impact, and then limiting the accelerations on the occupants in terms of intensity and duration.
The aim of this study is about the impact phenomenon, that is generally not addressed to understand if and how the structure is deformed, but if the structures allocate the kinetic energy resulting from the impact and if it is completely able to participate to the absorption of impact, all for the benefit of passive safety occupants. On the basis of this consideration, therefore, it becomes much more significant for the structural designer to try to correlate the paths of energy absorption, and this is obtained studying the composite materials and polymers, and their difference in behavior compared to metallic materials, highlighting the design parameters of the same material as a function of impact behavior.
A finite element model of a typical composite fuselage was developed using the nonlinear, explicit transient dynamic code, LS-Dyna. The numerical simulations aided to evaluate the part of the structure able to absorb the energy during the impact, the results allowed to reproduce the similar scenario but on a "scaled" numerical component.
The focus of this paper is to evaluate the scaling concept and its possible incorporation into the crashworthiness evaluation of fuselage as a potential crashworthiness evaluation tool.

Keywords: Composites material; aerospace applications; crashworthiness; dynamic loads; impact.

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1. Introduction

The research carried out in the field of passive safety (crashworthiness) and the analysis about the aeronautical accidents' dynamic have allowed to develop materials and manufacturing technologies that have led to the definition

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of solutions in which the possibility of occurrence of a structural failure in a collision is reduced. Furthermore the ability of these structures to absorb energy is increased and then their level of passive safety, [1].

The fuselage must meet criteria somewhat restrictive as regards the certification since the collapse of this structure causes, in the case of non fatal impacts, an increase of the risks to the passengers due to both the possibility of collisions with objects that the possibility of being trapped, [6]-[9].

The regulations require that the structure, containing the passengers, be subjected to the drop tests without showing cracks or deformations such as to be harmful or too high, [10]-[12].

An aircraft designed for impact must meet a number of requirements; in particular the passenger area and the safety of themselves must not be compromised and the structural components are able to dissipate the kinetic energy of the aircraft, maintaining the level of deceleration below a tolerable limit. In most aircraft structures designed to support the high loads encountered during the various types of accidents are often designed as thin-walled components of metallic material or composite material, [4].

In the case of conventional metallic materials the plastic collapse of structures subjected to impact phenomena is very important because the two most important forms of collapse, involved in energy dissipation during the impact, are represented by the collapse flexural and axial collapse. In situations of impact loading, in fact, the structure for energy absorption is loaded beyond its capacity of elastic resistance giving rise to the collapse of the same in localized areas with shapes or controlled processes; for example it can dissipate the kinetic energy with remarkable efficiency using the hinges in the joint areas, where, after impact, it has a plastic deformation. On the other hand a structure in composite material, made with carbon fibers immersed in an epoxy matrix, is not characterized by a plastic deformation. Initially, in this case, the stress is transmitted from the point of impact to the whole structure so that the energy can be absorbed with a high total load without permanent damage. Only when the load in the contact zone exceeds the absolute resistance of the laminate, the break in that area becomes total and the laminate tends to crumble progressively. The failure of composites ensures that they do not exceed the yield strength of processes characteristic of ductile metals, but the application of the load will deform elastically up to the point of fracture.

The department is involved in the study of preliminary design of a fuselage section in composite material. The study will be dedicated to design a five bay long section and in particular to design the cargo section and how to increase the ability of this structure to absorb energy and the level of passive safety. Finally a preliminary prototype will be subjected to the experimental drop test. In this paper the numerical simulation are performed to analyze the partial fuselage (cargo section, stanchions) when it is subjected to a 15 [m/s] vertical drop test to evaluate the impact responses of composite airframe structures, and to evaluate the capabilities of the explicit transient dynamic finite element code, LS-DYNA®, to simulate these responses including damage initiation and progressive failure. The properties of the composite material were represented using both a progressive in-plane damage model (Mat 54) in LS-DYNA, [2]. This paper provides the numerical analysis and the study of the time history responses and the location and type of damage for representative section components, this method is more considered by the tools able to optimize the structure using the certification by analysis approach, [5].

2. Fuselage section model development

The model geometry was developed from technical drawings of the fuselage section. Development of the model was performed using two pre-processing software package, MSC.Patran and LS PrePost. A geometric model of the fuselage section was developed containing the important structural features of the airframe. The geometric model was discretized, and element and material properties were assigned, all parts are modeled by two-dimensional elements. A database of composite materials and metal was implemented, to allow changing in the properties of each part to optimize the absorbing of energy. It is in fact thought to analyse the behaviour of non-homogeneous structures, creating models made entirely of composite material and other mixed composite material and aluminium, in order to highlight the structural solution faster in the event of a crash. All models have in common geometry, initial and boundary conditions.

The complete finite element model of the fuselage section with cargo section and passenger floor is shown in Fig. 1. Components of the model including the outer skin, fuselage frames, floor, longitudinal stringers, cargo and stanchions elements are shown in Fig. 2

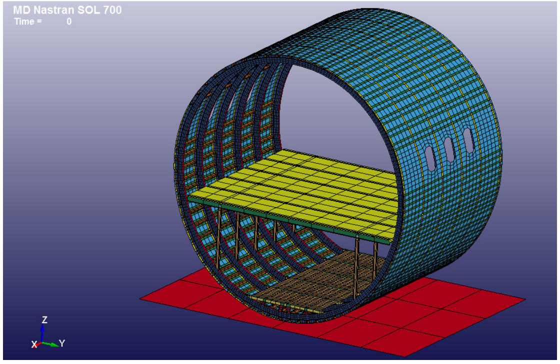


Fig. 1. Fem model of the fuselage section.

The section of the skin panel has a constant thickness and a mesh of CQUAD4 shell elements has been implemented. The surface was created following the two curves representative of the section of the double-lobe fuselage structure, in particular for the lower lobe the equation of an ellipse is used while for the upper lobe that of a circumference. The material of the base plate is an IMS with a specifically designed symmetrical lay-up, which has the distinction of being considered a quasi-isotropic material. The panel has a lay-up consisting of 10 ply.

The stringer has omega-section with constant thickness, extending in the longitudinal direction and has been modeled using CQUAD4 shell elements. The base material of the lamina is an IMS. The lay-up is symmetrical and is made from 10 ply.

The frame has section "F" with a constant thickness, extends in the circumferential direction in the YZ plane. The elements used are plans CQUAD4. The base material of the lamina is an IMS. The lay-up is unidirectional and is made from 5 ply.

The elements used to model the floor cargo are CQUAD4 and CTRIA3. The floor is composed of several parts connected by rigid elements. For all parties, longitudinal beam, cross beam, stanchion, skins, it is used as a base material of the foil IMS, but each of these parts has a different lay-up.

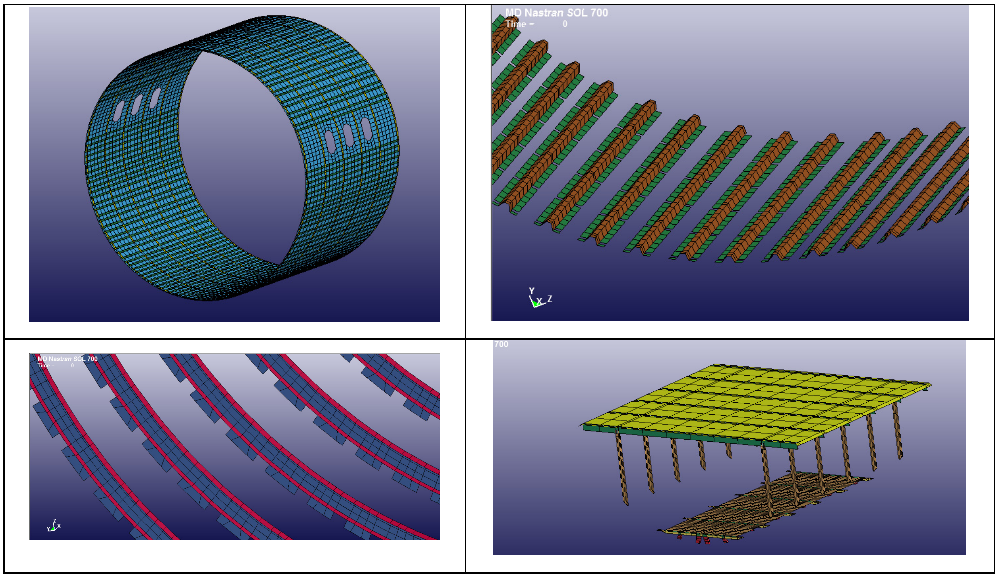


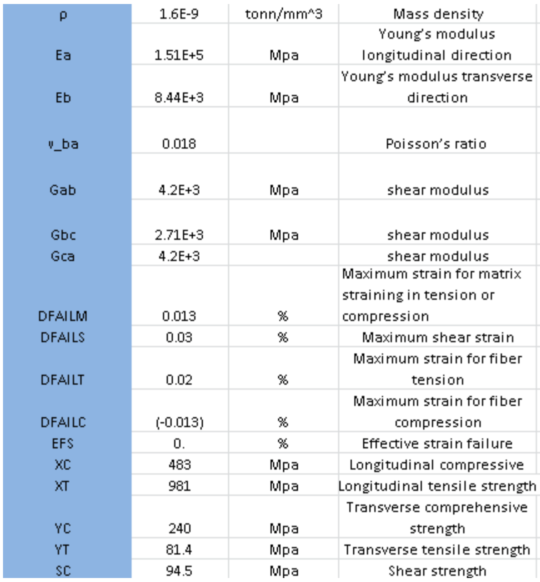
Fig. 2. Particular component of the fuselage section.

The fuselage is subjected to drop with a descent velocity so the constraint conditions have been applied only to the ground, which is modelled as a rigid plate fixed along the outer edges, since the structure must be free to impact the ground. A 15 [m/s] descent speed was assigned uniformly to the fuselage structure. Furthermore, since the structure is subjected to the action of gravity, a time constant acceleration equal to the acceleration of gravity, has been applied to the whole structure.

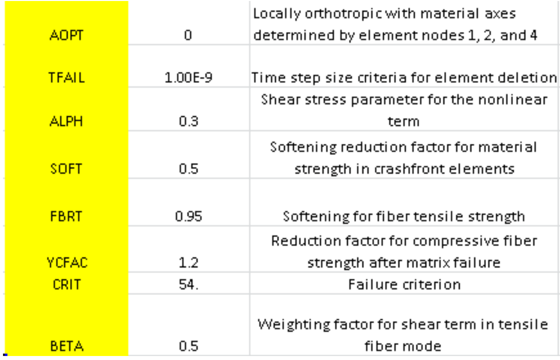
The assignment of a consistent contact is important for the discussion of the crash event. This is essential to allow the transmission of the load between the structure and the rigid ground, also allows to predict the load transmission among the different parts of the structure that are in contact during the deformation, so as to avoid the interpenetration among the parts that are in contact. The distance between the elements of the structure and the ground was introduced through the CONTACT tab, touch a master-slave type 'adaptive'. Furthermore, it has been used a self-contact, to avoid surfaces that fold back on themselves exhibit interpenetration of nodes, because of the large deformation on impact, the surfaces can turn in on themselves.

The problem of finding an appropriate formulation for the shell element for the prediction of damage on the composite material has been addressed using a model that predicts the progression of the damage reproducing an accurate coupling between the deformation modes. Assigning elasto-mechanical properties of the material using the card MATD54, that is a model for orthotropic materials. MATD54 also reduces the resistance of the fiber to account for the failure of the array and implements a model of progressive degradation after breaking. Optionally two types of failure are defined (Chang and Chang, 1984 (CRIT = 54.0) and Tsai and Wu, 1981 (CRIT = 55.0)). This model is valid only for thin shell elements. For all the shell elements this lamination theory is used. The theory of the laminate is properly applied uniformly to a constant shear strain through the thickness of the shell.

This material characteristics and layup used to model the FEM fuselage impacting on the ground are reported in the following Fig. 3 and then Fig. 4:

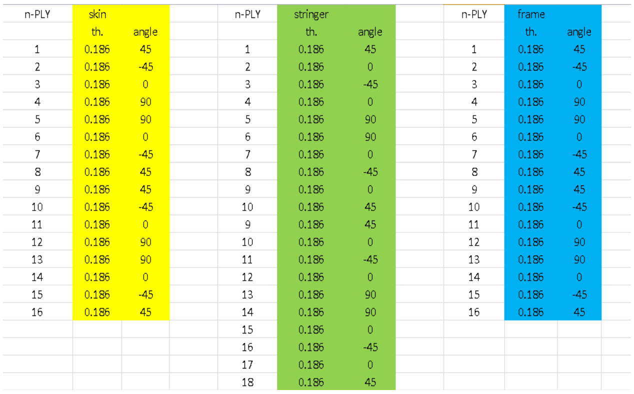


ρ	1.6E-9	tonn/mm^3	Mass density
Ea	1.51E+5	Mpa	Young's modulus longitudinal direction
Eb	8.44E+3	Mpa	Young's modulus transverse direction
ν_ba	0.018		Poisson's ratio
Gab	4.2E+3	Mpa	shear modulus
Gbc	2.71E+3	Mpa	shear modulus
Gca	4.2E+3		shear modulus
DFAILM	0.013	%	Maximum strain for matrix straining in tension or compression
DFAILS	0.03	%	Maximum shear strain
DFAILT	0.02	%	Maximum strain for fiber tension
DFAILC	(-0.013)	%	Maximum strain for fiber compression
EFS	0.	%	Effective strain failure
XC	483	Mpa	Longitudinal compressive
XT	981	Mpa	Longitudinal tensile strength
YC	240	Mpa	Transverse comprehensive strength
YT	81.4	Mpa	Transverse tensile strength
SC	94.5	Mpa	Shear strength



AOPT	0	Locally orthotropic with material axes determined by element nodes 1, 2, and 4
TFAIL	1.00E-9	Time step size criteria for element deletion
ALPH	0.3	Shear stress parameter for the nonlinear term
SOFT	0.5	Softening reduction factor for material strength in crashfront elements
FBRT	0.95	Softening for fiber tensile strength
YCFAC	1.2	Reduction factor for compressive fiber strength after matrix failure
CRIT	54.	Failure criterion
BETA	0.5	Weighting factor for shear term in tensile fiber mode

Fig. 3. Material characteristics



n-PLY	skin			n-PLY	stringer			n-PLY	frame	
	th.	angle			th.	angle			th.	angle
1	0.186	45		1	0.186	45		1	0.186	45
2	0.186	-45		2	0.186	0		2	0.186	-45
3	0.186	0		3	0.186	-45		3	0.186	0
4	0.186	90		4	0.186	0		4	0.186	90
5	0.186	90		5	0.186	90		5	0.186	90
6	0.186	0		6	0.186	90		6	0.186	0
7	0.186	-45		7	0.186	0		7	0.186	-45
8	0.186	45		8	0.186	-45		8	0.186	45
9	0.186	45		9	0.186	0		9	0.186	45
10	0.186	-45		10	0.186	45		10	0.186	-45
11	0.186	0		9	0.186	45		11	0.186	0
12	0.186	90		10	0.186	0		12	0.186	90
13	0.186	90		11	0.186	-45		13	0.186	90
14	0.186	0		12	0.186	0		14	0.186	0
15	0.186	-45		13	0.186	90		15	0.186	-45
16	0.186	45		14	0.186	90		16	0.186	45
				15	0.186	0				
				16	0.186	-45				
				17	0.186	0				
				18	0.186	45				

Fig. 4. Layup material

3. Post results discussion

The front view of the FEM model fuselage subjected to vertical impact is shown in Fig. 5. The rigid wall is located in the XY plane under the structure. The distance between the fuselage and the wall is 0.1 m, this means that the structure hits the wall after traveling this distance at a speed higher than that initially set, because it takes into account the acceleration of gravity.

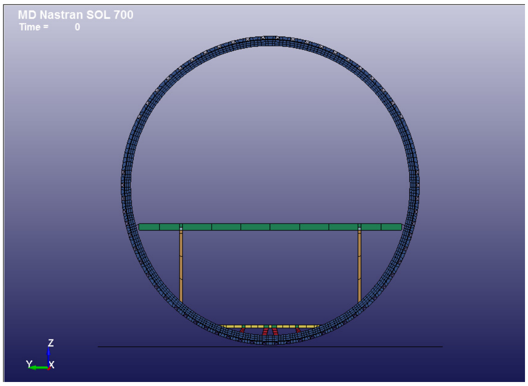


Fig. 5. Front view of the FE mode.

As soon as the structure impacts with ground the kinetic energy of the body decreases, and as the energy is absorbed by the inner parts of the structure that react. This shows that the structure hit the wall hard, and also shows that most of the energy at this time is absorbed by the structure as internal energy of the elements in proximity to the impact zone, [13]-[14].

The front view of the fuselage is shown at time 0.1 s in Fig. 6. The pavement passenger is involved in the phenomenon of impact. The deformation of the frame continues to be marked, while for the floor passenger appears to be small. It is noted that the area of attachment between the frame and the floor of the deformations presents very marked, because the structure of connection between the two parties has been modeled using a simple junction and then the floor is directly connected with the frame. There is no intrusion of components in the passenger area; the frame will not warp outwards by entering the passenger area. It has a significant decrease in the volume of the passenger area. The most stressed parts of the structure floor turn out to be the stanchions that act as beam column. This appears to be the most important moment of impact, because the affected area is occupied by passengers.

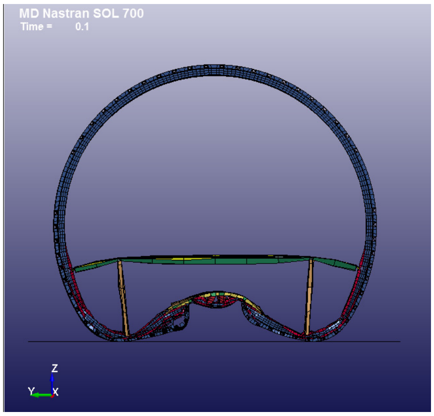


Fig. 6. The contact of the FEM fuselage and ground after 0.1 s

Analyzing the crash absorbing dynamic and failure characteristics related to the post-impacted fuselage it is possible to identify to the internal energy for each part involved in the impact as shown in Fig. 7. The floor passenger (Part 12, 13, 14, 15) absorbs the maximum amount of energy compared with the other parts, such as: cargo floor (Part 8, 9, 10, 11), skin (Part 2, 3, 4), stringer (Part 5). Nextly the passenger floor frame (Part 6, 7) absorbs more energy than the other components.

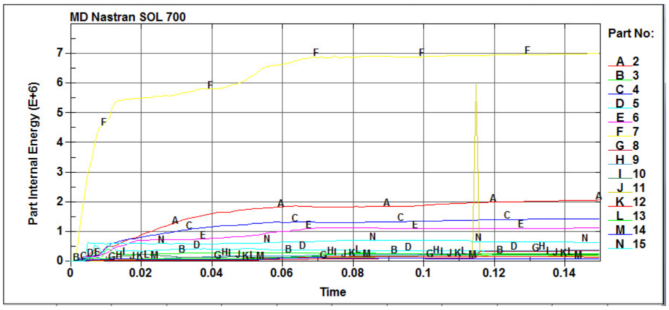


Fig. 7. Internal energy for each component of FEM fuselage.

The numerical results obtained on the fullscale fuselage subjected to the drop test, allowed studying and to define the best solution to scale a dedicated specimen as a portion of the fuselage, the final focus about this research project is define the design, the prototype ready to be tested at drop impact test.

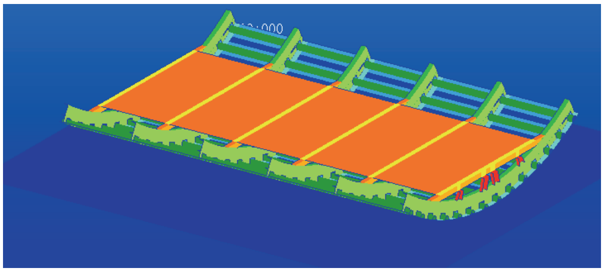


Fig. 8. Aircraft scaled fuselage model

The scaled prototype presents the partial fuselage. Pre-test simulations were performed to prove the effectiveness of the energy absorbing concept design, to minimize the test risks and to make predictions, which can be later compared with the experimental results.

The FE model mesh (Fig. 8) is a complete model of the structure, which is modeled with shell elements located in the center plane of the actual parts. The average element edge length is 10 mm. The different components of the model are connected by means of rivets in accurate number and position and by means of adhesive. Both, rivets and adhesive are modeled using rigid body multi-point constraints with rupture criteria. The masses that represent passengers, seats and the test guiding system are modeled with solid elements and they are attached to the top of the model. The ground is modeled as a rigid wall with sliding interface and a friction coefficient structure.

Analyses of sensitivity to material data, total mass, rivet and adhesive failure, floor beams center check, frame/skin and skin debonding, and splices/frame/skin fragile initial contact were performed. The results of these simulations showed that during the collapsing sequence the FE cargo model shows a deformed shape approximately similar between the simulation at the complete fuselage and the simulation partial fuselage, [15]-[16]. The time histories about the contact force, acceleration measured in correspondence of the fixed point, the displacement and contact forces are predicted fairly well between the simulation of the complete fuselage and the simulation partial fuselage, [17].

These wide range variables about the different simulation allowed focusing the study about the layup and material focusing the attention on the ability to absorb energy. The correlation between the simulations about the full scale of the fuselage and the scaled component allowed to evaluate the parameter that influence the cash absorbing characteristics of the cargo component. For example it was possible to identify the time histories of acceleration measured in correspondence of the possible attachments of the passenger seat about two different configurations. The Fig. 9 presents the acceleration of 20 g measured for a configuration with floor in aluminum, the Fig. 10 shows the acceleration of 10 g measured when the floor is in composite material.

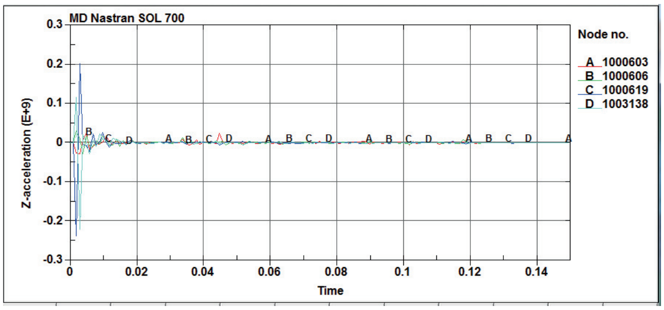


Fig. 9. THS of the acceleration in correspondence of the passenger seat with floor in aluminium.

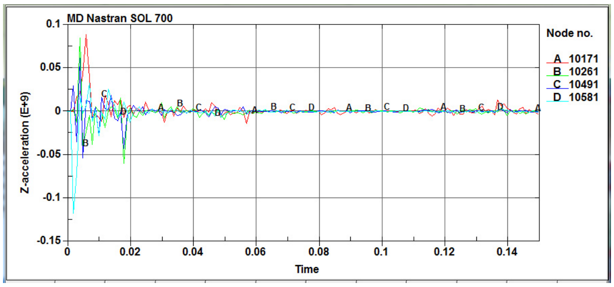


Fig. 10. THS of the acceleration in correspondence of the passenger seat with floor in composite.

4. Conclusion

The numerical simulation of structures subjected to crash loads is one of the most demanding topics in structural dynamics. All kind of non-linearity (very large displacements, material laws, ruptures...) has to be taken into account as well as all possible details. This paper has shown that a significant progress has been performed in recent years to the aim of having predictive tool that could be use to simulate structural behavior in survivable aeronautical crashes with any kind of fuselage materials (metallic and composite). Nevertheless, there are still some limitations in the methodology that need to be overcome and new approaches that need to be investigated.

The numerical simulations aided to evaluate the part of the structure able to absorb the energy during the impact, the results allowed to reproduce the similar scenario but on a “scaled” numerical component.

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