# ON THE SAFETY ASSESSMENT AND DAMAGE TOLERANCE OF COMPOSITE LATTICE TYPE AEROSPACE STRUCTURES

T. Kotzakolios[a], D.E. Vlachos[a], K. Antoniadis[a], V. Kostopoulos[a*]

[a] *Applied Mechanics Laboratory,Department of Mechanical Engineering and Aeronautics, University of Patras, PatrasUniversity Campus, GR-26500, Patras, Greece*

**kostopoulos@mech.upatras.gr*

**Keywords:** Damage tolerance, composites, lattice, aerospace

## Abstract

**In this work, impact and damage response of composite wafer structures is numerically modeled. The damage created on the structure is identified and the reduction of the airworthiness of the structure is investigated. Comparisons are made with conventional composite structures.**

## 1. Introduction

Composite lattice type structures have the advantage of high weight efficiency due to the use of unidirectional load carrying elements that lead to higher specific strength and stiffness, compared to contemporary composite structures. Aeronautical structures are often subjected to loads, such as impact, that often lead to damage. This fact, leads to design allowables for composites that are often 50-60% of the composite material failure strains. However, this practice is applied for conventional composite panels that follow the frame-stringer-skin approach where their damage tolerance characteristics are well studied. The damage tolerance of wafer and grid stiffened structures in general has not yet been studied in enough detail.

Lattice structures have the advantage of weight efficiency due to their high specific strength and stiffness as a result of the unidirectional ribs that are used as load carrying elements. Most of the work on this subject is dealing with analysis and optimization of statically loaded lattice structures. More specifically, Vasiliev et al [1] has described the integrated design, manufacturing and testing process for high performance lattice structures. Moreover, the same authors provide valuable information regarding the analysis of that kind of structures by using continuum models with ribs smeared over the structure surface. Vasiliev and Razin [2] also have published work regarding the applications of composite lattice structures in aerospace industry and the complications that arise from this concept compared with conventional “black aluminum” composite structures. Totaro [3] have developed a numerical optimization scheme for composite lattice structures in order to obtain a minimum mass solution based on stiffness constraints. Additionally, Morozov et al [4] have developed a methodology based on finite element analysis for the investigation of buckling behavior of composite lattice structures subjected to tension/compression, bending and torsion.

### *1.1. Vertical crash load case*

For the crash analysis, a fuselage section with approximate diameter of 1800 mm and length 2000 mm was chosen. This section is representative in dimensions of a typical fuselage section of a small business aircraft. The typical fuselage of currently used business jets are mainly made out from aluminium alloys. From the initial geometry of the fuselage section and the design loads of the aircraft, a conventional all composite fuselage section was designed. The geometry of the composite fuselage is shown in Figure 1, whereas the layup used for each part of the fuselage section is summarized in Table 1.

Regarding the lattice composite structure, a reinforcing scheme of +/-26$^{o}$ was selected, with 90$^{o}$ additional reinforcing ribs. The skin thickness of the lattice structure was 1.4mm thick with a +/-45$^{o}$ lamination. For reasons of comparison with the conventional composite structure, a similar floor structure was selected, which can be seen in Figure 2.

The material that was used for both composite structures (conventional composite and lattice) and its properties is summarized in Table 2. A static analysis was initially performed for both structures, in order to check for strains under flight loads. It is worth mentioning that knock-down factors were used for failure strains taking into account hail impact, fatigue among others, leading to a failure strain knock-down by 50-60%. However, the complete design process of a composite fuselage section falls beyond the scope of this paper.

The simulations were performed by using the LS-DYNA explicit Finite Element code [5]. The conventional CFRP structure was modelled with approximately 50,000 shell elements, including the fuselage frames and floor. The composite lattice structure was modeled with approximately 50,000 shell elements for the skin and floor and 20,000 beam elements for the reinforcing ribs. Regarding the passengers and the corresponding seats, there are several methodologies to model such systems. The simplest method is to substitute the passenger/seat system with concentrated masses [6]. Another method is to model the passenger/seat interaction by utilizing human occupant models and explicitly modeling the passenger seats [7]. Another method, is the Dynamic Response model [8], where a seated occupant is a single lumped mass representing the occupant upper torso mass, which can be connected to the seat or floor through a spring and damper that represents the spine. The Dynamic Response Index (DRI) model is such a model that has been correlated with ejection seat data to predict the threshold of spinal injury due to a vertical acceleration pulse. It is worth mentioning that it is still being used by NASA for assessment of landing systems for manned capsules [9].

The comparison between the composite lattice section and the conventional CFRP was made in terms of displacement, velocity and acceleration taken from the concentrated masses that represent the seat/passenger system. Figure 2 shows the acceleration results for each fuselage configuration, where it can be seen that the results are in favour of the lattice structure, since the maximum value of acceleration measured for the composite lattice structure is approximately 14% lower than the corresponding value of the conventional one. This advantage is attributed to the lower weight of the lattice structure and also to its ability to distribute loads more uniformly than conventional frame/skin configuration. A closer examination for the cases of conventional CFRP and lattice sections with the same subfloor structure can lead to this conclusion. More specifically, for the case of both sections the absorbed energies from different parts can be seen in Figure 2. It can be therefore concluded that regarding the fuselage structure itself, without taking into account the energy absorbed by the subfloor structure, the frames absorb more energy than the skin. As it can be seen in Figure 3, the subfloor crushing process starts with the facesheet buckling, where at the later stages of impact the compaction of the foam blocks occurs. This leads to a more progressive collapse of the subfloor structure, leading to lower accelerations.

Regarding the Dynamic Response Index for spinal injury, their values are summarized in Table 3. It can be seen that the lowest probability of spinal injury exists with the lattice sections by utilizing the foam block type. However, it is worth mentioning that for all three cases the probability of spinal injury is from small to moderate.

### *1.2. Hail impact*

The second load case concerns the hail impact of both conventional CFRP and composite lattice structure. In order to investigate the effects of hail impact, a certain degree of detail is required for the Finite Element Analysis. For this reason, Finite Element models of curved panels were generated by using solid elements in order to capture though the thickness damage and dents. The panels were clamped at the edges. The chosen hail size was 25mm in diameter, with a terminal velocity of 25m/s. This hail size and velocity, according to [10], represents an event of rare hailstorm.

For the conventional CFRP panel, two impact locations where investigated

- Impact on unstiffened skin
- Impact above stiffener

For the lattice panel, the following impact locations where selected

- Impact on the intersection area of the +/-26$^o$ and 90$^o$ stiffeners
- Impact on one of the +/-26$^o$ stiffener
- Impact on unstiffened skin

Approximately 500,000 solid elements where required for modelling each panel. The material model of the panels was identical with the one used for the crash analysis.

Regarding hail, it was modelled by using the Smoothed Particle Hydrodynamics (SPH) method instead of the Lagrangian one. SPH method overcomes the problem of large distortions often encountered in the Lagrangian method, which in turn lead to large computational times and loss of accuracy. The model of the hail consisted of 4,000 particles. The material model that was used for describing hail was LS-DYNA MAT_10 (elastoplastic hydrodynamic material model), with material properties summarised in Table 4 and found in [11]. The aforementioned material model was also accompanied by the water polynomial equation of state. This material model and equation of state combination, along with the SPH method has the advantage of modelling accurately the initial stages of impact, where ice has adequate stiffness and the later stages of impact, where ice fails and behaves more like a fluid.

In order to better assess and quantify the performance of the two configurations, it was decided to study the compression after impact behavior of the panels. The models of the panels right after the impact simulations were subjected to a quasi-static compression up to the limit load (collapse of the panel due to compression and buckling, as seen in Figures 25-26) by using the implicit solver of LS-DYNA. By comparing the limit load values for the impacted panels to the values obtained for pristine panels it is made evident which configuration is more sensitive to the impact damage. For the wafer panel the decrease of the limit load was close to 25%, significantly more than the case of the conventional design (~7%), as it can be seen in Figures 27-28. This was due to the fact that the local debonding between the skin and the due to the impact, weakens the structure significantly as opposed to the conventional design where the main load bearing members (frames) are not affected. Moreover, the ribs for the case of the wafer panel were manufactured with a unidirectional layup, which tends to be quite vulnerable to impact damage. Finally, there is a stiffness mismatch between the +/-45$^o$ lamination of the skin and the +/-26$^o$ orientation of the reinforcing ribs, a characteristic that generally initiates and promotes damage.

## **2. Tables and figures**

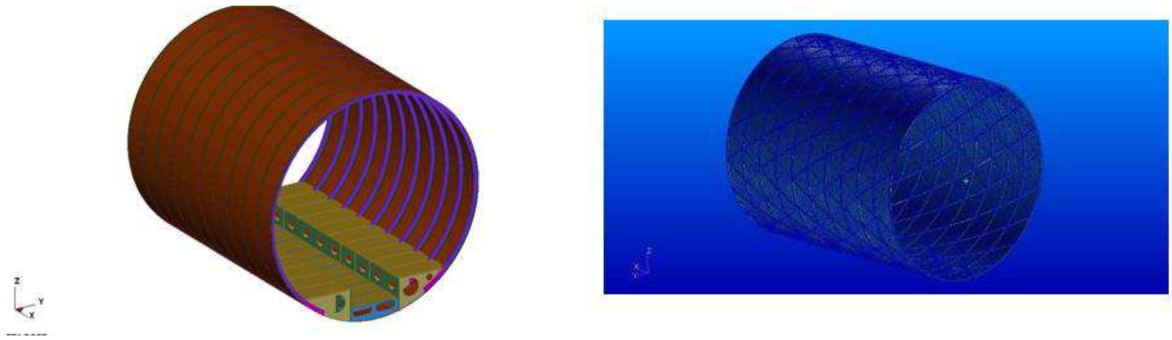

Figure 1: Geometry of conventional CFRP fuselage section(left) and composite lattice section (right)

| Part | Layup |
|---|---|
| skin | [±45, 0/90, ±45, 0/90, 0/90]s |
| frame | [±45, 0/90, 0/90, ±45, 0/90]s |
| floor | [±45, 0/90, 0/90, ±45, 0/90]s |

Table 1: Layup of conventional CFRP fuselage section parts

| Property | Prepreg type |
|---|---|
| | HTS5631 |
| Longitudinal Modulus ($E_1$, GPa) | 128.9 |
| Transverse Modulus ($E_2$, GPa) | 10.4 |
| Major Poisson’s Ratio ($\square_{12}$) | 0.34 |
| In-Plane Shear Modulus ($G_{12}$, GPa) | 4.11 |
| Longitudinal Tensile Strength ($F_{1t}$, MPa) | 2159 |
| Longitudinal Compressive Strength ($F_{1c}$, MPa) | 1330 |
| Transverse Tensile Strength ($F_{2t}$, MPa) | 70.3 |
| Transverse Compressive Strength ($F_{2c}$, MPa) | 200 |
| In-Plane Shear Strength ($F_{12}$, MPa) | 112.7 |
| ILSS ($F_{13}$, MPa) | 106.6 |
| Longitudinal CTE ($\square_1$, $10^{-6}$/ºC) | -0.9 |
| Transverse CTE ($\square_2$, $10^{-6}$/ºC) | 27 |

Table 2: Design values of composite material

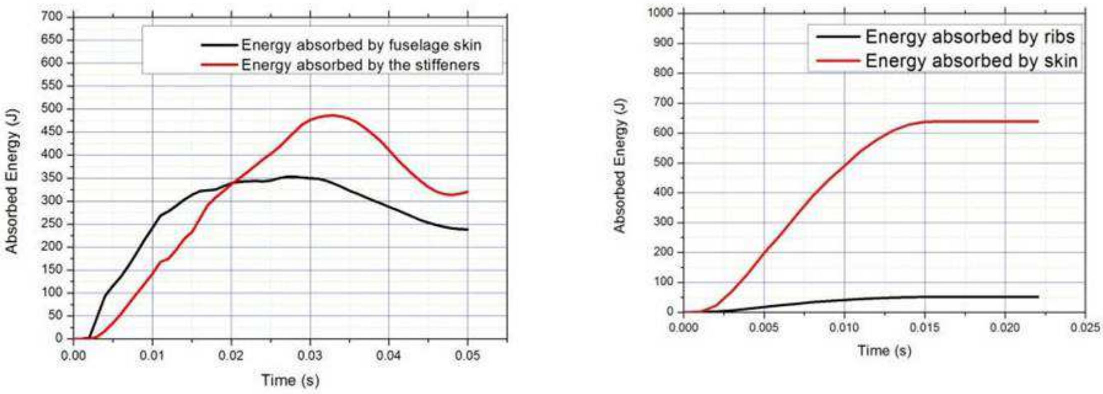

Figure 2: Absorbed energies for the conventional section(left) and the lattice one (right)

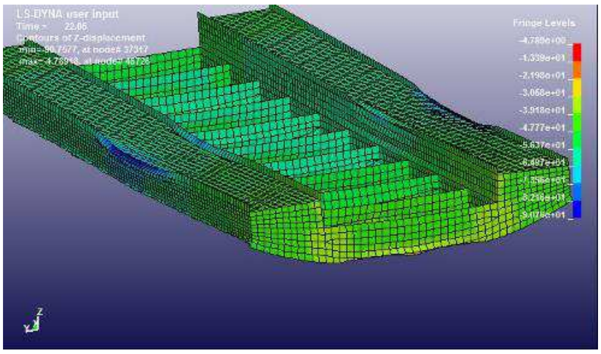

Figure 3: Facesheet buckling and foam crushing of subfloor

| | Conventional CFRP section | Lattice section with old floor | Lattice section with new floor |
|---|---|---|---|
| DRI Value | 21 | 19 | 17.4 |

Table 3: *Dynamic Response Index values for all three cases*

| Property | Value |
|---|---|
| Density | 848 kg/m$^3$ |
| Shear modulus | 3.46 GPa |
| Yield strength | 10.3MPa |
| Plastic hardening modulus | 6.89 GPa |
| Bulk modulus | 8.99 GPa |
| Plastic failure strain | 0.35 |
| Failure pressure | −4MPa |

Table 4: Hail material properties

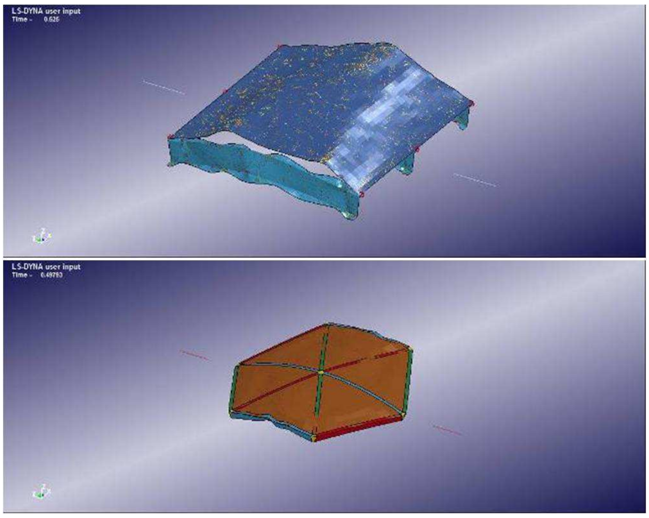

Figure 4: Failure of pristine panels due to compression

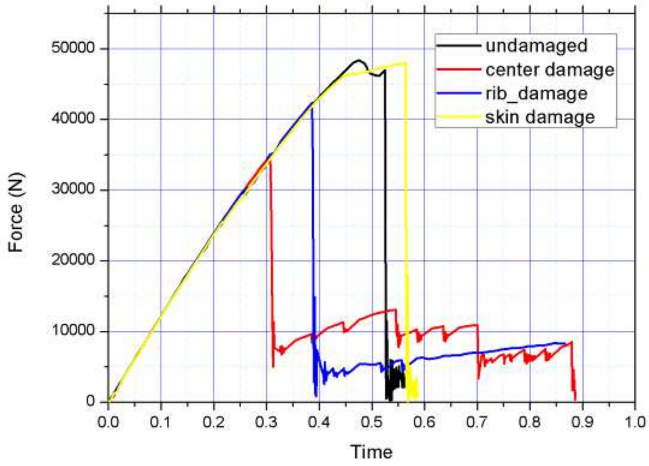

Figure 5: Limit load comparison between pristine and damaged wafer panels.

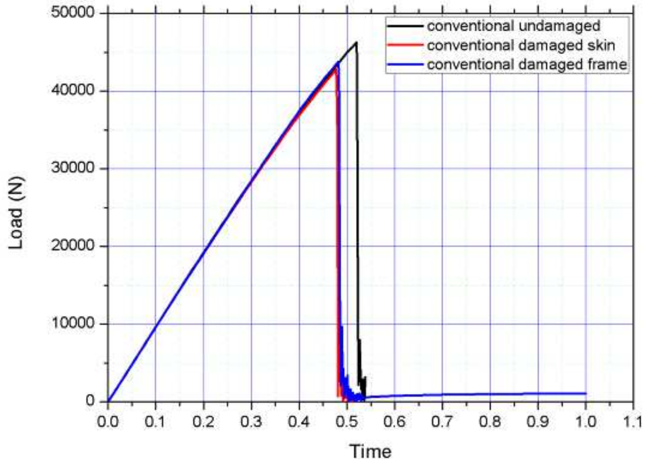

Figure 6: Limit load comparison between pristine and damaged conventional composite panels.

## 3. Conclusions

In this work, a safety assessment was done for the case of a composite lattice fuselage section. Two load cases were investigated, the crash of the structure and the hail impact on critical locations. For the case of a composite lattice fuselage section for the case of vertical drop with 6.1m/s initial velocity. Comparisons were made with a conventional composite fuselage that follows the “black aluminium” approach. The results have shown that for the specific load case, its lower mass and better stiffness characteristics contribute to its superior performance. However, significant drawbacks have initially arisen, such as large deformation and damage to the fuselage structure that could lead to occupant safety issues. initially arisen, such as large deformation and damage to the fuselage structure that could lead to occupant safety issues. Therefore, a new type of subfloor was introduced that could overcome these problems. Moreover, this design change led to reduction of the overall mass of the structure. . Regarding the hail impact load case, matrix damage was found in all cases. These results though, will contribute towards establishing design allowables for lattice structures for aeronautical structures.

### Acknowledgments

This work was supported by FP7-AAT-2010-RTD-1-265549 Composite fuselage section Wafer Design Approach for Safety Increasing in Worst Case Situations and Joints Minimizing (WASIS) Programme.

## References

[1]. V.V. Vasiliev, V.A. Barynin, A.F. Razin, Anisogrid lattice structures-survey of development and application, Composite Structures 54 (2001) 361–370

[2]. V.V. Vasiliev , A.F. Razin, Anisogrid composite lattice structures for spacecraft and aircraft applications, Composite Structures 76 (2006) 182–189

[3]. G. Totaro, Z. Gürdal, Optimal design of composite lattice shell structures for aerospace applications, Aerospace Science and Technology 13 (2009) 157–164

[4]. E.V. Morozov, A.V. Lopatin, V.A. Nesterov, Buckling analysis and design of anisogrid composite lattice conical shells, Composite Structures 93 (2011) 3150–3162

[5]. LS-DYNA KEYWORD USERS MANUAL, May 2007, Version 971, Livermore Software Technology Corporation, ISBN 0-9778540-2-7

[6]. A.Abramowitz,T.Smith,T.Vu; Vertical Drop Test of Narrow-Body Transport Fuselage Section with a Conformable Auxiliary Fuel Tank Onboard,DOT/FAA/AR-00/56(2000)

[7]. Edwin L. Fasanella, Karen H. Lyle, Karen E. Jackson, Developing Soil Models for Dynamic Impact Simulations, AHS International 65th Forum and Technology Display; 27-29 May 2009; Grapevine, TX; United States

[8]. J.W. Brinkley, J.T. Shaffer, Dynamic Simulation Techniques for the Design of Escape Systems: Current Applications and Future Air Force Requirements, Aerospace Medical Research Laboratory (AMRL Technical Report 71-292), December 1971.

[9]. Edwin L. Fasanella, Karen H. Lyle, Karen E. Jackson, Developing Soil Models for Dynamic Impact Simulations, AHS International 65th Forum and Technology Display; 27-29 May 2009; Grapevine, TX; United States

[10]. Emilie MORTEAU, Chantal FUALDES, Composites Airbus damage tolerance methodology, FAA Workshop for Composite Damage Tolerance and Maintenance July 19-21, 2006

[11]. Marie-Anne Lavoie, Manouchehr Nejad Ensan, Augustin Gakwaya, Development of an efficient numerical model for hail impact simulation based on experimental data obtained from pressure sensitive film, Mechanics Research Communications 38 (2011) 72–7