NONLINEAR TRANSIENT DYNAMIC ANALYSIS OF A LENTICULAR SANDWICH STRUCTURE, A NEW PERSPECTIVE FOR PRIMARY STRUCTURES OF AEROSPACE

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Abstract

The combination of light weight concept with optimized structural characteristics under varying arts of load is the center of expectation in every branch of mechanical construction. Sandwich is one of the new breed that was thought to fulfill the expected purpose, inspired from the principle of natural bionic.

But the expectation of science has no moral dimension and border. So although in the earlier stage the common rectangular cross-section of sandwich structure was vastly applied in secondary aerospace structure, but the need of further reducing the net weight gave impulse to think otherwise. As the primary structure has to perform under extreme load conditions, so the application of sandwich structure in primary assembly demands improved fail safe response, for example, through further development of material or structural model.

The deviation from the conventional concept is the new speculation “lens shaped concept”. But whether this new concept can compete with the older ones and add a new dimension in sandwich concept, whether its response under transient dynamic loading is well worth, was covered in cloud. Although the damping ability and damage resistance of lens shaped structure is theoretically estimated by the publication “Zuardy M.I., Herrmann A. S.: An advanced center box of a vertical tail plane with a side panel from CFRP foam core sandwich structure”, but numerical and experimental validation of the speculation was needed to establish its reliability for primary structure.

The numerical results calculated through ANSYS and LS-DYNA show, in comparison to conventional construction, the lenticular or lens-shaped sandwich structure within a definite thickness can decay the out of balance impact energy amplitude more efficiently. Even the damping of impact energy through uniform distribution of global displacement over the whole cross-section plays the key role to enrich its damage resistance.

The assessment of the lens shaped structure in respect to the ratio of pristine to damaged area provides also promising perspective. This structure reaches a more decreased minimum of equilibrium energy frequently than a structure with rectangular cross-section, which remains in an energetic unbalanced state after the impact phase. This phenomenon can stimulate the damage propagation rate in a rectangular sandwich structure. The results from FEM simulation prove the reality of the speculations validated through experiments.

Based on this results the construction of an Airbus next generation prototype is under observation.

Keywords Lenticular sandwich structure (LSS) · Transient dynamic · Rectangular sandwich structure (RSS) · Global displacement distribution · Inverse proportional relationship · Pseudo damping · Destructive interference · Convex phase · Constant ratio "1"

1. INTRODUCTION

In the aerospace “weight” are paramount and more efficient solutions for that are expected from aircraft designers. An unique approach is to design a hybrid structure so-called “Sandwich” that can withstand high impact loads. As a result, the focus upon sandwich wise construction principle for the next generation of aircraft may be the key for development’s revolution. [1, 2]

The investigation of damage tolerance behavior of plain sandwich-structured composite has been carried out rigorously; because critical non-visible core damage appears under low velocity impact. However the global distribution of deformation may influence the foreign object damage (FOD) resistance and-tolerance of composite sandwich structure, is brought in attention only in a several works. The result of those researches [1, 3, 4] focused on a new design aspect, like “Lenticular” cross-section of a sandwich.

After taking a view in the existing scientific literatures about this matter, several tasks were sketched to done. The most important goal was the verification of the described excellent structural response to impact of a large scale lenticular composite sandwich structure, specially by implementation of explicit FE-calculation. For this purpose a parametric study of lenticular sandwich-panel is done, using the applied parametric design language (APDL) of the FE-package, and analyzed with several configurations due to geometrical design variables (curvature and scaling).

1.1. Lenticular Design Concept

The lens-shaped (lenticular) cross-section geometry of the composite sandwich panel has the slightly curved aerodynamic surface or outer face skin (loft) and the flat inner skin (Fig. 1).

FIGURE 1. Lenticular Sandwich Cross-section

Between the two monolithic laminate skins exists a rigid foam core that is machined in the predefined lenticular shape. According to [5] the outer and the inner skin of the LSS have constant thickness along the cross section. Just at the middle of cross-section the sandwich thickness is the largest that decreases gradually from the mid-position to the edge.

1.2. The Hypothesis

Because of the special construction concept, the effective flexural stiffness gets declined in the cross-sectional edge direction as the yield curvature become smaller. The relative outcome is uniform bending over a large area (Fig. 2), as the flexure to bending moment remain over the whole cross-section constant. Meanwhile flexure undergoes inverse proportional relationship with the bending stiffness.

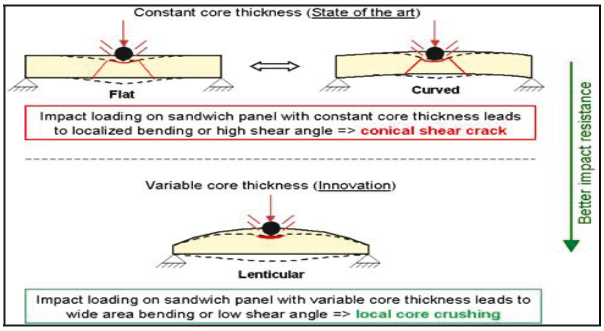

FIGURE 2. Influence of cross-section upon global deformation distribution under impact loading [5]

The uniform global deformation influences indirectly also the energy absorption behavior of the LSS structure. In case of dynamic impact loading the impact energy is dissipated as non-interfered flexural waves through the whole LSS structure. That hinders the concentration of impact energy for localized impact event to ensure shear angle and plastic strain of foam core within allowable range.

The another phenomena for reduced impact energy concentration according to [5] is the curved outer skin in place of a flat one, which provides the impactor a convex phase immediately at the start of the local impact event. As a result the loft undergoes compression that has to overcome by the impactor. This extra convex phase enable the lenticular structure to decentralize the impact energy for avoiding the unexpected shear crack of sandwich core. But for a RSS the absence of this additional convex phase brings difference in impact resistance (Fig. 3).

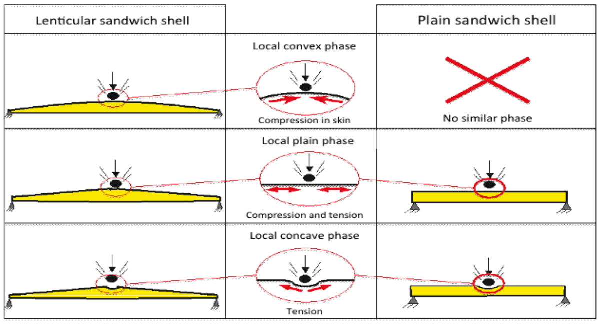

FIGURE 3. Influence of convex phase upon impact energy decentralization

2. THE STRATEGY OF APPROACH

Two methods, the real experiment and the numerical analysis are among the mechanical thoughts now-a-days, specially for scientific validation of theory. Although the numerical analysis is considered in view of finance consumption preferable, but the FEM results cannot be extrapolated to predict the real response of structures because of convergence and systematic errors. So emphasis upon both the methods is focused to evaluate the theoretical demand.

2.1. The Numerical Approach

The structural behavior under transient dynamic loading may be linear or nonlinear in nature. But the late Professor H. C. Martin noticed, in his paper of 1969 upon nonlinear structural analysis, that "Engineers by training and tradition are prone to think of nature as essentially linear in action and behavior; this, however, is seldom the case. [6]"

So in the aforementioned case, the assumed geometrical nonlinearity under impact load is analyzed by solving nonlinear algebra (for example, equation 1)

(1) $$\varepsilon_X = \frac{\partial u}{\partial x} + \frac{1}{2}\left[\left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial x}\right)^2 + \left(\frac{\partial w}{\partial x}\right)^2\right]$$

embedded in linear differential equation (equation 2).

(2) $$[m]\{\ddot{q}_{dy}\} + [c]\{\dot{q}_{dy}\} + [k]\{q_{dy}\} = \{Q_{dy}\}$$

2.1.1. The Workflow

The LS-DYNA preprocessor is used for the analysis, that has definite steps of execution (Fig. 4).

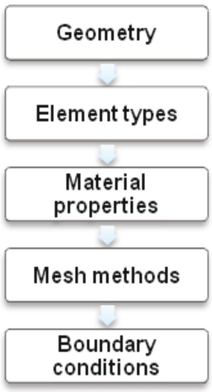

FIGURE 4. The executing steps in the LS-DYNA preprocessor unit

2.1.1.1. Geometry

The projectile is a hemispherical steel ball of diameter 25.4 mm. The motion of the impactor is defined at the direction normal to the mid-plane of sandwich (Fig. 5).

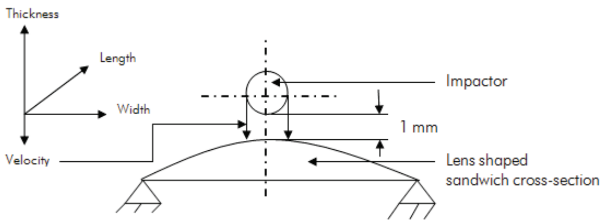

FIGURE 5. Impactor and sandwich geometry

The dimension of the lenticular sandwich prototype panel is considered 2000 mm (length) ×1000 mm (width) (Fig. 6). The sandwich thickness at the clamped edges is kept 5 mm.

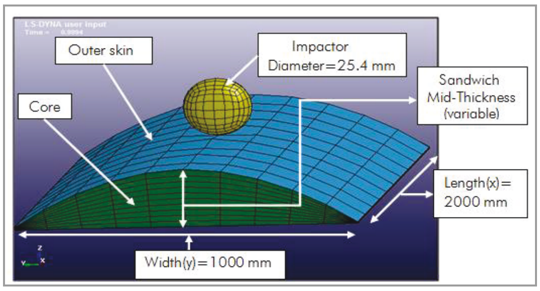

FIGURE 6. The FE-geometry of analysis

2.1.1.2. Element of Mesh

The process of transferring a geometry into discrete counterparts differs according to dimension. The 4 nodes fully integrated (with the element card "ELFORM=16") quadrilateral Belytschko-Tsay shell element type 163 is implemented here to define the quasi-isotropic composite outer skins of the sandwich structure (Fig. 7, left), as the element prevent shear locking because of assumed strain under transverse shear.

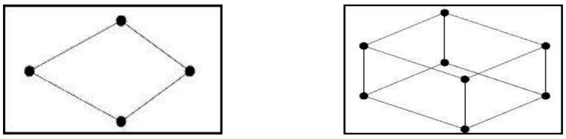

FIGURE 7. 4 node shell element type163 (left) and The 8 node solid brick element type 164 (right) [26]

For the discretization of the three dimensional foam core and the impactor 8 node hexahedron solid element type 164 was used over the element card "ELFORM=1" that can maintain constant stress over the whole volume of the element (Fig. 7, right).

2.1.1.3. Material Properties

As the lens-shaped sandwich structure is assumed to be inherently capable to bring down the external load within the elastic region through its favorable damping property, so that no energy dissipation due to the micro scale fraction inside the material may occur.

Property (unit)	Value
Density(kg/mm^3)	2.30E-08
E_{11}(GPa)	146
E_{22}(GPa)	10.5
E_{33}(GPa)	10.5
NU_{12}	0.03
NU_{23}	0.3
NU_{13}	0.03
G_{12}(GPa)	5.25
G_{23}(GPa)	3.48
G_{13}(GPa)	5.25

TAB 1. The material model of sandwich outer skin

That's why orthotropic elastic material properties of lamina are considered as input parameter (Tab. 1). The isotropic elastic material "steel" used for impactor is defined over the material card "020-RIGID" in the material dictionary of LS-DYNA preprocessor. Meanwhile the material card "001-ELASTIC" is concerned for the mechanical properties of Rohacell sandwich core (Tab. 2).

Property (unit)	Value
Density(kg/mm^3)	7.00E-08
E (GPa)	0.04
G(GPa)	0.015

TAB 2. The material model of sandwich core

2.1.1.4. Discretization

The mesh is necessary to define an indefinite continuum through definite size of elements. It is done through approximation of indefinite dimensions by definite form function. For the purpose two types of meshing techniques are mostly in use such as mapped-and free meshing. In this work the mapped meshing technique is used to mesh the whole LSS. Due to the curvature of

LSSLS[1] the discretization of the surface has to be done with the number rather than the size of the element. The impactor can be free meshed without complication.

2.1.1.5. Boundary Conditions

The analysis required clamped edges that are applied at the sandwich edges in assist of "*BOUNDARY_SPC_" (Fig. 8), which set all translation and rotation components of the nodes in three dimensional directions to zero.

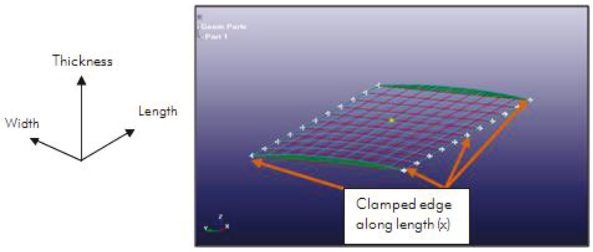

FIGURE 8. Fixed clamped edges in a sandwich panel

2.1.1.6. GUI Settings

The impact energy is controlled over the impactor velocity. So the impact velocity has to be defined, here as initial condition. "Initial" means the velocity of the impactor after the impact phase changes, as the kinetic energy of the impactor converts into deformation energy of the sandwich panel during impact.

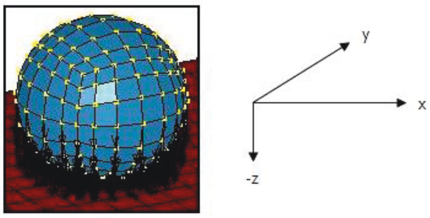

FIGURE 9. Impactor velocity in –Z direction

The impactor and the sandwich panel interact in the analysis as a contact pair. The contact pair definition is built up through the "*SET_PART" card where the impactor and the sandwich panel have to be picked by GUI.

To establish the contact of the impactor with the sandwich panel, automatic single surface contact[2] is used for the defined contact pair. For the contact definition, SSTYP is set to 2 that refer to part set ID. This type of contact is established when a surface of one body contact the surface of another body.

The termination time of calculation for the LS-DYNA explicit solver is set to "ENDTIME=10 ms" over the "*control" panel of LS-DYNA. The mathematic shows, if the velocity of the impactor is 10 mm/ms, then the impactor need 0.1 ms to travel the distance of 1 mm up to the upper sandwich surface. So during the calculation it must be ensured that the total calculation time is greater than the time needed by the impactor to reach the sandwich upper surface.

3. EVALUATION OF RESULTS

Several parameters are considered that may affect the mechanical behavior of LSS under a transient loading. Among them the variable mid-thickness and the impact velocity are assumed to have dominance. So the evaluation of result also take those two variables in consideration followed by a definite sequence (Fig. 10).

FIGURE 10. Chronological orientation of factors for evaluation of structure performance

3.1. Local Displacement of LSS

The impact upon LSS can bring two types of deformation such as local and global deformation. As local displacement of a structure is important to define the extent of local deformation, so it is an important phenomenon to investigate. The local structural displacement is illustrated here graphically to visualize the local effect of impact and it's variation through the change in mid-thickness of LSS (Fig. 11).

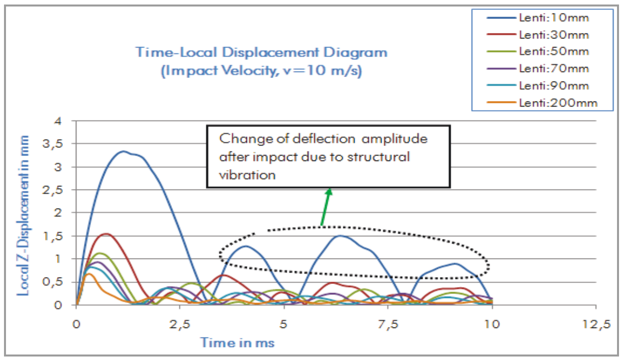

FIGURE 11. Local displacement in lenticular sandwich panel under impact

Here to pursue, the difference in local displacements for 10 mm and 30 mm sandwich mid-thickness is about 1.8 mm. Meanwhile between 30 mm and 50 mm sandwich mid-thickness it's about 0.3 mm. That reveals, the structure could show a stabilized state if the mid-thickness is set within 30 mm to 50 mm.

The brief explanation is, local displacement of LSS inverse proportionally change with the mid-thickness, while the impact resistance proportionally.

As after the impact phase the sandwich structure undergoes oscillatory motion so the local displacement

[1] Lens Shaped Sandwich Loft Skin
[2] ASSC

takes a gradual change in amplitude which can be described through the sinusoidal motion described by

(3)... $Q = Q_0 \sin \omega_d t$

where, Q_0 is the deflection amplitude at the time of impactor contact, Q is the deflection amplitude during the rebound phase, ω_d is the frequency at the damped state.

3.1.2. Comparison between LSS and RSS

The difference in local displacements between the LSS and RSS, having equivalent thickness and equal volume, is critical to evaluate the beneficial uses.

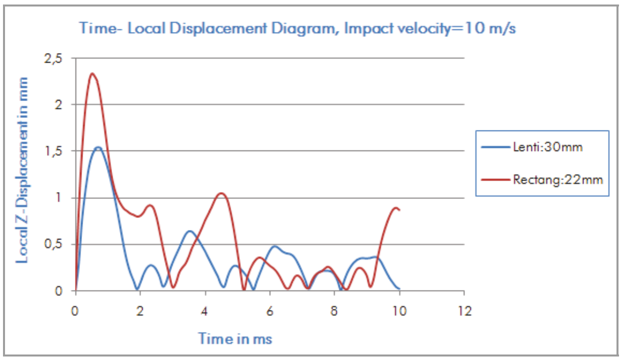

FIGURE 12. Comparison in local displacement (Lenti: 30 mm, Rectang: 22 mm)

As per figure (12), the local displacement of RSS, comprises equivalent thickness of 22 mm, is about 0.8 mm higher than of the LSS with mid-thickness of 30 mm, although both of them have the same volume. As the RSS under lower velocity impact responses through dilatational wave, because of constant thickness and possesses constant bending stiffness over the whole cross-section, so the local deformation of RSS is larger at the point of impact in comparison to LSS.

3.2. Global Displacement of LSS

The global displacement and its distribution across the whole cross-section of a structure directly affect the damage resistance[3] of it, which can be improved through damping of impact energy by uniform global displacement. So the matter is taken into consideration (Fig. 13).

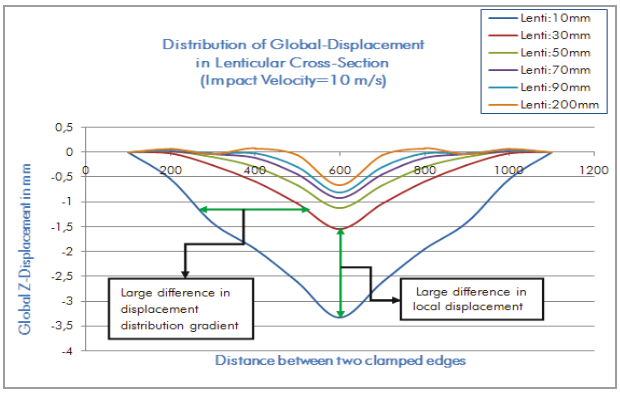

FIGURE 13. Global displacement in lenticular sandwich panel

The FE-simulation reveals that, the LSS with mid-thickness of 10 mm has the largest global displacement and largest displacement gradient across its cross-section, while compared to the structures having mid-thicknesses between 30 mm to 90 mm. At about 50 mm mid-thickness the minimum displacement distribution gradient is reached.(Fig. 13)

Cue According to the schematically sketched figure (14),

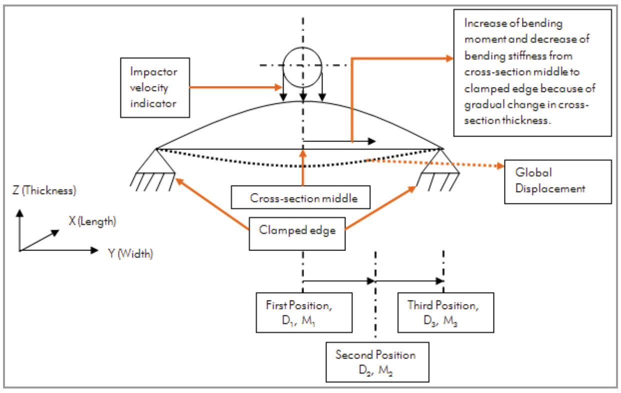

FIGURE 14. Change of bending-moment and stiffness along lens shaped cross-section

D_1, D_2 and D_3 are the bending stiffness at the cross-section middle, near the edge and at the cross-section edge respectively, while M_1, M_2 and M_3 are the bending moments at the aforementioned cross-section positions accordingly. Both the ratio of change in bending moment (M_2/M_1 and M_3/M_2) and in bending stiffness (D_2/D_1 and D_3/D_2) from cross-section-middle to edge becomes more gradual with the increase of sandwich mid-thickness, which brings smaller displacement gradient and smaller change in shear angle for better damage resistance.

3.2.1. Comparison between LSS and RSS

The difference in global displacement between the LSS and RSS, considering equivalent thicknesses and equal volume, is depicted here to re-visualize the unique mechanical response of the LSS.

[3] Structural compliance

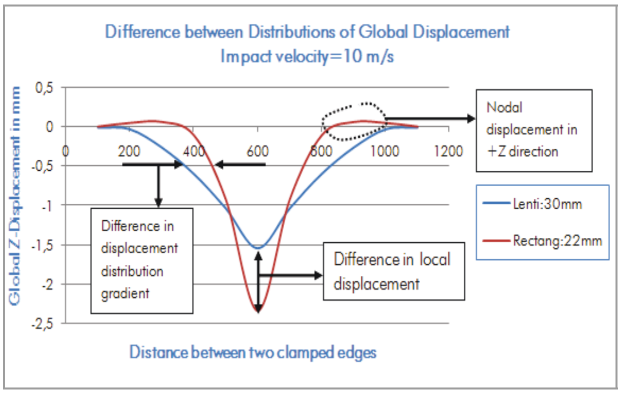

FIGURE 15. Global displacement comparison (Lenti: 30 mm, Rectang: 22 mm)

The gradient of global displacement distribution for the LSS is smaller than of the RSS for equivalent thicknesses (Fig. 15).

Cue The theoretical explanation for the decrease in gradient of global displacement distribution and its switching to local effect for RSS can be mechanically proven (Fig. 16).

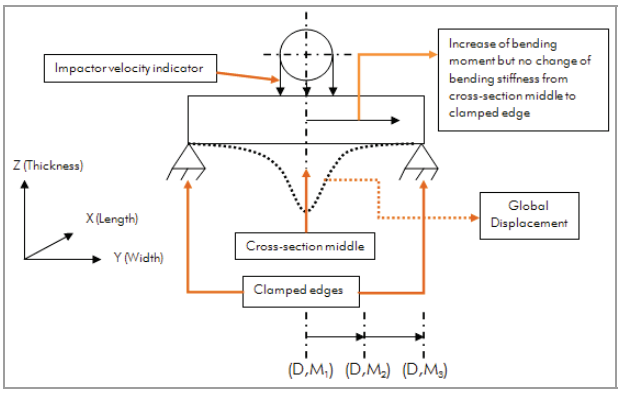

FIGURE 16. Change of bending moment and-stiffness in rectangular cross-section

At the middle of the rectangular cross-section the bending moment is minimum in comparison to the clamped edge. Now from the cross-section middle to the clamped edge, the bending moment increases means $M_3 > M_2 > M_1$, but no change in the bending stiffness (D) results in as the RSS has the same thickness over the whole cross-section. As follows, the ratio of change in bending moment (M_2/M_1, M_3/M_2) deviates from the constant ratio “1” of flexural stiffness along the cross-section. As a result the localized deformation dominates over the global structural response for a RSS. (Fig. 16)

For the lens-shaped cross-section the bending moment and the bending stiffness change from the cross-section-middle to-edge with the equal contrary ratio, so the global displacement is more uniformly distributed and the distribution gradient is smaller in contrast to rectangular cross-section.

3.2.2. Global Displacement of RSS

The global displacement and its distribution of a RSS get importance because of the decrease in local displacement with increased rectangular sandwich thickness.

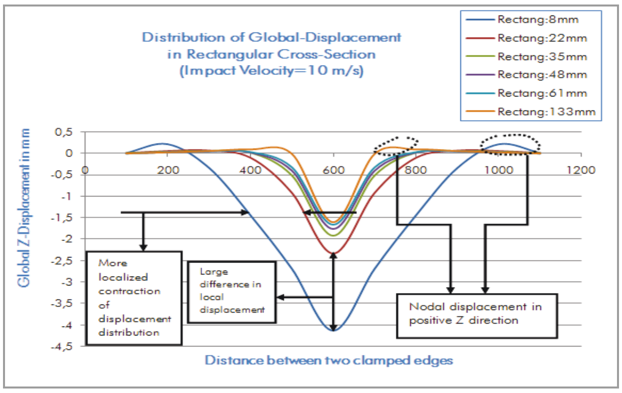

FIGURE 17. Global displacement in rectangular sandwich panel under impact

The FE-simulation denotes that the rectangular sandwich panel with equivalent thickness of 8 mm (LSS with 10 mm) has the largest global displacement and largest displacement distribution gradient across its cross-section. Upwards from 35 mm sandwich thickness no change in displacement distribution gradient is seen. But the global distribution of displacement becomes more localized[4]. (Fig. 17)

The displacement at the clamped edges in the positive Z direction for sandwich thickness of 8 mm and 133 mm are crucial. Outside of the optimum thickness limit the feasibility of flexural wave interference at the place of higher structural integrity becomes most probable. As a result anomaly can be seen.

3.3. Damping Ability of LSS

Damping ability of a structure is responsible to determine how much external impact energy can be saved inside the structure as elastic strain and how faster the structure can restore its equilibrium state through dissipation of the stored elastic energy.

The figure (18) depicts the internal energy of LSS which is consist of the sum of damper or spring energy of discrete elements. Stiffness damping energy also lumped into internal energy [7].

[4] Marginal localisation

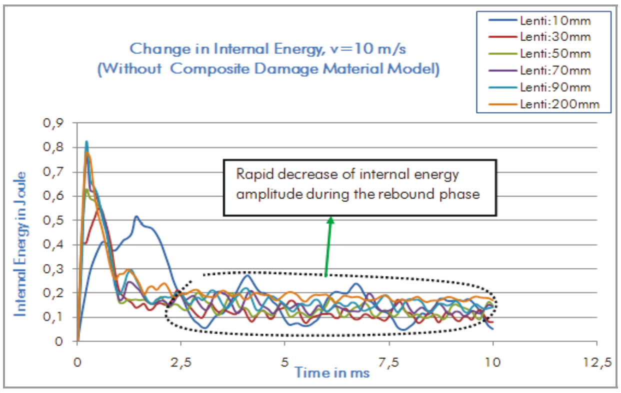

FIGURE 18. Change in internal energy with change in lenticular mid-thickness

During impact the internal energy of LSS attain a definite peak of about 0.8 Joule. As the lenticular mid-thickness increases upwards, the oscillation of energy wave decay in amplitude in a definable regular manner. Between 30 mm and 70 mm mid-thickness the damping property of the structure illustrated through FE-analysis is optimum, as the peaks of energy waves level off over a short time interval. (Fig. 18)

Cue The damping characteristics of the sandwich structure can be described through pseudo-damping. Pseudo-damping is a phenomenon which is to found in a special class of structures that shows linearity to impact loading with impulse response characterized by decaying amplitude, although any dissipation mechanism may be absent. During impact loading the designated parts of the system conserve the impact energy within them. Pseudo-damping in a system is possible only when condensation points exist within the natural frequency distribution of the system. The curvature of the structure can naturally introduce condensation points in the modal density which stimulates pseudo-damping. [8]

Also the interference of energy waves plays an important role in the damping behavior of structure. As the bending stiffness become uniformly distributed along the lenticular sandwich cross-section with increased mid-thickness, so the stress or energy waves, generated at the place of impact, may reach the clamped edges one after another without getting interfered with each other or the energy waves undergo destructive interference due to phase angle of 180° between them.

3.3.1 Comparison between LSS and RSS

The difference in damping ability between the LSS and RSS with equivalent thicknesses, calculated over equal volume, took the place of interest because of plastic strain phenomena (Fig. 19).

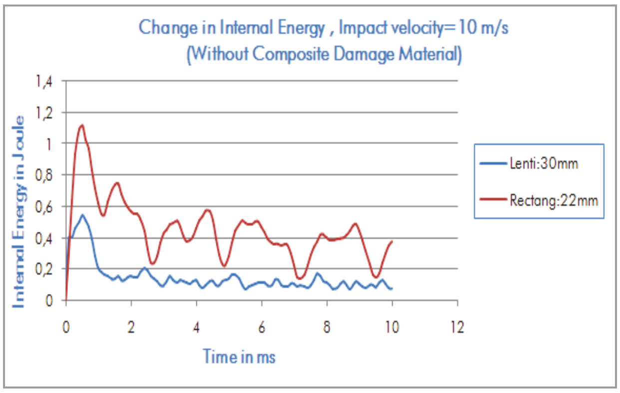

FIGURE 19. Comparison in damping ability

The amplitude of internal energy after impact changes in an irregular manner for the RSS, while for lens shaped cross-section with equivalent thickness the amplitude of internal energy decay in a gradual manner with a discernable pattern to a minimum[5]. Even during the impact phase the internal energy of LSS stay about 0.7 Joule below than of RSS, specially for the tested thickness pair. (Fig. 19)

Cue As discussed in the earlier section the curvature in the structure introduces more condensation points for the energy waves. Along with that the initiation of energy waves in the structure at a definite time interval prohibits the constructive interference of energy waves. That's why the damping behavior of the LSS is considered to be superior to that of the RSS.

3.3.2. Damping Ability of RSS

Damping ability of a RSS has got interest because of the dominating local deformation and the declined possibility of impact energy reservation as elastic energy inside the structure.

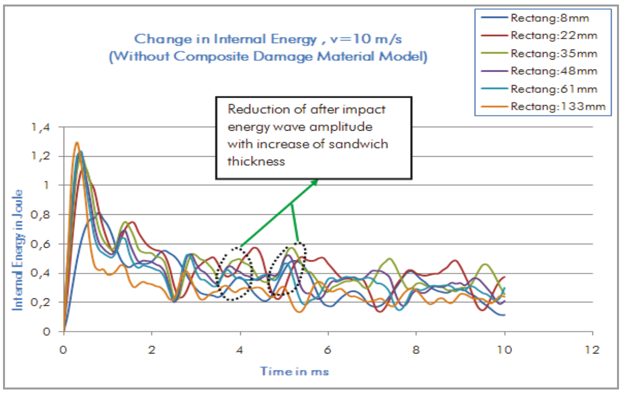

FIGURE 20. Change in internal energy with change in rectangular sandwich thickness

The damping behavior of the RSS shows no definite pattern of internal energy change after the impact phase, although the increase in the sandwich thickness upwards until 61mm blunts away the after impact amplitude peaks during the rebound phase (Fig. 20).

[5] Equillibrium state of energy

3.4. Co-efficient of Restitution (COR)

Co-efficient of Restitution (COR) is defined as the ratio of rebound to impact velocity. It is used as an indicator of structural damage resistance. For geometries exhibit linear response to impact, COR provides valuable information about the residual stiffness of an impact damaged structure. The value of coefficient of restitution varies between 0 and 1, where 0 means whole transfer of impact energy to the sandwich structure which reveals zero rebound velocity, while 1 means no transfer of impact energy that result in equal impact and rebound velocity.

3.4.1. Co-efficient of Restitution of LSS

The COR of LSS is encompassed under two conditions. At first the COR of LSS is measured for unchanged lenticular mid-thickness, means curvature of loft skin, under variable impact velocity from 10 m/s to 50 m/s (or variable impact energy). Later the velocity is kept invariable, while the lenticular mid-thickness is changed from 10 mm to 200 mm (Fig. 21).

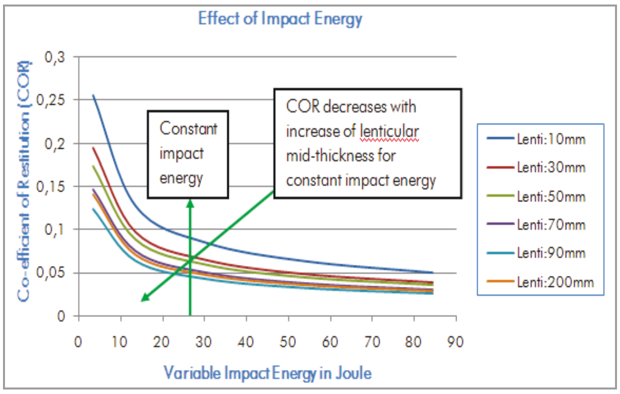

FIGURE 21. The co-efficient of restitution LSS

So for the first condition, the lenticular mid-thickness considered fixed at 30 mm. Then the change in co-efficient of restitution along with the increase in impact energy is calculated (Tab. 3).

Impact Energy (Joule)	Co-efficient of Restitution (COR)
3.36	0.1948
13.47	0.0973
30.30	0.0649
53.88	0.0486
84.18	0.0389

TAB 3. COR for lenticular mid-thickness of 30mm

The increase in impact energy from 3.36 joule to 30.30 joule brings sharp decrease in co-efficient of restitution. That visualize, at the low velocity impact most of the incident energy can be dissipated through uniform global deformation of the structure. But for intermediate or high velocity impact most of the impact energy may transform in local plastic strain energy. As a result the rebound velocity decreases with increasing impact velocity. This trend is similar for other lenticular mid-thicknesses. But special is, after definite impact energy for example 53.88 joule no significant change in COR is seen. That levels off the damage extent in LSS. (Tab. 3)

Now if the impact energy remains inalterable, for example 3.36 joule, and the lenticular mid-thickness is increased gradually, then co-efficient of restitution according to the figure (21) and the table (4)

Lenticular Mid-Thickness (mm)	COR
10	0.2561
30	0.1948
50	0.1735
70	0.1470
90	0.1241
200	0.1413

TAB 4. COR of LSS for impact energy of 3.36 joule

decreases accordingly. This is because mid-thickness has an inverse proportional relationship to the maximum shear angle and shear angle gradient. Meanwhile the ability of structure to decentralize the impact energy through uniform deformation increases. So the structure can conserve more impact energy through elastic strain. As following the rebound velocity changes inverse proportionally to lenticular sandwich thickness.

3.4.2. Co-efficient of Restitution of RSS

As discussed in the previous section (3.4.1) for LSS, the COR of RSS is also measured with the same concept (Fig. 22).

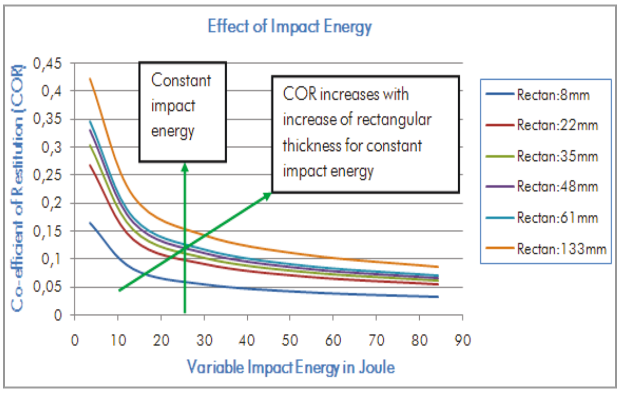

FIGURE 22. The co-efficient of restitution of RSS

The analysis of result can be done similar to the LSS. The COR of RSS shows the identical manner of change like of LSS while the impact energy increases and the rectangular sandwich thickness remains unchangeable.

But worthwhile is to notice for the inalterable impact energy and variable sandwich thickness,

Rectangular Sandwich Thickness (mm)	COR
8	0.1628
22	0.2668
35	0.3034
48	0.3301
61	0.3443
133	0.4217

TAB 5. COR of RSS for impact energy of 3.36 joule

the increase of rectangular sandwich thickness brings sharp increase in COR, that is the opposite of the LSS (Tab. 5). The cause is, the thickness of RSS is proportional to the unbalance of tension and compression at the outer skins[6]. Meanwhile the global distribution of displacement becomes more locally margined as aforementioned. As a result less impact energy can be dissipated through uniform structural displacement. So the rebound velocity has proportional relationship to rectangular sandwich thickness.

3.4.3. Comparison between LSS and RSS

The difference between LSS and RSS in respect to COR is predicted to clarify the contrast of structural response.

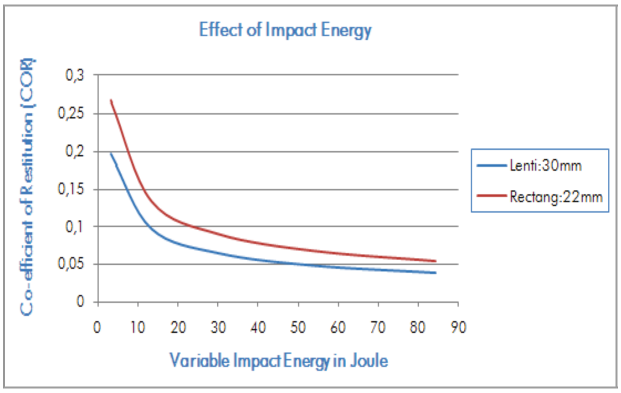

FIGURE 23. Comparison of COR for lenticular mid-thickness (30 mm) and rectangular sandwich thickness (22 mm)

For a given impact velocity (or corresponding impact energy) the co-efficient of restitution of a LSS is smaller than of a RSS both having equal volume (Fig. 23). That re-indicate the aforementioned beneficiaries of LSS which stimulate large conversion of impact energy because of uniform distribution in structural stiffness.

4. EXPERIMENTAL EVIDENCE

4.1. Impact Tests (Validation)

To gain a basic understanding and the characteristics for the damage tolerance capability of CFRP sandwich panel, the residual compression-strength after Impact of relatively small specimens, the CAI-coupons, were investigated.

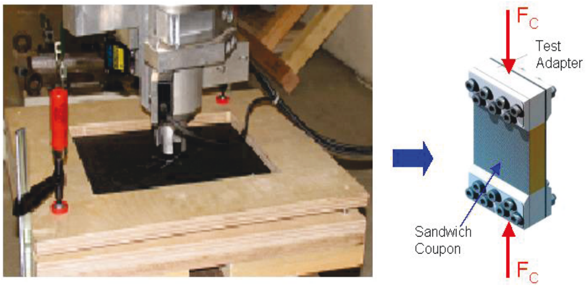

FIGURE 23. CAI-test: impact (LH) and comp. loading (RH)

The test results show, especially for the reinforced sandwich configuration, a sufficient residual strength even in the case of large impact damage.

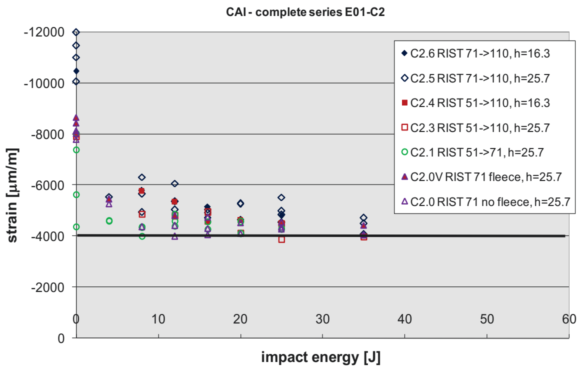

FIGURE 24. CAI-Strength up to impact energy of 35J [9]

It has been observed, that the most small scale test specimens get conical shear cracks around the impact points for the impact energy more than the 30 Joule. Therefore it is difficult to conduct CAI-test for such specimens.

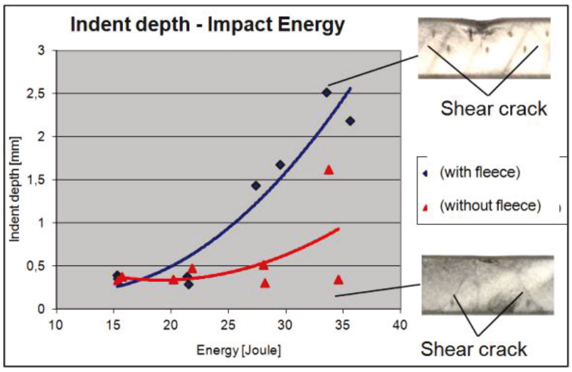

FIGURE 25. Indent depth over the impact energy, where the shear crack occurs from energy level 30 J [10]

Additionally two representative sandwich panels from the box of the mentioned VTP, the so called 19er M-Schale, with different face skin thickness are loaded at different positions with different impact energies.

[6] Maximum shear angle and shear angle gradient

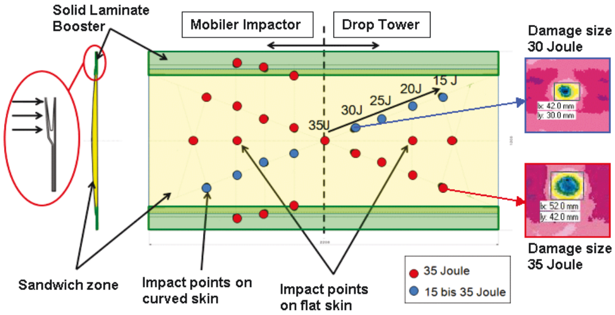

FIGURE 26. LH: 19er M-Schale with distributed impacts RH: typical damage diameters (sizes)

In contrast to the small specimens for assessment of CAI strength the impact damage in the 19er M-Schale was limited to the zone immediately under the impact point irrespective of face skin thickness. The damage has the size of about 80% smaller and shows no conical shear crack in the foam core. The indent depth over the impact energy up to 40 Joule is shown in the following diagram:

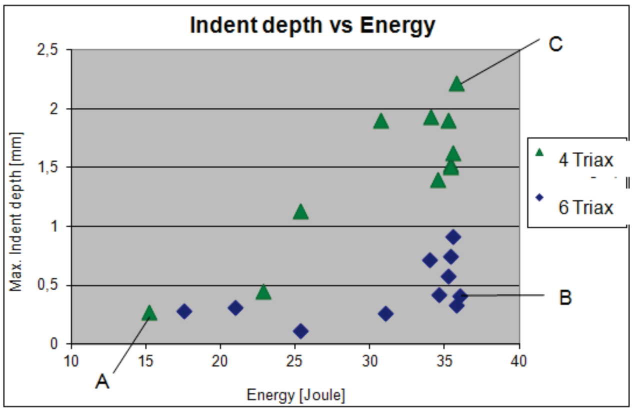

FIGURE 27. Indent depth vs. impact energy, where no shear crack occurs on the panel) [10]

The corresponding micrographs of the three basic points of the impact events (A, B and C) of the lenticular sandwich panel are as follow:

FIGURE 28. Core crushing only at energy of 15 J (Point A) [10]

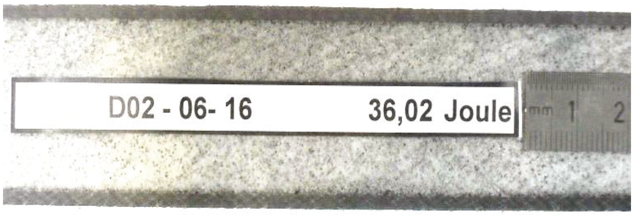

FIGURE 29. Core crushing only at energy of 36 J (Point B) [10]

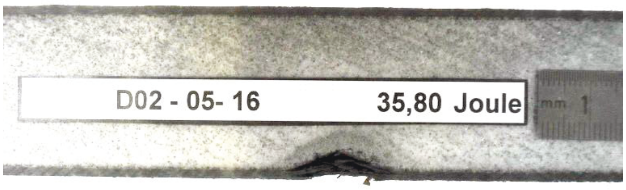

FIGURE 30. Core crushing only at energy of 36 J (Point C) [10]

These test results verify the transient dynamic FE analysis results from the previous chapter, which predicts no shear crack on the panel slightly away from the edge support thanks to the “lenticular effect”.

Another explanation and experimental evident of the lenticular effect has been described in 0, where two lenticular foam core sandwich panel with aluminium face skin as shown in Fig. 31, top are loaded transversally (bending). Slices are introduced in the foam core of the second panel to reduce the shear rigidity. The experiment shows nearly the same bending behaviour both of the panels and hence proofs, that the lenticular cross section reduces the shear loading of the sandwich panel in case of transversal loading, statically and also transiently.

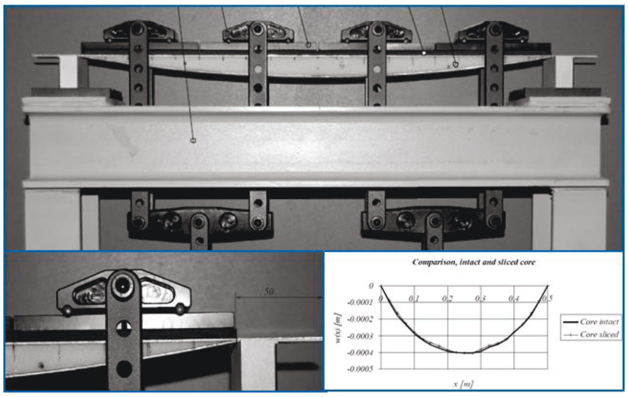

FIGURE 31. Lenticular foam core sandwich under transversal loading (bending) with and without slices in the foam core [11]

5. SUMMARY AND OUTLOOKS

This whole A to Z work was carried out for the recognition of the new concept and to distinguish the lens shaped structure from the conventional thoughts. The Know-Why from this analysis may help in future for evaluating the existing results, obtained through different key settings and by experimental results, and to recycle the thoughts.

Although the results gathered through numerical analysis prove the reality of the speculations made over the lens-shaped structure, confusions may arise but the exceptions are unexpected, as Albert Einstein quoted “Das, wobei unsere Berechnungen versagen, nennen wir Zufall”.

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References

[1] Damodar R. Ambur: Scaling the non-linear impact response of flat and curved composite panels, NASA Glenn Research Center, OH 44135, 2005.

[2] Herrmann A.S., Zahlen P.C. Zuardy, I.: Sandwich Structure Technology in Commercial Aviation-Present Application and Future Trends, ICSS 7, Alborg, 2005.

[3] Cantwell W.J.: The influence of target geometry on the high velocity impact response of CFRP, 1988.

[4] Cantwell W.J, Morton J.: Geometrical effects in the low velocity impact response of CFRP, 1989.

[5] Zuardy M.I., Herrmann A. S.: An advanced center box of a vertical tail plane with a side panel from CFRP foam-core sandwich structure, DLR Congress, 2011.

[6] Wilhelm Rust: Nichtlineare Finite-Elemente-Berechnungen, 2009.

[7] John O. Hallquist: LS-DYNA Theory Manual, 2006.

[8] Carcaterra A., Akay A.: Pseudo-damping in undamped plates and shells, 2007.

[9] J. Leijten, et al.: Experimental study of the low-velocity impact behaviour of primary sandwich structures, TU Delft, Composites: Part A, Elsevier, 2009.

[10] J. Eckhardt: Schadensbeurteilung von verstärkten Kernverbundstrukturen nach Schlagstoßbelastung, Diplomarbeit, FH-Aachen, 2010.

[11] J. A. Kepler: Sandwich / Catenary Hybrid Beams – Stiffness assessment and experimental verification, ICSS 9, Pasadena, California, USA, 2010.