Design for manufacturing of fuselage panels with curved grid stiffening

NLR-TP-2013-310 - April 2014

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EXECUTIVE SUMMARY

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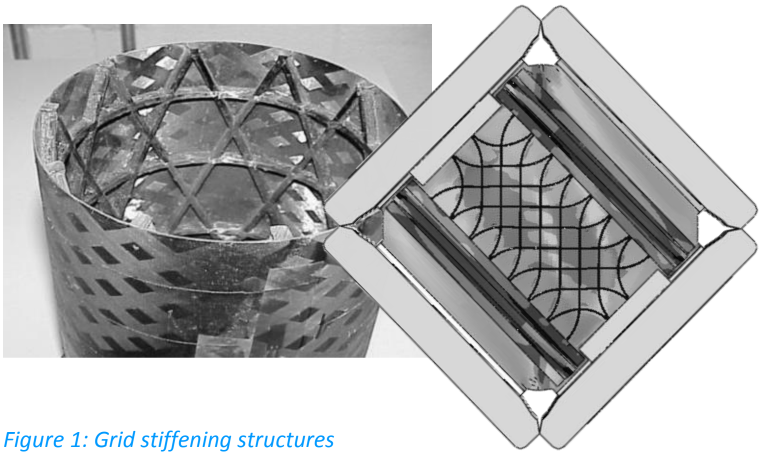

Figure 1: Grid stiffening structures

Report no.
NLR-TP-2013-310

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Report classification
UNCLASSIFIED

Date
April 2014

Knowledge area(s)
Computational Mechanics and Simulation Technology

Descriptor(s)
composites
fibre steering
grid stiffening

Problem area

With recent developments in the fibre placement manufacturing technology for composite structures, new opportunities will arise for the Dutch aerospace industry. For example thermoplastic composite material can be fibre placed using this technology, allowing complex lay-ups with full automation and high quality products. The fibre placement manufacturing also allows local reinforcement of composite structures with the so-called grid-stiffeners of which two examples are shown in Figure 1. In the past the grid stiffening, also known as isogrid or lattice structures, have been used for metal space applications. The automated manufacturing of composite laminates allows grid stiffening to become a feasible and viable approach for weight reduction and structural performance improvement in aircraft structures. However, the optimal grid-stiffening design is not straight-forward and more research is needed to achieve weight efficient structures. A large number of design variables such as grid shape, stiffener height and how the cross sections are managed, need to be part of the design routine.

This report is based on a presentation held at the 17th International Conference on Composite Structures (ICCS17), Porto, Portugal, 20 June 2013.

Description of work

This study has been performed within the European project More Affordable Aircraft through eXtended, Integrated and Mature nUmerical Sizing (MAAXIMUS). The grid stiffening approach for composite structures is addressed on a fuselage barrel case with the overall aim to reduce the weight. In the front section of the fuselage, the so-called low loaded area, the design reserve factor on buckling is high which translates to a structure which is too heavy.

The running loads from the fuselage barrel global finite element model are extracted for a large number of load-cases to be used on the panel level analysis. On the panel level a parameter variation analysis is performed on the grid design to determine the sensitivity towards the buckling resistance of the structure. The grid structure is modelled using four-node shell elements for the skin sections and beam elements for the grid stiffeners. Two buckling load-cases, shear and compression, on the panel level are analysed using a linear buckling method. For the final panel level designs additional detailed nonlinear finite element analyses are performed with representative boundary conditions for later experimental validations of the structural performance.

Results and conclusions

From the design analysis on the grid stiffened structures it is clear that a weight gain can be achieved by applying grid stiffening instead of traditional stiffeners for the low loaded area in the fuselage. The use of grid-stiffeners allowed that use of a lower skin thickness on the panel level further reducing the weight. The sensitivity analysis showed that a 45 and -45 degree grid design has good performance to improve buckling resistance.

For the low-loaded area of the fuselage structure, the use of grid-stiffening allows a theoretical weight reduction of 8.49 kilogram when compared to the traditional structures. In general it is observed that for small buckling load increases the grid stiffening concept is interesting, whereas for higher recoveries of buckling loads the traditional design with lower stringer pitch is expected to be more efficient.

Applicability

When considering the flexibility of the fibre placement manufacturing technology, this study can be used as a basis for further grid stiffening developments. For instance the grid-stiffening can be combined with other technologies to improve impact resistance such as interwoven tows, or using fibre steering in the skin laminate.

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This publication has been refereed by the Advisory Committee AEROSPACE VEHICLES.

Owner	NLR
Division NLR	Aerospace Vehicles
Distribution	Unlimited
Classification of title	Unclassified
Date	April 2014

Approved by:

Author	Reviewer	Managing department
W.M. van den Brink	M.H. van Houten	A.A. ten Dam
Date 2-4-2014	Date 2-4-2014	Date 02-04-2014

Summary

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This study has been performed within the European project MAAXIMUS. The grid stiffening approach for composite structures is addressed on a fuselage barrel case with the overall aim to reduce the weight. In the front section of the fuselage, the so-called low loaded area, the design reserve factor on buckling is high which translates to a structure which is too heavy.

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Content

Abbreviations

Acronym	Description
FE	Finite Element
NLR	National Aerospace Laboratory NLR
TU Delft	Technical University of Delft
MAAXIMUS	More Affordable Aircraft through eXtended, Integrated and Mature nUmerical Sizing
GFEM	Global Finite Element Model
UD	Uni Directional
RF	Reserve Factor
S4R	Four node shell elements
B31	Three dimensional beam elements
ABAQUS	Numerical analysis software
LL	Limit Load
UL	Ultimate Load

ICCS17, 2013

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Keywords: Composites, grid stiffening, aircraft

Abstract *This paper presents a design study of composite panels with advanced structural architectures specifically tailored for low loaded areas in aircraft fuselages. The approach in this study is to reduce structural weight and manufacturing cost of the stiffened panels by replacing traditional stiffening structures by lightweight grid stiffeners. This approach is based on the further exploitation of the load carrying capability of the fuselage skin in the low loaded areas, as well as efficient manufacturability of the stiffening structure by automated fibre placement. Moreover, the integration of the traditional panel topology, consisting of skin, stringers and frames, with the new structural design and manufacturing aspects of curved grid stiffening is addressed.*

1 Introduction

With the recent development of fibre placement manufacturing technology for composite structures, curved grid stiffening is becoming a feasible and viable approach for weight reduction and structural performance improvement in aircraft structures. Previous limitations such as high manufacturing costs and out-of-plane failure modes at the skin-stiffener interface have been mitigated with the improved automated manufacturing and tougher resins as available today [3]. The panel designs considered in this study are based on grid stiffening in combination with low skin thickness. Assessments and parameter variation analyses of the grid stiffened panels were performed, for the main load cases only, i.e. buckling resistance for shear and compression loads. The height of the grid stiffeners is constrained by the manufacturing criterion that no tooling is required to stabilize the grid stiffeners during production, i.e. during tape laying, vacuum bagging and autoclave curing. In the assessments and parameter variation analyses, finite element (FE) simulations were used to evaluate the buckling response by linear buckling and non-linear post-buckling analyses. In Figure 2 several applications of the isogrid design are shown.

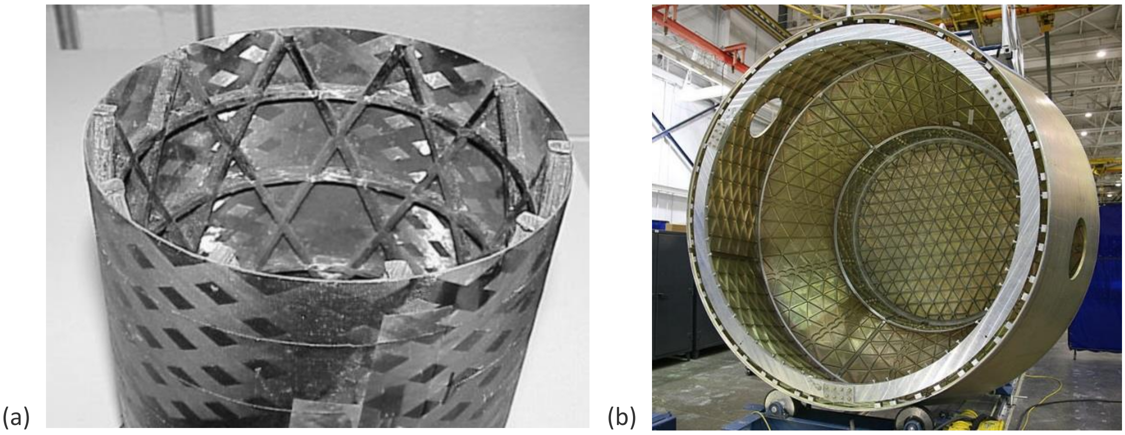


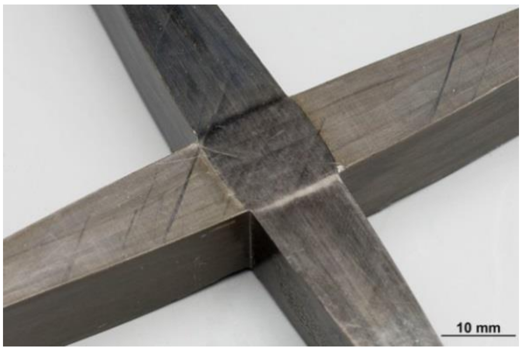
Figure 2: (a) Composite isogrid stiffened cylinder [1] and (b) Dragon spacecraft with isogrid structure[11]

Grid stiffening for metal and composite structures has been used in the past for space applications [6]. An interesting paper by Vasiliev [2] discusses the Russian experience with the application of composite aniso-grid structures. The isogrid stiffening architecture has been investigated intensively for space applications, in particular the Minotaur space launch vehicle [5, 9]. In the past it was observed that from a manufacturing viewpoint, isogrid stiffening was too complex for mass-production [3]. With the wide use of filament winding [4] and automated fibre placement manufacturing technology for composite structures, the grid stiffening architecture has become more interesting for large scale applications in aircraft structures, e.g. for structural performance improvements in helicopter applications [3]. Further studies including numerical analyses and testing have been performed on the so-called isogrid-lattice structures [1, 7]. A more recent investigation into grid-stiffening for a whole fuselage section with topology optimization has been performed in the Alasca project [10]. Other application of grid stiffening has been found for example in a car roof to absorb more energy during a rollover [8].

In the current work the isogrid and also alternative grid structures are investigated. As the name isogrid suggests, the grid has (approximately) isotropic properties (direction independent). In this study also alternative grid structures with more directional designs and including curved grids are investigated.

2 Manufacturing and test verification

Previous research by the NLR and TU Delft has been performed into composite grid stiffening design including manufacturing trials and testing, see Figure 3. This study was mainly aimed at grids with relatively high cross-sectional aspect ratios (of ~1.5; ~9mm high and ~6mm wide) and therefore special tooling for manufacturing and consolidation was required. The grid structure was laminated and consolidated separate from the skin. Later the skin and grid structure were bonded together.
For low grid cross-sectional aspect ratios (of ~0.3, height < 2mm and ~6mm wide) limited previous experience in manufacturing and testing is available. It is expected that placing low grids directly on the skin is feasible without very large deformations during curing.

(a) 

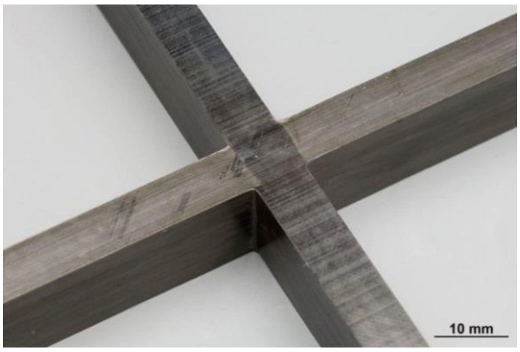
(b) 

Figure 3: Grid intersection designs as manufactured "alternate grid widening" (a) or "alternate grid tow cutting" (b)

For the study, the main focus was on the intersection of grid design because of the tendency of thickness build-up. With respect to the grid intersections the earlier research has resulted in two concepts as shown in figure 3 earlier in this paper. The first grid intersection concept involves the cutting of the strips in order to prevent the overlapping at the intersection. The second concept involves the waving out of the strips and thus in effect halving the grid thickness at the intersection. With this approach the grid intersection height remains on a constant height.
An example of the manufacturing process with fibre placement of the intersection is shown in Figure 4.

Figure 4: Grid intersection manufacturing with metal support blocks

Several samples of the intersection concepts were manufactured and tested in tension and compression. The final failure of both intersection concepts is shown in Figure 5 and Figure 6.

(a) (b)

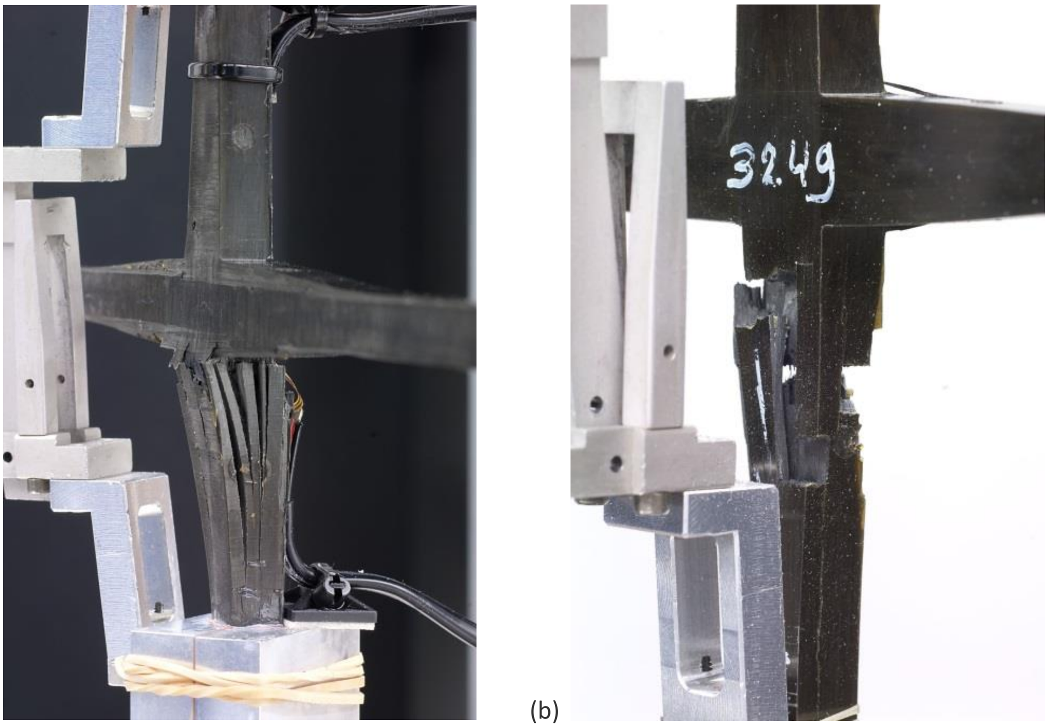
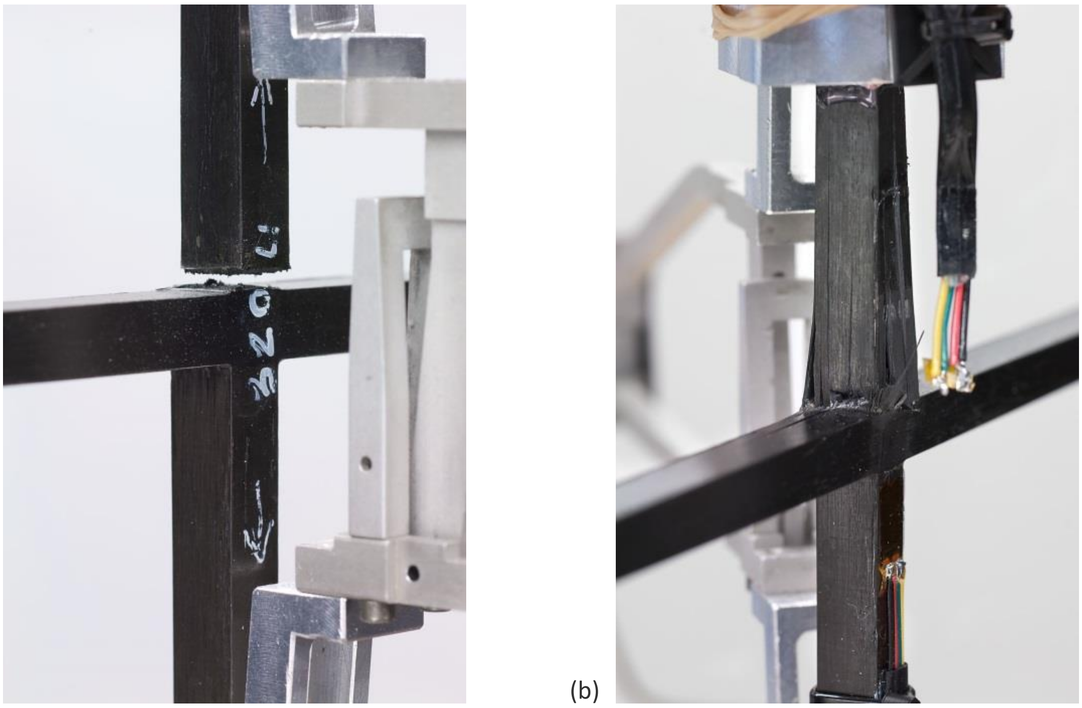


Figure 5: Failures mode for uncut stiffener crossing in compression (a) and tension (b)



(a) (b)

Figure 6: Failure mode for cut stiffener crossing in compression (a) and tension (b)

To enable manufacturing and curing of the grid structure without additional metal support blocks as shown in Figure 4, the grid stiffener height used in this study will be limited to 2.0 mm. The experience gained with these manufacturing trials and testing will be used for the final panel manufacturing of which the design and analysis is discussed in this paper.

3 Design requirement for fuselage structure

In this section the design requirements for the fuselage panels with grid stiffening design is described. The typical bending moment distribution in an aircraft fuselage is shown in Figure 7 with a decreasing moment towards the front of the fuselage. This is referred to as the low loaded area in this paper.

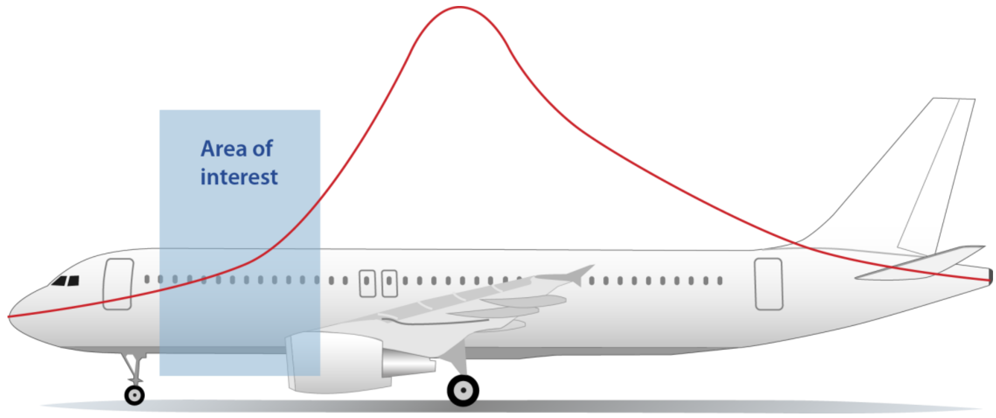


Figure 7: Typical bending moment distribution in the fuselage, which is representative for the barrel loading, and indication of the area of interest in this study

The general approach in this study is to improve structural efficiency for panels with increased stringer pitch in fuselage barrel structures. Varying stringer pitch over frame sections in one barrel cannot be simply achieved because of unwanted discontinuity of stringers. A straight-forward approach is the local removal of one stringer, thus doubling the local stringer pitch. An analytical buckling calculation on a flat (isotropic) plate is used for an indication of the effect of doubling the stringer pitch on the buckling response.

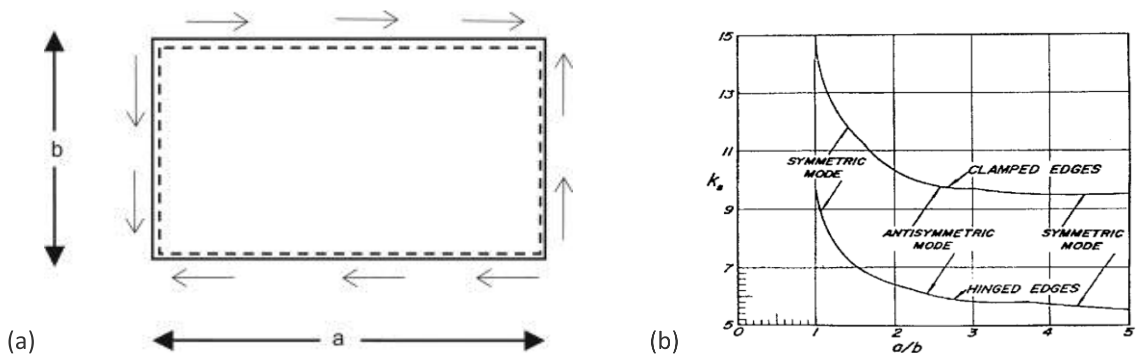


Figure 8: (a) Flat plate geometry and (b) diagram of flat plate shear k_s factor depending on a/b value [Singer].

The critical shear buckling load for a flat plate (dimensions *a, b* and thickness *t*) is expressed with the following equation. For compression a similar equation is used.

$$\sigma_{cr} = \frac{\pi^2 k_s E}{12(1-\upsilon^2)}\left(\frac{t}{b}\right)^2$$ Eq. 1

$$k_s(a,b)$$

Where E is Young's modulus, k_s is a constant which is extracted from a graph, t is the thickness of the plate and a and b are the length and width. When the width of the flat plate is doubled, in effect doubling the Stringer Pitch (SP), the following expression is used to determine the change in critical buckling load

$$\eta_{\sigma_{cr}} = \frac{\sigma_{cr-2sp}}{\sigma_{cr-1sp}} = \frac{k_{s-2sp}}{k_{s-1sp}}\left(\frac{t}{\alpha \cdot b}\right)^2$$ Eq. 2

In which the single and double stringer pitch is indicated with the subscripts *1sp* and *2sp* and α is the multiplication factor for the panel width. From this analytical calculation it can be concluded that doubling the stringer pitch leads to a strong reduction of 75% in critical buckling stress for both shear and compression loading. Grid stiffening is used to increase the critical buckling stress to an acceptable level that is described in the next section.

The loading of the panels in the low-loaded areas for shear and compression loads are derived from a global FE barrel model (GFEM), see Figure 9. The GFEM consists of 20 frame segments with 58 stringers, yielding 1160 skin bay panels, of which about 400 are not included in the output as shown in this section. A large number of load cases are included in the GFEM model including internal pressure and temperature effects.

The maximum loads for shear and compression are of main interest and are extracted for all the panel skin bays, for all load-cases. The resulting maximum shear and compression loads are shown in Figure 9.

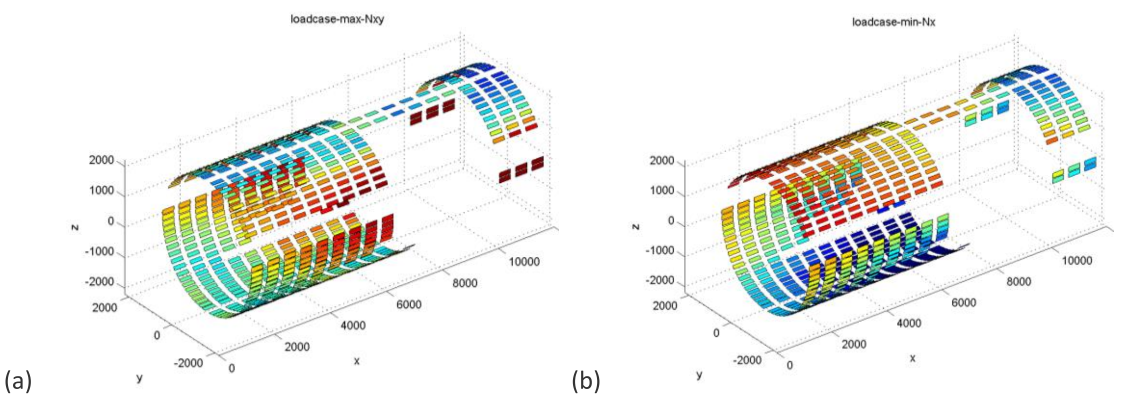
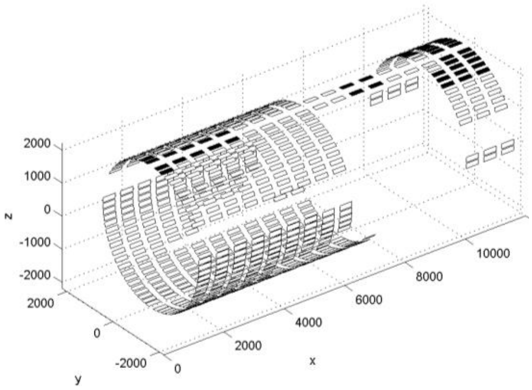
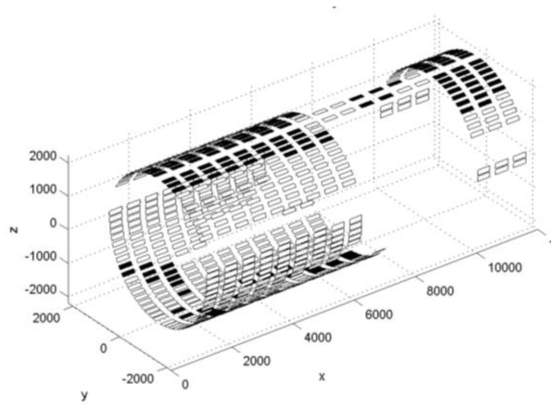


Figure 9: Fuselage model (GFEM) with (a) maximum shear loads and (b) compression load for the panels in the model (all load-cases included)

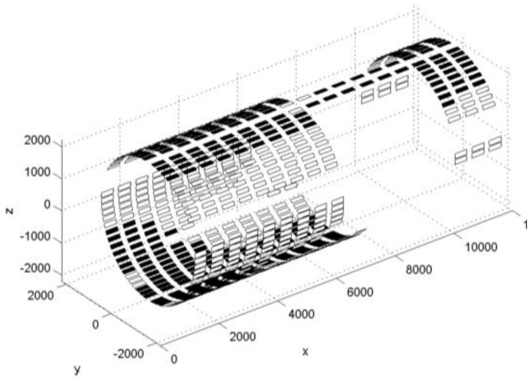
From these loads per panel in both shear and compression the interesting areas within the fuselage can be investigated. Depending on the buckling response of the optimized grid panels in shear and compression the number of panels to be replaced in the fuselage can be determined. In Figure 10 the load threshold levels for shear loads in the panels are shown.



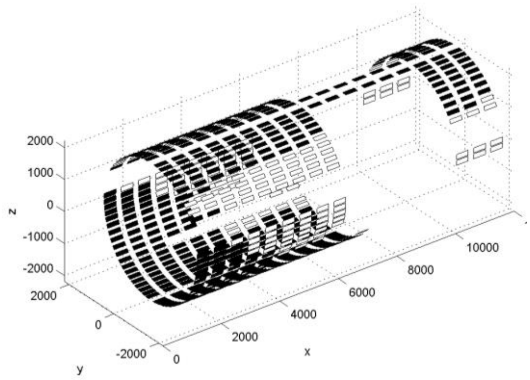
(a) *Shear load, low loaded areas*



(b) *Shear load, medium loaded areas*



(c) *Shear load, medium/high loaded areas*



(d) *Shear load, high loaded areas*

Figure 10: Fuselage model overview of the panels to be replaced (indicated by black) with a certain shear load levels

As can be observed the number of panels indicated with black increases as the threshold is increased. At a low load levels only six conventional panels can be replaced where at medium load levels this increases to around 40 panels. For the compression loads a similar assessment is performed. In the next section these requirements are used to determine the grid stiffening design.

4 Grid stiffening parameter study

In this section the design approach for the grid stiffening of fuselage panels is discussed. From the design requirements it was shown that the shear buckling and compression buckling values are considered the driving factors for the design. The tension and out-of-plane load-cases were therefore not included in the parameter variation investigation. The design options for grid design were limited to parameter variations that constrain the grid angle, grid height and grid offset. A design parameter sensitivity analysis was performed following the design approach as presented in Figure 11

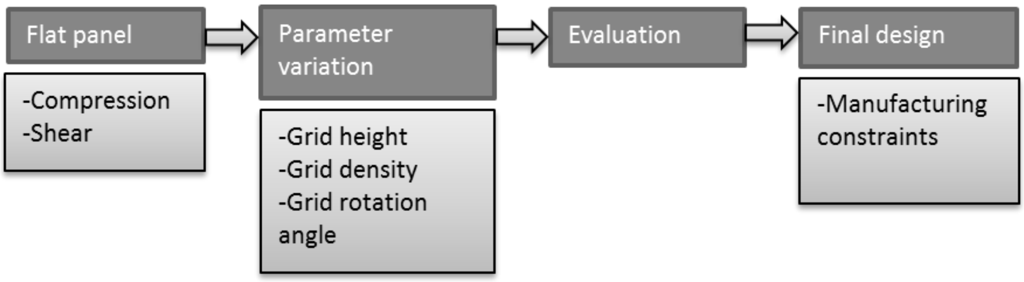


Figure 11: Grid design parameter optimization

For the parameter sensitivity analysis a simplified flat plate model was used with external dimension of 600 [mm] length and 308 [mm] width. The width of the flat plate corresponds with the free area from the reference fuselage when the stringer pitch is doubled.
A reference quasi isotropic composite laminate with a thickness of 1.60 [mm] was used for the parameter sensitivity analysis. The flat plate was modelled and partitioned using finite element software and included three steps; linear buckling compression, linear buckling shear and one step for extracting the modified mass.

For the parameter sensitivity analysis the following parameters and ranges were included with the index used in the results:

- Grid rotation angles [30 – 60 degrees] (a)
- Grid height [1.0 – 4.0 mm] (t)
- Grid offset/density [20 – 90 mm] (o)

Note that these parameter ranges are chosen to limit the design space and do not include manufacturing constraints. In the finite element model the grid sections were modelled using beam elements in combination with composite UD properties. By adjusting the beam cross-sectional profile the height was adjusted, the width of the grid section is fixed to ¼” (6.35 mm). In Figure 12 two examples are shown of the parameter sensitivity models used for determining the compression buckling and shear buckling loads.

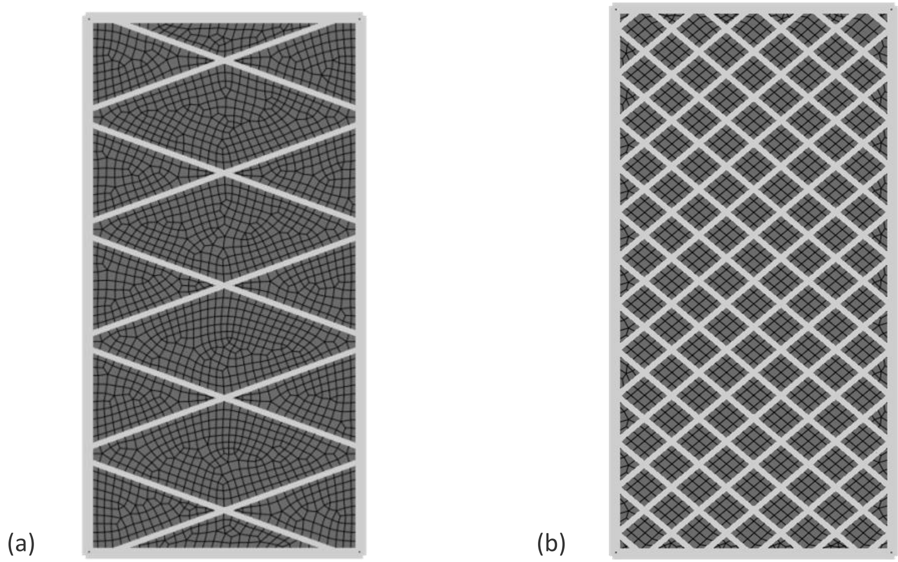


Figure 12: Overview of grid designs with (a) a low density and low angle and (b) high density grid and 45 degree angles

With the parameter ranges as described above a total of 225 simulations were performed using an automatic model generation script. The performance indices shown in the following graphs are a combination of compression/shear buckling loads and weight reduction of the analysed design with respect to the reference design without any grid sections (Eq.3).

$$Perf\_i = \tfrac{1}{2}\frac{(\Delta\lambda_c + \Delta\lambda_s)}{\Delta w} \qquad \text{Eq.3}$$

The parameter indices for grid angle (a), grid height (t) and grid offset (o) are used.
In Figure 13 the angle sensitivity is shown for three constant values of grid height of 2mm and for grid offsets of 40, 50 and 60 mm.

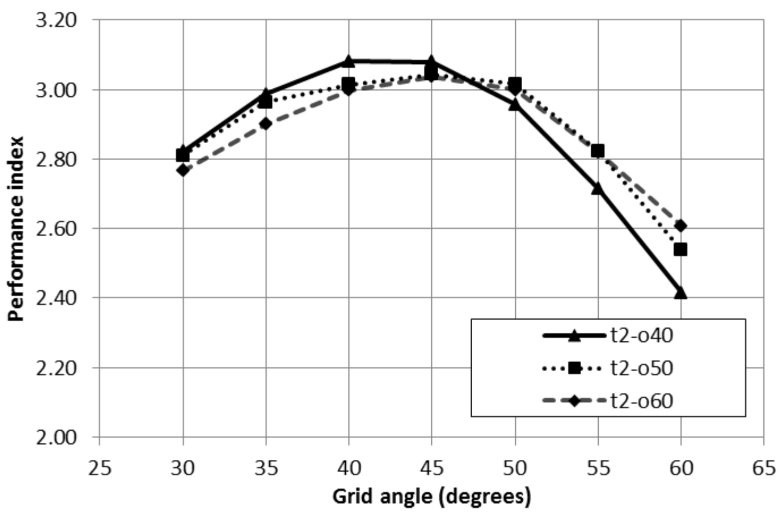


Figure 13: Grid angle sensitivity

For the grid angles it can be observed that the performance increases between 40 and 45 degrees depending slightly on the grid offset (o). Overall it is observed that a 45 degree grid is a good candidate for the design. In Figure 14 some data-points are shown for the angles of 30, 45 and 60 degrees and a constant grid offset of 50 [mm].

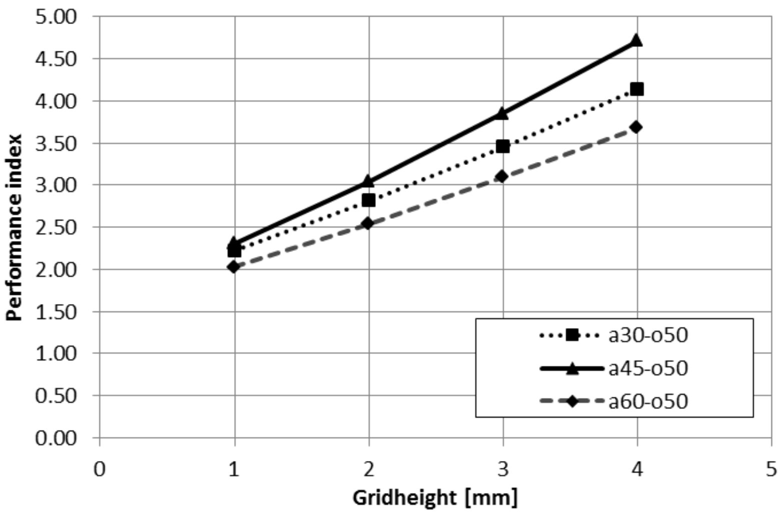


Figure 14: Grid height sensitivity

From the grid height diagram in Figure 14 it can be observed that, as expected, the performance is very dependent on this value. A thick grid section is thus more effective than a thin grid section in buckling performance. In Figure 15 the results for the grid offset variation is shown with angles of 30 – 60 degrees and a constant grid height of 2 [mm].

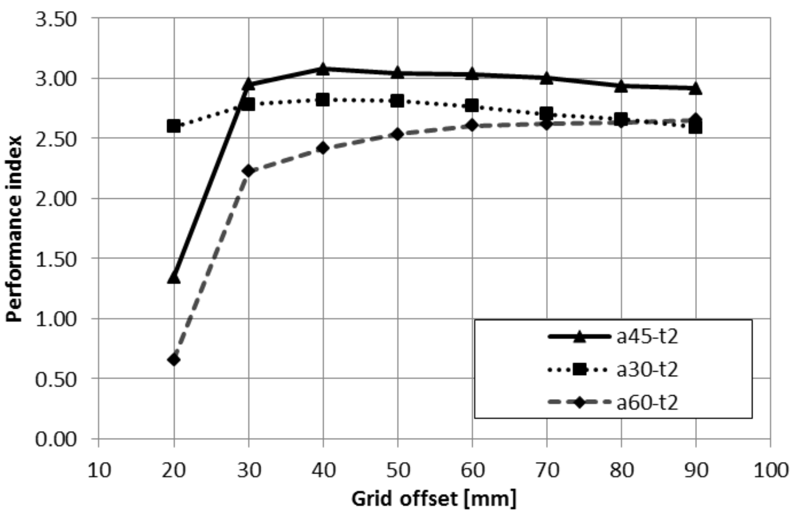


Figure 15: Grid offset sensitivity

It is observed that the grid offset sensitivity is low for grid offsets above 50 [mm]. In the range of 20 and 30 [mm] the performance drops considerably as the weight for these designs is increasing rapidly.

Other design variations using a spline definition of the grid section have been performed to investigate their influence. It was observed that for this flat panel case the curvature of the grid apparently has little influence on the performance. Some finite element designs using the curved spline grid section approach are shown in Figure 16.

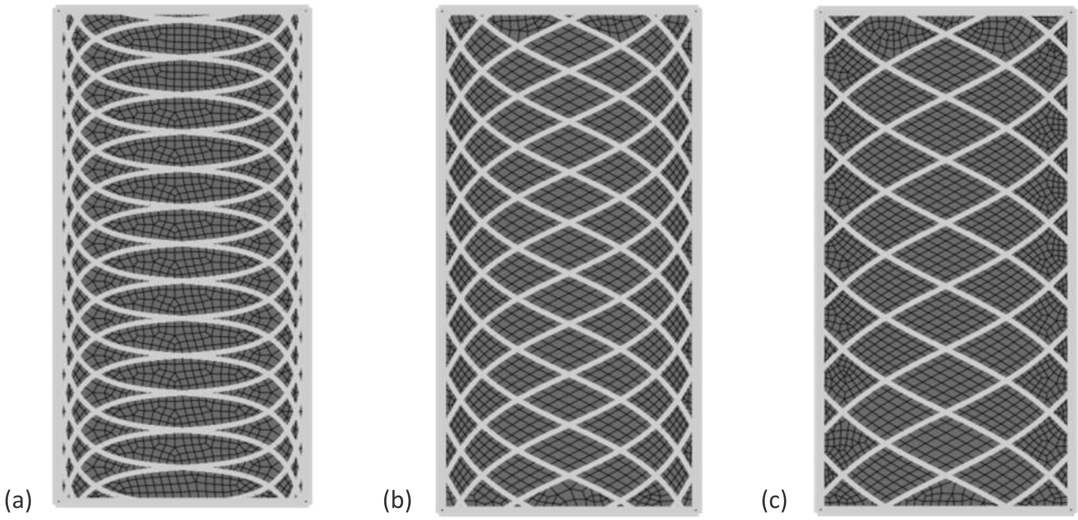


Figure 16: Curved spline finite element grid designs

After the parameter sensitivity analysis as discussed the following was observed:

- Grid angles of 45 degrees show good performance for both compression and shear buckling with respect to weight
- Grid height has a significant influence on the buckling performance and does not show an optimum (manufacturing dependent parameter). Therefore the upper limit of grid manufacturing without additional tooling, 2 [mm] is chosen.
- Grid offset shows low sensitivity influence on the buckling performance when a value larger than 50 [mm] is chosen. This value will therefore also depend on the manufacturing choices made.

For the evaluation phase as indicated in the schematic in Figure 11 the most promising design is further analysed. Also manufacturing constraints were addressed which indicated some issues with the current design envisioned. Specifically the grid offset in combination with the cut-cross-section design as shown in Figure 3 needed attention, because the minimal strip that can be placed is 90 [mm] in length. Especially near the edges of the panel section this led to issues with the minimal strip length. Therefore it was chosen to curve the strips at the panel edges.

Two detailed finite element models were created that included these manufacturing changes and included representative load introductions. These models also correspond with the test setup envisioned for the compression and shear buckling test phase and were used to correlate with the design requirements as discussed in section 2.

The detailed compression panel model is shown in Figure 17 and consists of the grid stiffened centre section, composite omega stringers and two aluminium frame segments. The top and bottom is connected to resin blocks for load introduction and the sides are simply supported. The shear panel in Figure 17 uses a picture frame test-setup to load the panel in shear. Two composite omega stringers are included and aluminium tabs are shown for correct load introduction in the composite laminate. In the next section, *Nonlinear analysis procedure and results*, the model will be discussed in more detail.

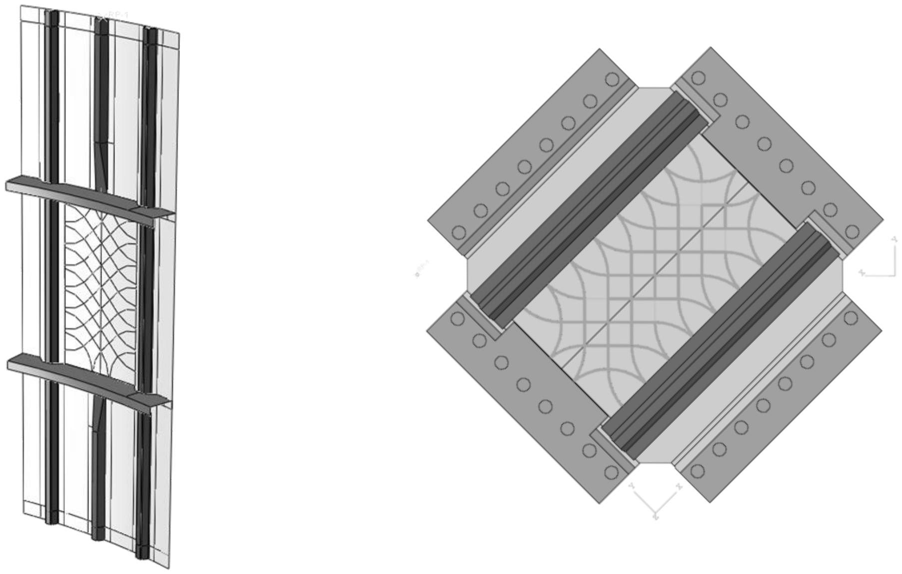


Figure 17: Compression and Shear panel with updated grid design including manufacturing constraints

For the final design the sizing was performed to identify the largest weight gain in the fuselage. There is a strong relation between the buckling loads of the panel design and the number of panel bay sections where the grid design can be used. The final design was fixed at a 45 degree grid angle, 2 [mm] grid height and grid offset of [52.5 mm]. In Table 1 the design values are stated for the compression and shear panel.

Table 1: Design values

Parameter	Value
Curvature radius R	2000 [mm] (compression panel), Shear panel is flat
Size total	1800 [mm] x 670 [mm] (length/width compression panel), 760 [mm] (length/width shear panel)
Stringer cross section	125 mm^2
Stringer pitch	419 mm
Frame pitch	600 mm
Stiffener laminate: 9 PLY	[-45/45/0/0/90/0/0/45/-45]
Reference skin laminate: 13 PLY	[-45/45/90/0/-45/45/0/45/-45/0/90/45/-45]
Skin laminate: 10 PLY	[-45/45/90/0/-45/45/0/90/45/-45]
Elements	Shell elements (S4R) and beam elements (B31)

This final design buckles (linear analysis) in compression at 75.7 N/mm and in shear at 43.6 N/mm. This buckling performance makes the design suitable to use in 44 skin bay sections from the fuselage, derived from the GFEM calculations, see Figure 10. With this grid design the reserve factor (RF) in these skin bay sections is lowered from ~2.0 towards 1.0, which results in a more effective structure and a weight saving of 8.49 kg is achieved. In Table 2 an overview of the performance is shown.

Table 2: Design result overview

	Total panel Mass [kg]	*Skin Thickness [mm]*	*Lambda [N/mm] LL, mode (I) and mode (II)*	*Lambda [N/mm] UL*	*Grid height [mm]*	*#Bay replaced*	*Weight gain [kg]*
Shear panel	1.68	1.25	(I)43.6 (II) 44.7	65.4	2.0	44	8.49 kg
Compression panel	"	"	(I)75.7 (0.7LL), (II) 77.3 (0.7LL)	162.1	"	"	"

In the following section the analysis procedure that was used for the final design is discussed.

5 Nonlinear analysis procedure and results

The detailed simulation models discussed in the previous section are further explained in this section including linear buckling and post-buckling analyses results. The models represent realistic (flat and curved) panel geometries and load introductions. For the final grid design the detailed simulation model included the skin section and stringers with conventional linear shell elements (S4R) 13 and grid stiffening as linear beam elements (B31) 13. In Figure 18 the meshed models are shown.

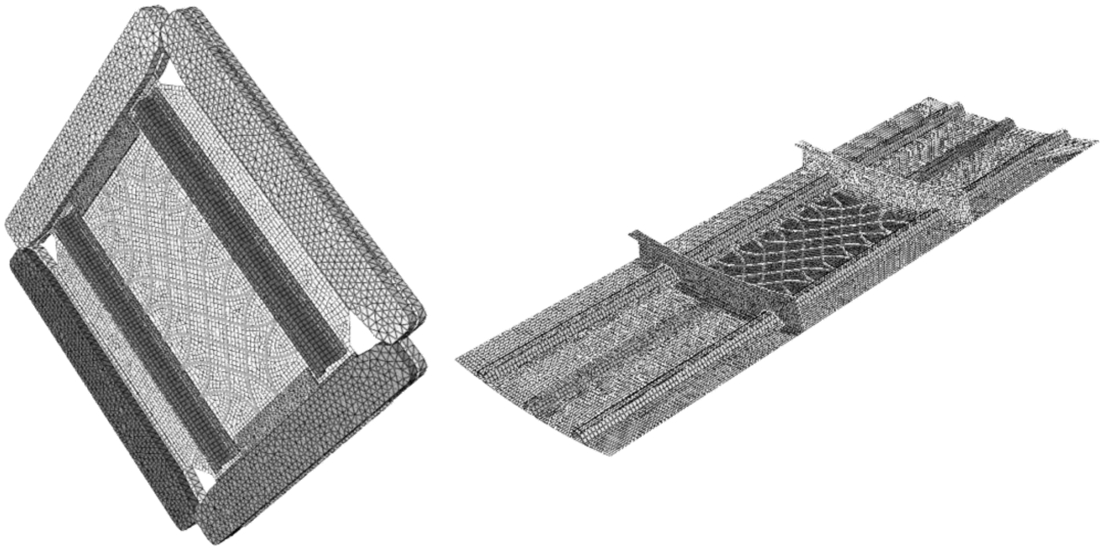


Figure 18: Meshed models for the shear panel (left) and curved compression panel (right) designs

The boundary conditions for the shear model are defined on the picture frame (modelled as steel beams by linear solid elements and connected by frictionless rotational joints in the corners). The bottom corner is fixed and the top corner is loaded in upward direction, similar to the physical test. Also the out-of -plane displacements are constrained to prevent rigid body modes. The compression panel model is supported on top and bottom with epoxy equivalent blocks with a 50 mm section. The bottom part is fixed, the top part is loaded. At the sides the panel is simply supported.

The material properties of the Hexcel composite material used for the panel models are derived from UD coupon test data. This material data cannot be disclosed for publication because of confidentiality agreements. Linear buckling analyses are executed for the shear and compression panels. The Lanczos solver is used and the first two buckling modes are retrieved, see Figure 19.

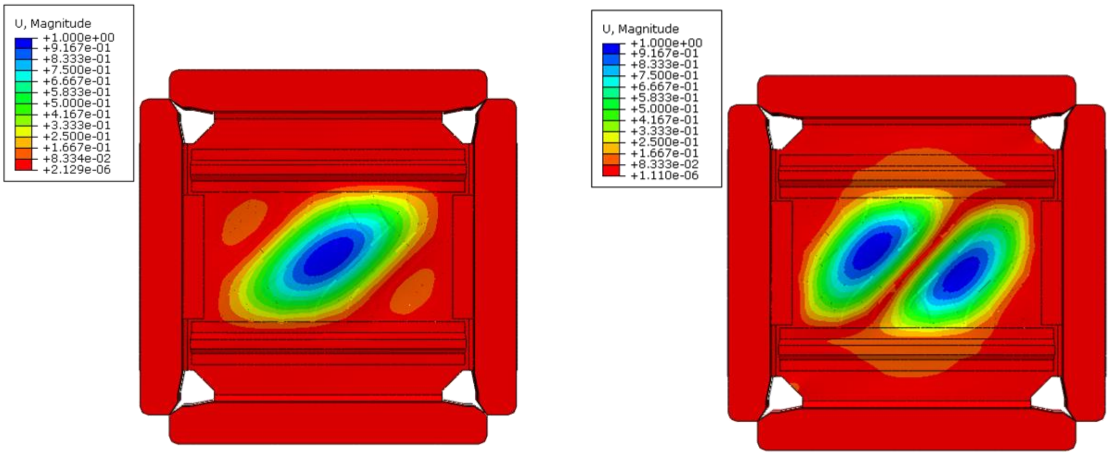


Figure 19: Buckling mode shapes of mode 1 (left) and mode 2 (right) for the shear panel with grid design

As presented earlier in Table 2, the linear buckling values for the shear panel of mode 1 and mode 2 are: 43.6 N/mm and 44.6 N/mm, respectively. For the compression panel with grid stiffening the buckling modes as shown in Figure 20 were obtained with linear buckling analysis.

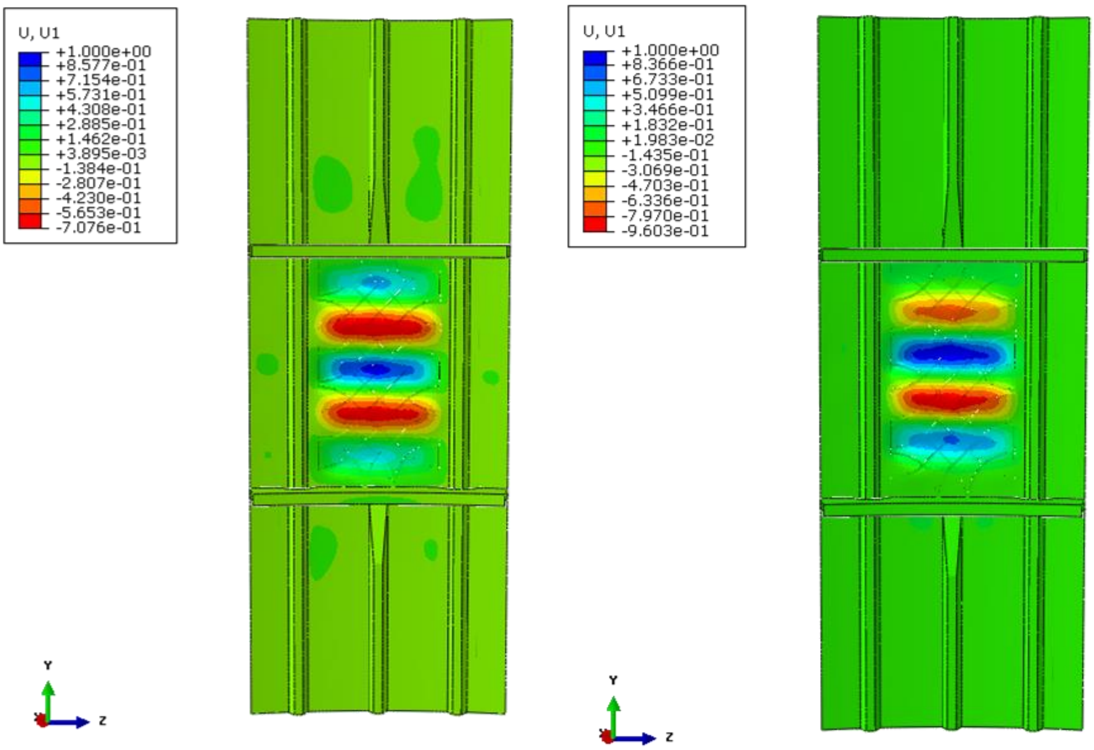


Figure 20: Buckling mode shapes of mode 1 (left) and mode 2 (right) for the compression panel

The linear buckling values that are found for the compression panel of the first two modes are: 75.7 and 77.3 N/mm. The resulting limit load for the compression panel is 108.1 N/mm as indicated in Table 3.

Table 3: Limit load (LL) and Ultimate load (UL) values

	LL [N/mm]	UL [N/mm]
Compression panel	108.1	162.1
Shear panel	43.6	65.4

In a nonlinear pre- and post-buckling analysis the behaviour of the panels is investigated further. The displacements and maximum principal strain fields at LL and UL are retrieved for the shear panel as shown in Figure 21 and Figure 22.

LL results | **UL results**

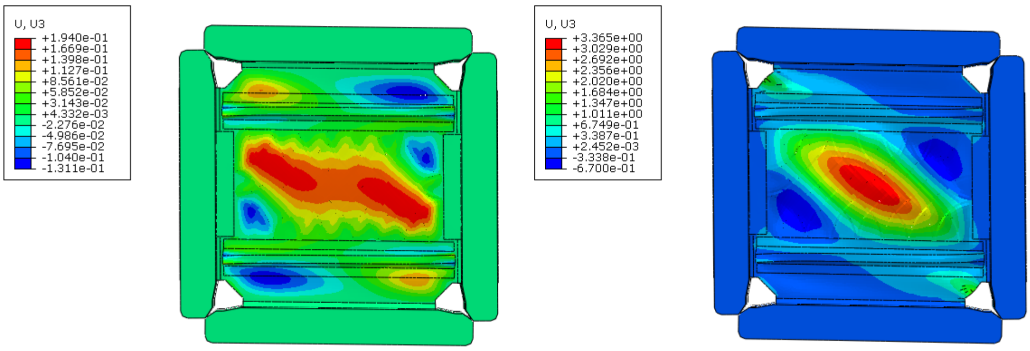


Figure 21: Displacement out-of-plane for LL and UL

LL results | **UL results**

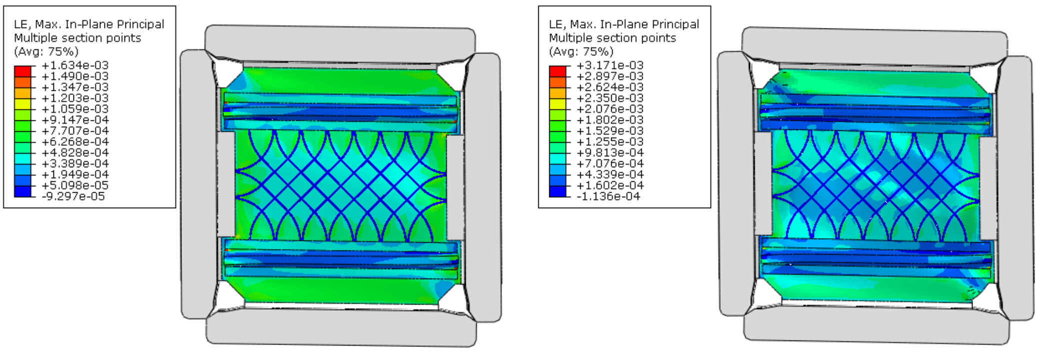


Figure 22: Max. principal strain in-plane LL, UL

The skin buckling combined with grid is predicted with the results shown. The shear panel with grid stiffening shows a stable post-buckling path with no expected failure up to UL. Final failure is expected in the corner section of the shear panel with high deformation gradients. This will occur at higher loads than UL and is expected to be a stable damage development from the corners inward.

Also for the compression panel the displacements, stress and strain fields at LL and UL are retrieved for the shear panel from the non-linear post-buckling analysis, see Figure 23 and Figure 24.

LL results	UL results

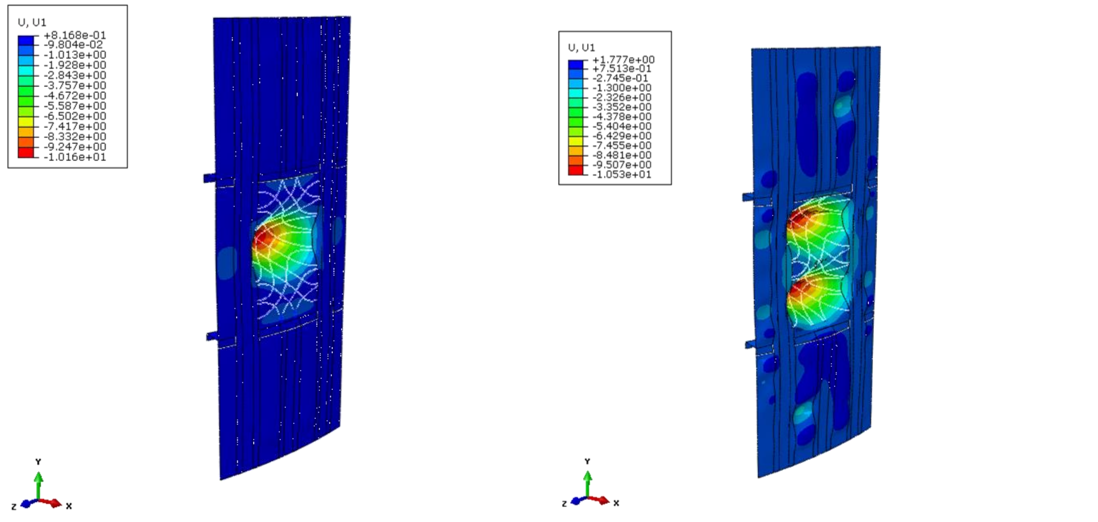


Figure 23: Displacement in post-buckling with LL and UL

LL results	UL results

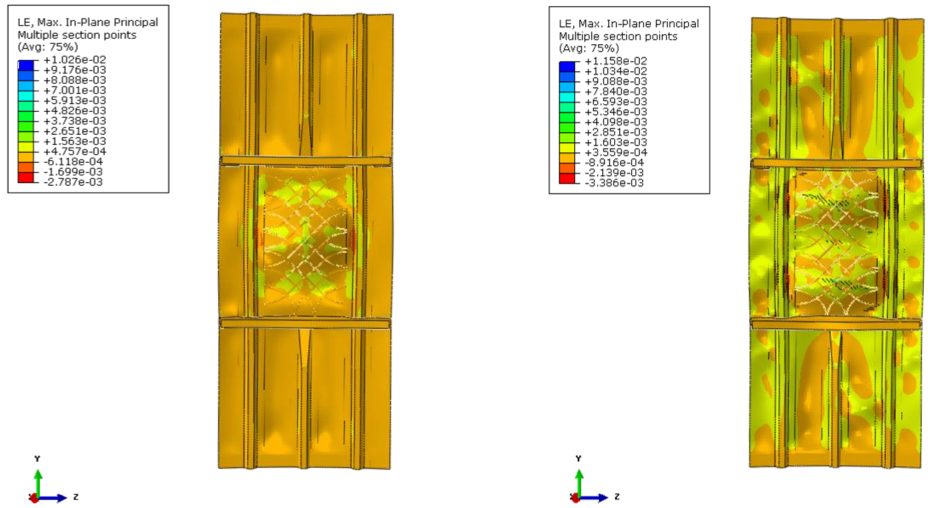


Figure 24: Max. principal strain in-plane LL, UL

Also for the compression panel no failure is expected before ultimate load. The strains are high at the connection between the grid and stringer and failure is expected to initiate at that location.

At the time of writing of this paper, the preparations for manufacturing of the panels are on-going. The shear panel will be manufactured and tested in the picture frame. The test results will be compared with the predictions from the linear buckling and non-linear post-buckling simulations.

Conclusions

Grid stiffened design as presented in this paper shows an improvement in buckling performance. Weight gains can be achieved by applying grid stiffening instead of traditional stiffeners for the low loaded area in the fuselage. The final design for the grid stiffening in combination with a lower skin thickness was assessed on a shear and compression case. Finite element models were created to determine the linear buckling response for the final design ¼” (6.35 mm) wide grids and a height of 2 [mm]. The intersections are created using the cutting option to reduce the weight and better correlation with the simulation results. The grids are a combined 45 degree and -45 degree topology with an offset of 52.5 [mm].

Structural performance analysis of grid stiffened panels, involving linear and non-linear FEM analyses with ABAQUS 13, have been done for the panels. These panels are designed for low loaded areas in a fuselage barrel. The focus is on the prediction of skin buckling onset and post-buckling behaviour and the final failure, intended for tests preparations.

For the total fuselage structure as defined the weight reduction is approximately 8.49 [kg] per panel when compared to the traditional structures. It is observed that for small buckling load increases the grid stiffening concept is interesting, for higher recoveries of buckling loads the traditional design with lower stringer pitch are expected to be more efficient.

Acknowledgements

The research leading to these results has received funding from the European Community’s Seventh Framework Programme FP7/2007-2013 under grant agreement n°213371 (MAAXIMUS, www.maaximus.eu).

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