STRUCTURAL TESTING AND SIMULATION OF COMPOSITE ISOGRID STRUCTURES FOR AEROSPACE APPLICATIONS

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Keywords: SHM, strain measurements, distributed sensing, fiber optic sensor, isogrid.

Abstract

Isogrid structures show a high potential for weight saving in thin skin compression structure scenarios, which can be found in space launchers, satellites or similar applications. However, the difficulties found in design, simulation and manufacturing these kind of structures with composite materials limit their use in comparison with other reinforcement solutions. Distributed sensing systems provide strain measurements all along a single optical fiber, and not only in a few local points as traditional strain gauges or Fiber Bragg Grating sensors (FBG); then it is possible to obtain the strain profile in different sections of the structure. This information will be useful to understand the buckling and non linear behaviour of a complex composite structure as those. Two different design solutions for isogrid reinforced structures are studied, focusing on the intersections of the grid nerves. Each design solution is modelled by Finite Element Method (FEM) . Results are validated by a compression test on a specimen which are fully instrumented with a fiber optic distributed sensing technology. Useful information about the strain profile is obtained, and ways for improvements are derived.

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1 Introduction

The aerospace industry requirement for low weight structures has led to a continuous seek of optimal structural arrangements. Isogrid structures are advanced shell structures with stiffeners arranged in equilateral triangles. With relatively low material input these structures show high stability and stiffness, especially when build from composite material. Largely manual and immature manufacturing methods however still limit the wide application of composite isogrid structures. Furthermore, the complex mechanical behavior of isogrids needs to be understood in order to optimize the stiffener geometry.

In this work we investigate a small panel with only a small number of stiffeners, this investigation can provide conclusions about the behaviour of the intersections of the stiffeners and the interaction between skin and reinforcement. Especially local buckling of the skin was found to be a critical failure mode. Local bucking modes are difficult to predict and test, making difficult to upgrade the structural optimization and the competitiveness of this structural configuration. Nowadays, using optical distributed techniques, is possible to measure the strain field of the full structure, measuring all along an optical fiber and not only in singular points, as traditional strain gauges. This information will be used to a better understanding of the compression behavior, the most critical for this structural solution. [1]

The designer of the first isogrid structures, which were manufactured from aluminum and used for the fuselage of a space shuttle booster of the NASA in the 70's remark the following advantages for isogrid structures made from isotropic material [2]:

- Easily analyzed
- Can be optimized for a wide range of loading intensities
- Readily reinforced for concentrated loads and cut-outs
- Redundant load path
- Less structural depth
- Standard pattern for attachments (nodes accommodate equipment mounting without change)

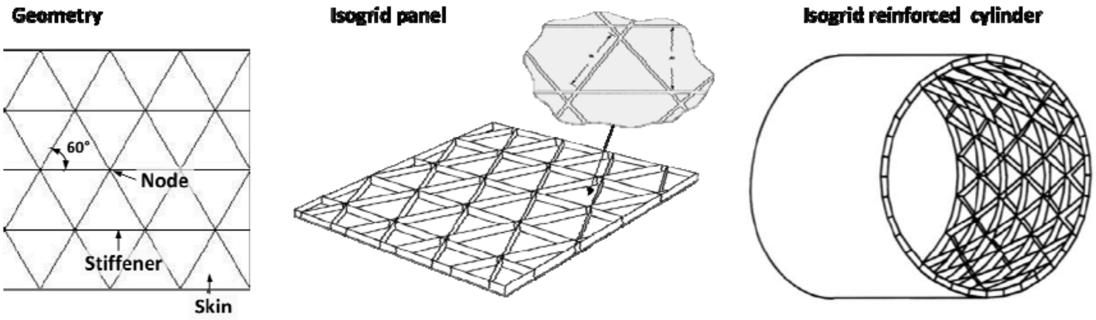

Figure 1. Isogrid structures

2 Manufacturing isogrid structures

Initially isogrids were manufactured from aluminium. The costly and inefficient milling process however prevented a wide application. In the course of the implementation of carbon fibre reinforced plastics manufacturing concepts for composite isogrid structures have been developed.

In [3] a reinforced panel was manufactured using prepreg tow and unidirectional tape. First a metal isogrid tool was designed, which is used to cast a high temperature silicon rubber mould. The rubber tooling was chosen because due to a high coefficient of thermal expansion the rubber, the mould expands during the curing process, resulting in excellent consolidation of the ribs. The stiffeners are formed by winding the prepreg repeatedly into the isogrid shaped grooves of the silicon mould stacking each tow fibre on top of the previous until it is filled to the top. Prepreg tape is laid over the mould to form the skin. A steel caul plate is placed on top in order to obtain good compression and a smooth skin surface finish. The entire piece is vacuum bagged and cured in an autoclave. Another similar possibility is to laminate the stiffeners on top of the skin plate and insert silicon spacer before the curing process.

This manufacturing process requires labor intensive handling, however on-going developments promise methods to create isogrid structures at high quality and lower cost. Casa-Espacio has developed a procedure to built isogrid structures based on the automated fibre placement process. In the automated fibre placement process a bundle of prepregged fibres, called tows, are pulled off from spools and fed through a fibre delivery system into a fibre placement head. A rolling compaction device laminates the tows onto the surface of the mould or the previously laid ply. The compression combined with heat removes the air and promotes the adhesion between the plies. A typical computer numeric controlled fibre placement system can operate with up to seven axes of motion for positioning the fibre placement head normal to the surface, which can be plane or concave. Tensioners provide individual tow payout and maintain a precise tension. Fibre placement has the capability of reducing material cost (material scrap only 2 to 7 %) and labour cost. Furthermore it provides the possibility to arrange the fibres so they follow the applied stresses. However, a minimum steering radius depending on the tow width needs to be respected in order to avoid buckling.

The most difficult design aspect for isogrid is the nodal point between the stiffeners. The construction and analysis of those cross-sections is subject of various investigations. If the stiffeners simply cross in one point the increased fibre content will lead to undesired bending. Furthermore it is impossible to compact the triple amount of fibre in the node areas keeping the same height as the rest of the stiffener. Three different approaches have been proposed to solve this issue, sketched at figure 2, the performances of two of them are compared in this paper.

In method 1 the stiffeners are arranged with an offset (only two cross at a time). The two structures that were examined in this work were manufactured using method 2 and 3 respectively. Method 2 is an evolution of method 1. The fibre path undergoes a slight deflection (steering) in the intersection area. Additionally the tape is spread. In this way the initially increased amount of fibre in the cross-section is reduced by spatial distribution. In method 3 two of the three tapes are cut before the intersection in a rotational manner. In this way a uniform fibre content is kept at the cross-section.

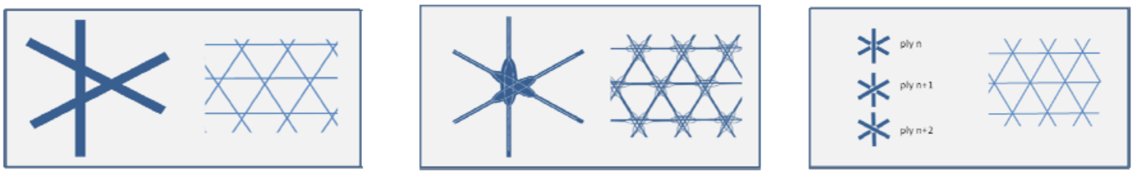

Figure 2. Three different solutions for the nodal point of composite isogrid structures

3 FEM simulation of isogrid structures

3.1 Description of the Model

The initial geometry of the panel is modeled with two-dimensional surfaces, which are divided into shell elements. Those elements are assigned with the composite properties and the three-dimensionality is given through a thickness variable. The boundary conditions represent the real test conditions as close as possible.

The FEM model was created in an iterative process. Every step was checked regarding its feasibility and compared with the results from the compression test. The correlation of the final simulation results with the test results was found to be satisfactory. Especially the clamping condition was subject to various changes throughout the development of the model and was adjusted iteratively. In a first step the area inside the aluminium fixtures was considered to be perfectly rigid and therefore not represented in the model. However, more detailed observation of the conditions on the bottom clamp during the compression test has revealed small deformation in this area, which lead to critical deformations in the unreinforced zone directly above the fixture and increases overall flexion of the panel. For this reason the aluminium fixtures where included in the final model.

3.2 Geometry

The initial geometry is composed of a rectangular surface in the xy-plane representing the skin and perpendicular surfaces representing the stiffeners. The skin is 577 mm long, 343 mm wide and has a thickness of 1.5 mm. The width of the isogrid-stiffeners is 7 mm and the width of the stiffeners at the panel borders is 10 mm. All stiffeners are 10 mm high. These are idealized dimensions. The real structure has a lot of deviations due to the difficult manufacturing process, which may lead to strain peaks that will not be reproduced in the model. The geometry of the two models differs only in the position of the stiffener planes. For the model of Panel I merely two stiffeners cross at the same time, creating the intersection displayed in Figure 3. For Panel II all three stiffeners cross in one common point. Materials properties for IM7/8552 tape were taken from Hexcel datasheets.

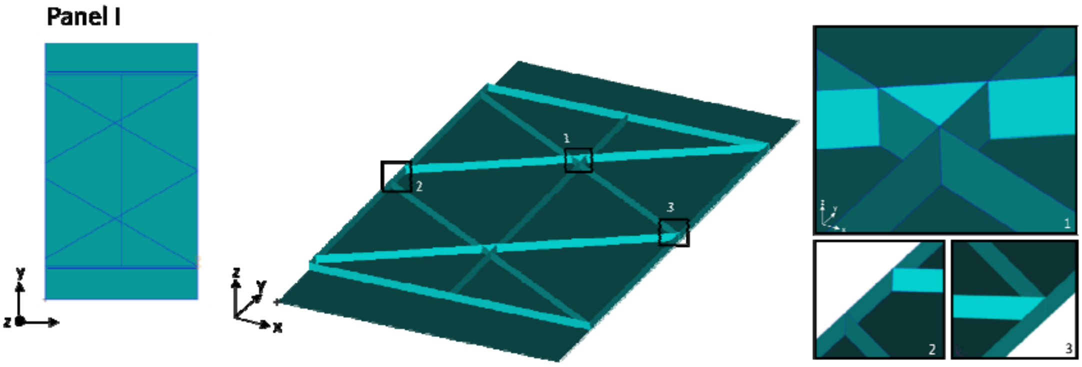

Figure 3. Geometry of panel I, showing a detail of the nodal points

3.3 FEM mesh

The previously created geometry is meshed with rectangular shell elements, which have an edge length between 1.3 mm and 2.4 mm (Figure 4). The fine mesh results from the fact that the small area between the fixture and the horizontal stiffener on the bottom and the top is considered to be the weak point of the structure under flexion. An accurate simulation of the behaviour of this critical area requires a high number of elements in y-direction. In order to maintain the ratio of the element edges between 0.8 and 1.2 the number of elements in x-direction increases as well. The elements of the skin and the elements of the stiffeners are connected by sharing their nodes in the xy plane.

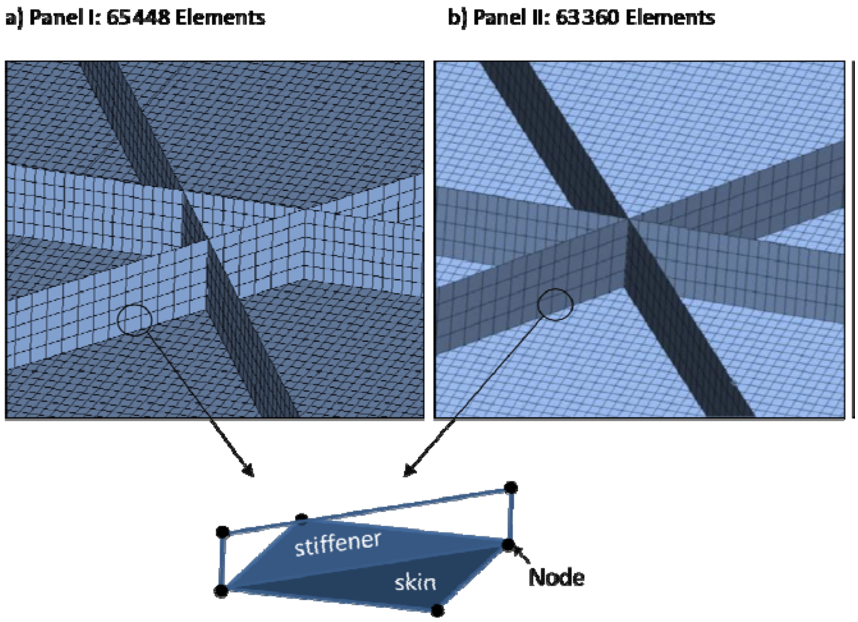

Figure 4. Details of the Finite Element mesh

4 Tests of the isogrid specimens

4.1 Strain measurement technique

FBG (Fibre Bragg Grating) sensors, have been used for the last 20 years, and they have built up a confidence in its performances. FBGs can measure the strain with a similar accuracy to the standard strain gages and extensometers, and they are also comparable in many aspects from a user’s point of view. Indeed, their measurements are local and directional, they require compensation for temperature, they are commonly used bonded onto the structure surface and it is also possible to embed the optical fiber in the laminate in the case of composite structures. The main advantages of the FBG over the electrical strain gage are its reliability for long term measurements; because it is frequency coded, without drifting by aging, and its ability for multiplexing; since several FBGs can be engraved on the same fiber at different positions, resulting in the simultaneous measurement points. The most common procedure for multiplexing is to use a different central frequency for each grating, allowing up to ten FBGs in a single optical fiber, for conventional applications. This technology is well known and proved, further details on FBG extensometry can be found in many academic texts, as in example ref [4].

The Optical Backscatter Reflectometry (OBR) offers the possibility of getting strains all along the optical fiber, with adequate spatial resolution and strain accuracy. It opens new possibilities for structural tests and for structural health monitoring. This is what is understood as ‘distributed sensing’, with the main difference that the fiber does not need to have local engraved sensors. As the light is travelling along the optical fiber, a very small amount is reflected back at every position, due to the small imperfections of the fibre. This light reflected back has the same frequency as the incident light, and it is called Rayleigh backscattering. The OBR uses swept wavelength interferometry (SWI) to measure the Rayleigh backscatter as a function of position on the optical fiber with high spatial resolution. An external stimulus (like a strain or temperature change) causes temporal and spectral shifts in the local Rayleigh backscatter pattern. These temporal and spectral shifts can be measured and scaled to give a distributed temperature or strain measurement. The SWI approach enables robust and practical distributed temperature and strain measurements in standard fiber with millimeter-scale spatial resolution over tens to hundreds of meters of fiber with strain and temperature resolution as fine as 1 µstrain and 0.1 °C. A detailed description of the principles can be found at Ref [5].

4.2 Compression tests setup

The test specimens were a quasi-isotropic skin of 1.5 mm thickness with an isogrid configuration; rib height and thickness were 10 mm. In this structure the grid consists on a rib lattice of equilateral triangles. The upper and lower edges have metal fittings to introduce the load, then the specimen was mounted in a MTS test machine. The two lateral edges were free. Further details of the setup can be observed at figure 5.

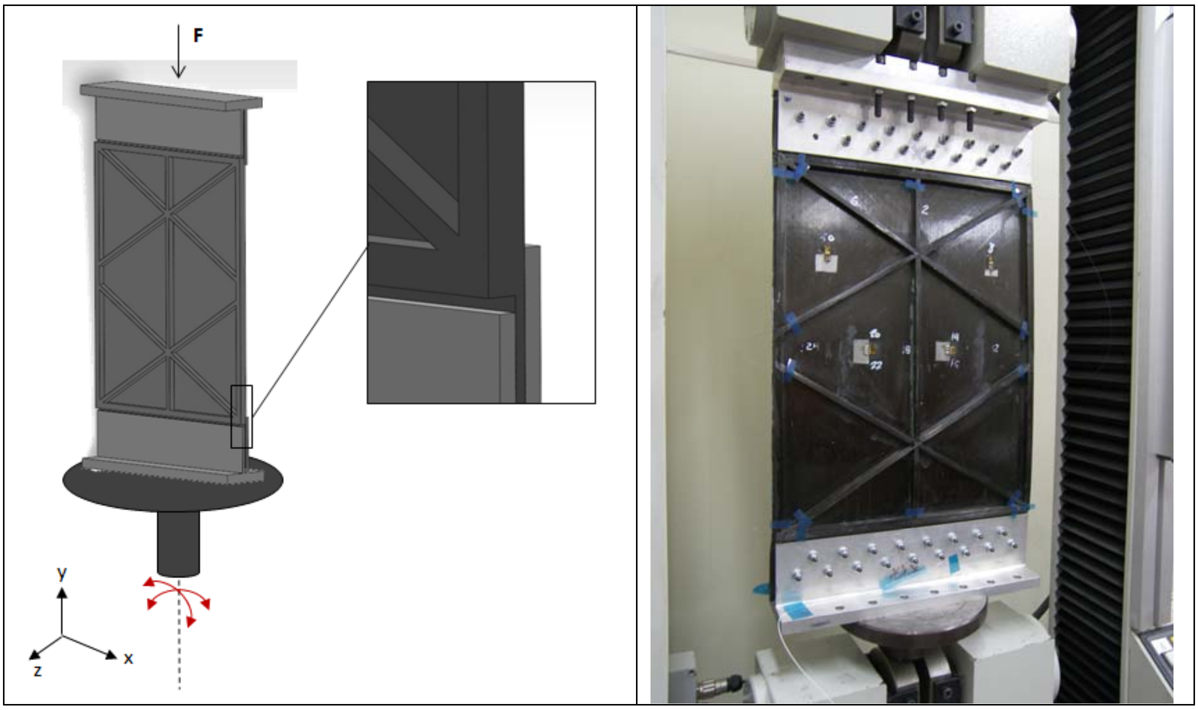

Figure 5. Isogrid structure prepared for compression test

4.1 Strain measurement setup

A single mode optical fiber was bonded on the flat surface of the specimen with a crooked configuration that cover the full area in the direction of load introduction. Close to the edges, each fiber line has a separation of 20 mm to the others, and in the center this distance is the half (10 mm).

5 Experimental results, compared to non-linear FEM analysis

It was soon realized that a non linear FEM model was required due to the large geometrical displacements caused by the misalignments of loads and constraints. At figure 6 numerical and experimental results are compared, and it is clearly shown how non-liberalities influence the results. The experimental measurements are also included, with a reasonable agreement.
At figure 7 results are also presented for another sections of the structure, showing the complexity of the response, and the good resolution and usefulness of the strain measurement system.

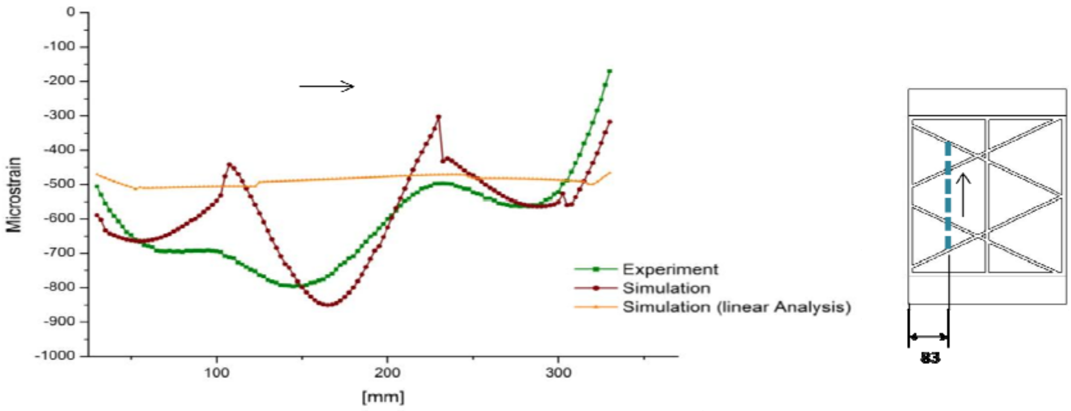

Figure 6. Isogrid structure under compression test (20 kN), left side

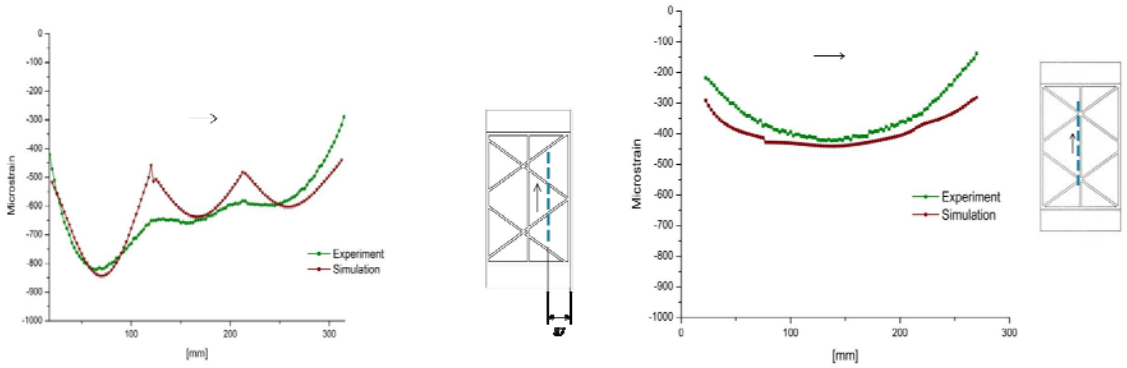

Figure 7. Isogrid structure under compression test (20 kN), middle and right side

Conclusions

With the fibre distributed sensing technique strains were obtained along vertical lines on the back of the panel. By interpolating between those lines it is possible to create a full representation of the strain distribution over the surface of the structure. It can be said that the analysis results from the finite element model and the strain data measured by the experiments are largely consistent. It can be seen that the regions between the stiffeners experience stronger deformation and non-linear behaviour.

Onset of buckling can be predicted by the FEM, and is detected by the distributed sensing, as a intense local waviness in the strain field with increasing loads.

Using OBR distributed sensing technology is possible to detect the regions which show non-linear behaviour and buckling with a high areal accuracy. Strain special resolution allows perceiving even the reinforcement effect of the stiffeners.

Local non-linear behavior of the skin between the stiffeners was identified in these experiments. The fibre distributed sensing technique can be utilised for an easy and descriptive comparison of simulation and experimental strain results over large linear, but also two-dimensional surfaces. Experimental results obtained with fiber distributed sensing makes it possible to create a strain map over the full surface of the structure's skin.

Acknowledgements

This work was partially supported under a grant of the Spanish Ministry of Science and Technology, grant number DPI2011-28033-C03-03

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