Health Monitoring of a Weight Efficient Lattice Spacecraft Structural Element with FBGS Sensors

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ABSTRACT

A weight efficient lattice cylinder of high modulus carbon fiber has been manufactured by EADS CASA Espacio using a new cost efficient fiber placement layering technology and curing process. The open iso-grid structure is formed of composite lattice bars of unidirectional fiber direction where the half of these bars have been instrumented with fibre Bragg grating sensors, FBGSs. These sensors measured the structural strain and the integrity of the structure during static tests conducted until rupture.

The sensitivity to detect the fracture of the bars "far" from the FBGSs have been evaluated during the tests of the structure and with a dedicated test campaign of smaller iso-grid elements. The results showed that damages in the same lattice bar and adjacent bars but several grids far from the sensors could be detected. Structural FE models were prepared and used to compare the test results with the corresponding load cases and with the damage detection sensitivity.

INTRODUCTION

Launcher structural elements need to be very efficient in weight to increment the payload by minimizing the structural weight. An open iso-grid structure, better known for the name of "lattice structure", made of composite material has been demonstrated to be a promising weight efficient structural concept, [1].

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An integrated health monitoring system could supervise the loads of such a structure and flag possible damages during the testing and instrumentation campaign and could give important information of the structural integrity during the launch phases. In [5] Takeda et al describes tests on an isogrid-skin structure where embedded FBGSs were used successfully for damage detection. An open iso-grid lattice structure could also be used for reusable launchers where the implementation of structural health management approaches will be required to asses the structural health for each turn around. Different iso-grid structures have been manufactured before by EADS-CASA Espacio in automatic tape laying process and have been instrumented with embedded FBGSs and compression tested at RT and 200ºC in earlier test campaigns, [2, 3]. In these cases the grid-structure had the function of stiffeners of a skin where they where bonded to.

In the case of the presented paper the lattice structure is open and has no skin where it is bonded to. This kind of structure has an inherent high mechanical efficiency. It can carry higher loads as grid stiffened skin structures because it gets rid of the quite weak grid/ skin interface where the load introduction from skin to grid is only performed by the foot section of the grid. The before mentioned test campaign [2] showed that grid stiffened skins tend to fail locally in this interface. Tests performed on smaller test elements confirmed this result [3]. The open lattice structure avoids this problem because the load is only carried by the bars and seems to be a very promising economical structural element for future launcher structures.

Two different techniques for damage detection have been studied in the lattice structure; one is based on the principle that damage in a bar of a grid or in a nod produces an instantaneous redistribution of the loads in the structure. If sensors are near enough to the damage, an instantaneous jump in the measured strains can be detected that is an indicator for the produced damage. The other technique is based on the principle that the strain distribution changes after damage had occurred and the strain in bars that are broken differ from the strain of adjacent bars that are not broken. The degree of this change is also an indicator for the damage.

These two techniques have been studied in compression tests of a cylindrical lattice structure that has been tested until rupture. Both techniques have been able to detect that damage had occurred and could identify damaged zones in load tests performed after the rupture of the structure. The results have been verified later on using three segments cut from the damaged cylinder, repairing the damaged grids and repeating the compression load tests with well defined introduced damages. The damages were introduced by cutting individual bars of the grids whilst load was applied simulating real damage scenarios. After these tests, the cuts have been repaired and a rupture test has been performed where damage occurred in a normal way in bars and nods that were undamaged before this final test. The obtained results verified the results from the tests on the entire cylinder structure and showed a good agreement with finite element models made of the entire structure and the individual segments.

SPECIMEN

The tested element is a lattice structure of 1095 mm in height and 800 mm in diameter. The structure has been manufactured by automatic tape laying process using high modulus fiber and out of autoclave curable resin system. The cylinder has been screwed to massive aluminum inserts to guaranty a good load introduction in the compression tests. The cylinder has been instrumented with a net of 36 Fiber Bragg grating sensors, FBGSs, surface bonded around the perimeter in the upper half of the cylinder to the inner side of the cylinder on each bar of a grid in clockwise direction. The FBGSs are Ormocer coated high strength sensors manufactured in the draw tower process form FBGS Technologies company, [6, 7]. The excellent performance of these sensors has been studied before in static and fatigue tests in a wide temperature range from -100ºC to 160ºC, [7]. The bonding of the sensors has been made using a typical strain gage adhesive type X60 from HBM company. The sensors have been monitored at 5 Hz using the SI 405 lecture equipment from HBM company.

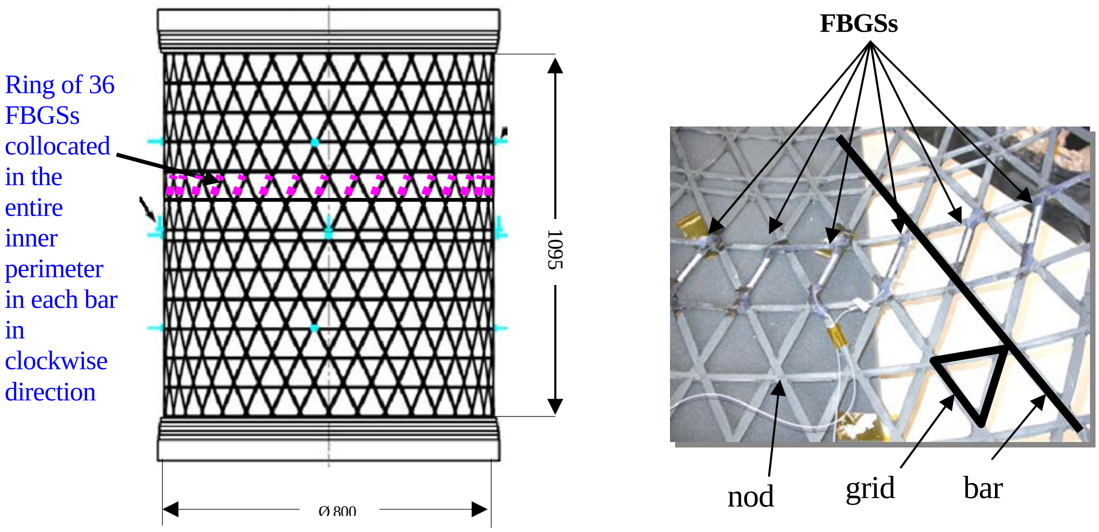

Figure 1. Left: Sketch of the cylindrical lattice structure. Right: Detail of the instrumented vertical bars in clockwise direction with bonded Ormocer coated high strength FBGSs

MECHANICAL TESTS ON THE LATTICE CYCLINDER

The lattice cylinder has been loaded continuously in compression. The strain was quite uniform in the all the grids where the 36 FBGSs measured, figure 2 up. The rupture of the cylinder was a catastrophic failure in the centre of the cylinder. Many bars and nods broke instantaneously in the centre region. The strain distributed instantaneously and the FBGSs showed a pronounced jump in their measured strain values. Whilst the load was still maintained, some FBGSs measured compression whilst other tensile strain because the broken bars were flexed in one or the other directions. After the load was released, a significant residual strain could be measured in many of the broken bars. After unloading, the structure has been loaded again with a small compression load of about 15% of the rupture load to determine the residual structural stiffness and to determine the redistribution of the load paths. The results show that there is a significant difference in the strain measured by the sensors integrated in the damaged grids and the ones that are on the undamaged ones. The undamaged grids deform corresponding to the applied load whilst the damaged ones show strange deformations, see figure 2 down. This behavior is a measure of the resulted damage. Comparing adjacent sensors, the damaged grids can be identified.

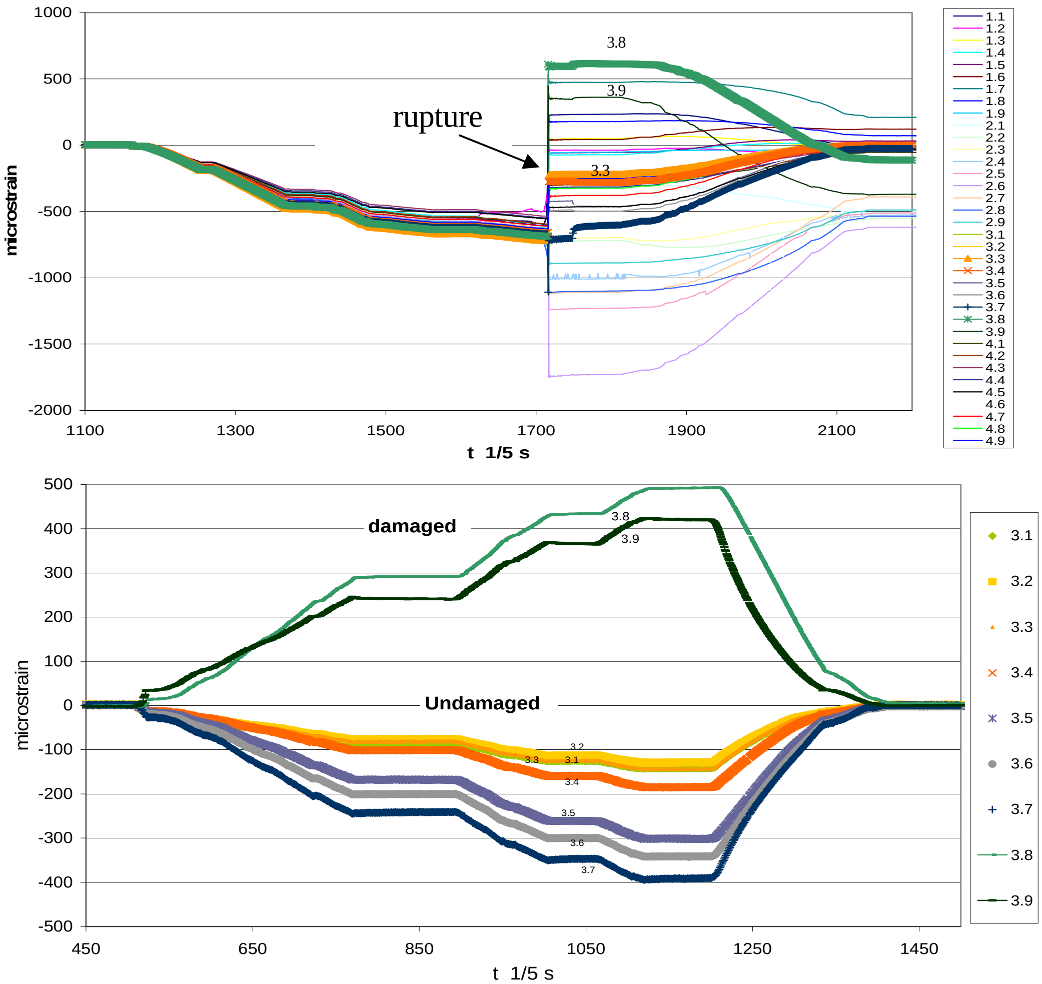

Figure 2. Up: Strain values of the compression until rupture tests of the 36 instrumented bars. The structure broke at -330 kN. Down: Loading of the structure after breakage. Two from the nine bars where the sensors are bonded to are broken and show a clear different behavior in the load tests.

MECHANICAL TESTS ON LATTICE STRUCTURE SECTORS

The lattice cylinder failed in catastrophic rupture and many bars and nods have been broken at the same time. The mayor parts of the ruptures have occurred very near to the bonded sensors and the ruptures of the structure have been detected very clear. The following tests are focused on to study how sensible the sensors are to detect damage far from the sensors and when only one bar breaks. To study this behavior three sectors of 45º to 60º of the cylinder perimeter have been cut from the damaged lattice structure and the broken or delaminated bars and nods have been repaired so that they are able to carry again load in the following tests. The sectors have been loaded in compression step loading until about 100 to 250 microstrain have been measured in the central monitored grids, figure 3 left. At maximum load, controlled damages have been introduced by cutting bars with a small radial disc cutter. The strain redistributed very fast into the adjacent grids when the grid was cut and a jump of the strain could be measured in the sensors corresponding to the bar that has been cut and also in the instrumented adjacent bars, figure 4.

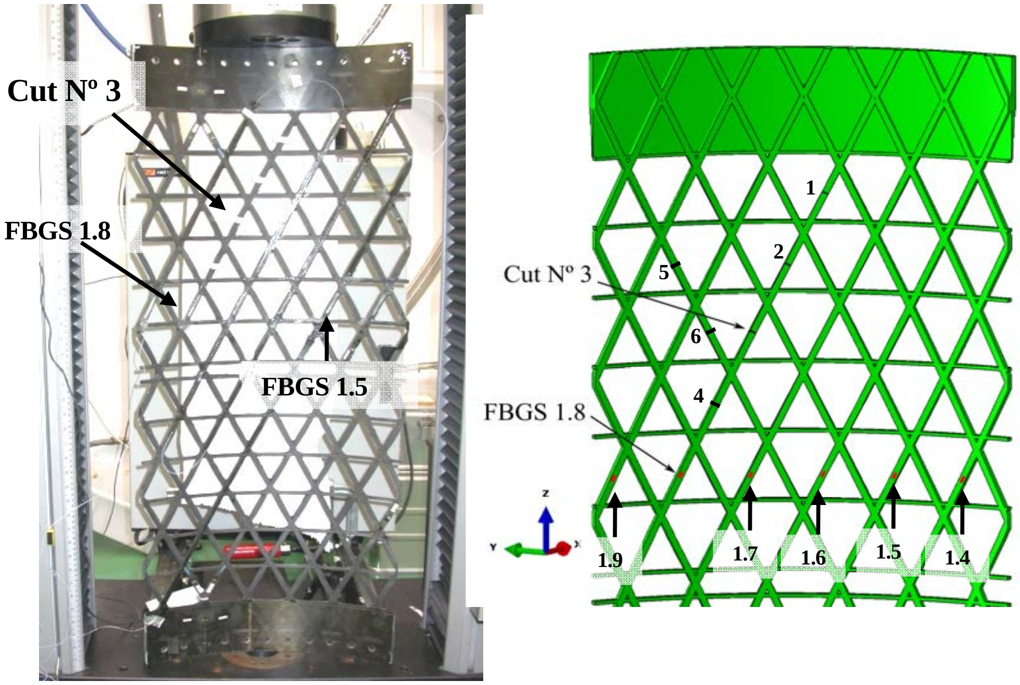

Figure 3. Left: Section (60º) of the lattice cylinder during compression test where bars have been cut consecutively in six positions at maximum test load of 7kN. Right: FEM of the sector showing the cuts and the sensor positions.

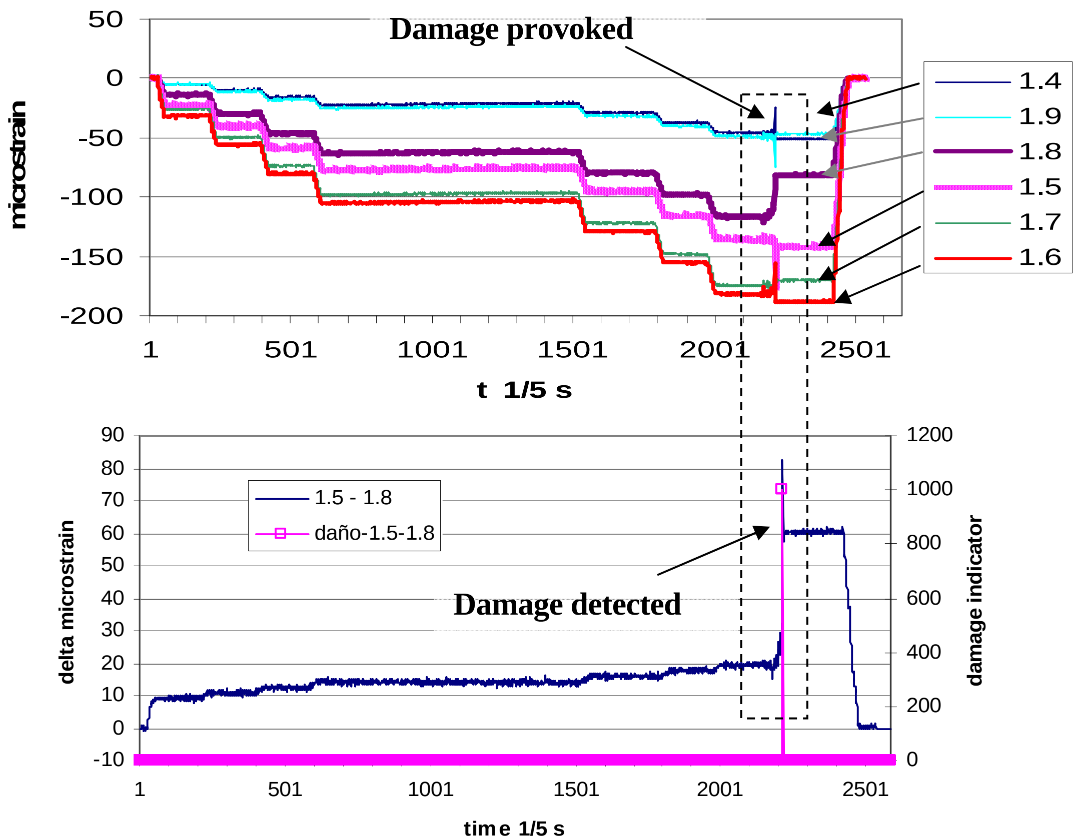

Figure 4. Test result of the cut Nº 3 two layers above sensor 1.8. UP: Strain measured in the six FBGS of the panel. Down: The diagram shows the strain difference between FBGS 1.8 and FBGS 1.5 and the moment when the damage have been detected.

To identify if a jump in the strain values is produced by damage or by a fast step load of the structure without damage, the results of all the sensors need to be compared. If a jump in the strain values is provoked by damage, sensors near to the damage show a more pronounced strain jump than sensors far from the damage. Applying this technique, the introduced damages have been detected in the tested sectors until four layers far from a sensor and this not only when the cut was in the same bar but even when it was in the adjacent bar. The strain jump between compared sensors at the maximum observable distance of four layers (about 330 mm) was 6 $\mu\varepsilon$ that was clearly above the noise threshold of the used equipment. The strain jump increases when the cut was nearer to the sensor being about 10$\mu\varepsilon$, 30$\mu\varepsilon$ and 50$\mu\varepsilon$, in the cut of the same bar of FBGS 1.8, three, two and one layer far from the sensor 1.8, respectively. Cuts in perpendicular bars were detectable two to three layers far from the sensor with a strain jump of about 10$\mu\varepsilon$ and 6$\mu\varepsilon$, respectively. Horizontal bars cut at 4 and 3 layers above the sensor show a strain jump of 6$\mu\varepsilon$ and 20$\mu\varepsilon$, respectively.

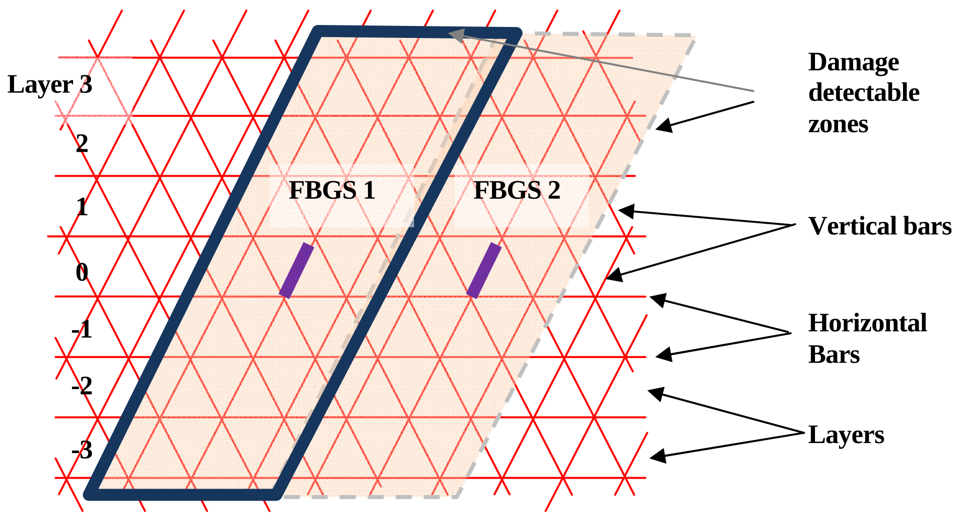

Figure 5. Detectable damage area for one FBGS collocated in the centre of the square. The strain values from FBGS 1 will be compared with a second FBGS collocated more far from the damage.

With the obtained results an area has been defined in which damage detection appears to be possible using a combination of two FBGS, figure 5. Damage detection of the entire cylindrical lattice structure seems to be possible with in total 18 FBGSs collocated in a distance of three horizontal layers and collocated in each second grid in one direction.

A finite element model has been programmed to verify the test data. The lattice cylinder and the lattice structure sectors have been modeled with ABAQUS solid elements *C3D8*, figure 3 right. The mechanical tests have been reproduced and the strain of the elements located at the FBGSs positions have been monitored in function of the load. The intact model has been submitted as a reference. In order to assess the strain redistribution, the model has been run introducing the cuts carried out in the mechanical tests. The obtained results are comparable with the theoretical ones and the principle behavior of the damaged panel is more or less matched by the FEM. The strain redistribution detected in the mechanical tests is also found in the FEM. Stiffness differences between both results could be explained by the simplifications applied in the rib intersections modeling.

CONCLUSIONS

It has been shown that a damage monitoring of a lattice structure with an integrated FBGSs network is possible. It is not necessary that the FBGSs are embedded in the structure, but it would be a next step to embed them during the automated manufacturing process to get more reliable long time sensors results and a better sensors protection. The damage detection is based on the technique to monitor strain jumps provoked by the rupture of individual bars under load and the consequent load distribution and change of the load path. The monitoring technique has been used in the compression tests of a 1,1 m high and 0,8 m in diameter lattice cylinder and has been verified in tests of sectors cut from the original cylinder. The FBGSs are able to detect bar breakages that are quite far from the sensor. It seems to be possible to monitor the entire tested lattice cylinder with a sensor network of about 18 FBGSs distributed in the structure. The sensor position should be optimized using a FEM that showed to be a good tool for the analysis of these structures. Tests under dynamic load should follow to determine the robustness of the technique when mechanical noise is high.

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