REPAIR PROCEDURE ON VEGA SRM SKIRT

G. Giusto[1,4], F. De Nicola[1] , F. Di Caprio[1] U. Mercurio[1], A. Zallo[2], V. Vinti[2], A. Cutolo[3], M. Fraldi[3]

[1] CIRA (Italian Aerospace Research Centre) Via Maiorise, 81043 Capua (CE), Italy
Email: g.giusto@cira.it, Web Page: http://www.cira.it
[2] Avio s.p.a, Via Ariana Km 5.2 - 00034 Colleferro (Rome), Italy
Email: antonio.zallo@avio.com, Web Page: http://www.avio.com/it/
[3] University of Naple Federico II, Via Claudio, 21, 80125 Napoli, Italy
Email: fraldi@unina.it, Web Page: http://www.dist.unina.it/
[4] IMAST Distretto Tecnologico sull'Ingegneria dei Polimeri e Materiali Compositi e Strutture,
P.zza Bovio 22, 80133 Napoli, Italy

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Abstract
The aim of the present work is to present a repair procedure for composite skirt of VEGA Solid Rocket Motors (SRM), validated on scaled cylinder representative of the Skirt of the P80-SRM.
The developed repair procedure foresees the evaluation of the impact damage by means of numerical simulation, to estimate the structural behaviour at different impact energy levels. The aim of these numerical simulations is to identify the energy threshold, which guarantees the reparability requirements. The repair scheme includes the definition of geometric parameters, of the materials and stacking sequence.
Starting from the global-local FE approach, the repair scheme was implemented on a refined 3D local FEM that also included the modelling of adhesive between the skirt and the repair patch.
The numerical analysis procedure and the patch design was validated by experimental compression test on two scaled cylinders (reference and repaired). The work shows also the repair manufacturing process. The repair patch was realized with prepreg made with a new resin formulation developed to be cured at 80°C and to be compatible with the original prepreg.
The developed activities allowed verifying the feasibility and efficacy of the overall repair procedures, including new formulated resin and numerical design methods.

1 Introduction

This work was performed in the frame of the projects "Processi Ausiliari: le giunzioni adesive e il repairing – PRADE, PON02_00029_3205863" granted to IMAST S.c.a.r.l. and funded by MIUR.
The VEGA Launch vehicle has performed up today 6 flawless missions: qualification maiden flight on February 13th 2012, first commercial flight on May 8th 2013.
The motor case is, at the same time, the combustion chamber of the SRM and the structure subjected to the mechanical loads of the launcher. Lightweight composite structures are necessary in order to obtain the optimized mass ratio (MR) requested for the stage, so due to the high pressure reached in the combustion chamber, material with high ultimate stress are needed.
Further important characteristics required for the case is the stiffness in order to contain the induced stress on the propellant. For such reasons, material with high E/ρ and σ/ρ are used in the solid rocket case design.
VEGA LV is currently equipped with 3 SRMs and the biggest one is currently the P80, which is shown in picture below.

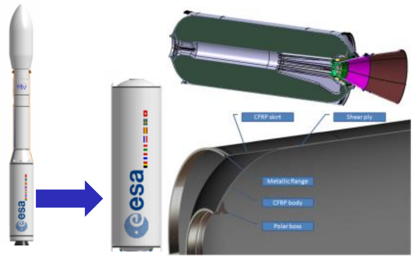

Figure 1: SRM case architecture.

The SRM composite structural Case can be schematized as a cylindrical pressure vessel with ending domes which mainly sustains the internal pressure, due to propellant combustion, and two cylindrical Skirts, connecting the SRM to the adjacent stages, which have to sustain quite high compressive loading due to Launch Vehicle maneuver, external aerodynamic and SRM thrust.
In case of impact damage during manufacturing and handling phase, the more critical area is represented by the skirt location: the cylindrical part can be repaired by simply resuming the strength in hoop direction by replacing 90° damaged plies, but in the skirt area the load is mainly transmitted in longitudinal compression and then it is necessary to design an adequate patch to fully recover the strength in 0° direction.

2 Definition of damage scenario and repair scheme

2.1 Damage scenario

The requirements to define an effective repairing prescribe that the occurred damages do not involve more than 1/3 of the total thickness. Several numerical analysis were performed to define an impact energy threshold, which guarantees the reparability of the SRM P80. Considering the real dimensions of the P80, it was possible to neglect the curvature and to perform the damage investigation considering only flat panel both of real and scaled thickness. The real number of plies of the P80's stacking sequence is greater than 50, while the plies number related to the scaled test cases was 24. The reduced plies number was considered also to produce the representative cylinder of the SRM P80 Skirt.
Explicit numerical analysis were performed with Ls-Dyna code in order to estimate the energy threshold of an impact event. Figure 2 shows the relation between the impact energy relative to the scaled panel and the full-scale panel, the damaged area on the scaled panel and the damage depth on the full-scale panel in function of impact energy level. The analyzed impact energy level ranges from 5J to 150J on scaled model, corresponding to 14J and 414J on full-scale model, respectively.
It is possible to note that the energy threshold is 25J (69J), since over this value, the damage depth is greater than 1/3 of the total thickness.

Impact Energy on P80 Skirt	
Scaled Model [J]	*Full Scale [J]*
5.0	13.79
10.0	27.57
15.0	41.36
20.0	55.14
25.0	68.93
30.0	82.71
50.0	137.86
100.0	275.71
150.0	413.57

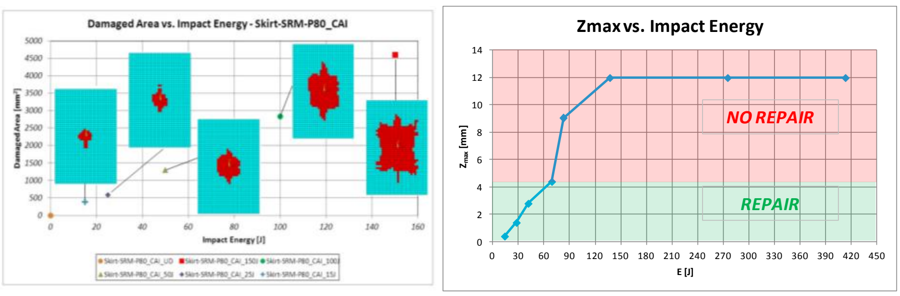

Figure 2. Relation between scaled and full-scale impact energy. Damaged Area on scaled thickness flat panel. Damage depth on full thickness flat panel.

2.2 Definition of a repair scheme

Stepped repair was selected since guarantees the best performances and small complexity.
The most important parameter at this phase is the overlap length between the damaged and repair layer: adequate load transfer shall occur, in shear mode, at the interface between the damaged 0° and the 0° repair layers. Such length has to be as small as possible in order to limit repair dimensions but long enough to produce acceptable shear stress peaks.
The patch design proposed for the repair of the P80 Skirt is shown in Figure 3.

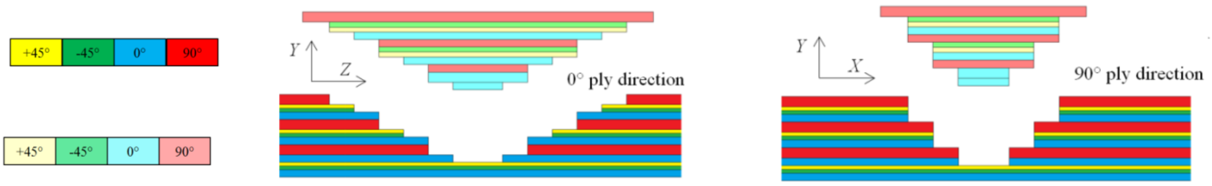

Figure 3. P80 Skirt repair schema

The repair scheme was implemented on the P80 finite element model (Figure 5), developed in MSC Marc and validated in VEGA program, to verify interfaces shear stress and lamina stresses distribution. A Global local approach was:

1. A global FE model validated in the frame of VEGA program is used to determine global stress distribution in SRM skirt location; modelling details are reported in [3].
2. A local FEM simulating the patch geometry is implemented to get detailed stress distribution in any ply of the patch (see Figure 4). The local was a layer-wise model where each single layer was discretized through eight nodes brick elements; Global model shell displacements and rotations are reported to 3D section by means of RBE2. In such model in order to limit the number of the degree of freedom, the length L (see Figure 5) had been set to 5mm; such value should be extended to 20mm in real application.

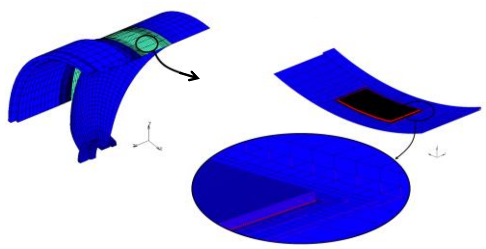

Figure 4. Global-Local models used for the numerical analysis

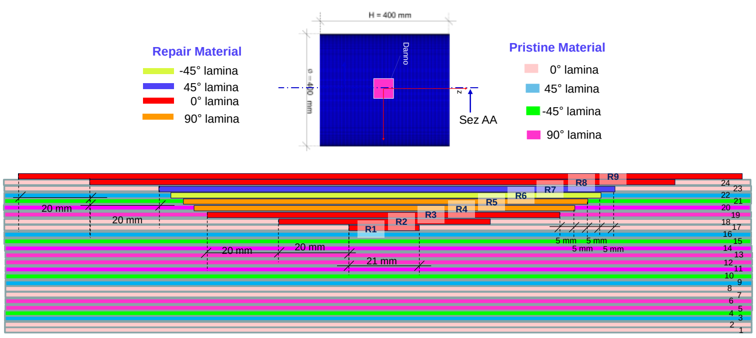

Figure 5. Repair scheme

Due to the buckling-like deformation of the skirt under external loading, the maximum compression stress, due to bending, arises in the outer 0° ply. Results are reported in Figure 6.

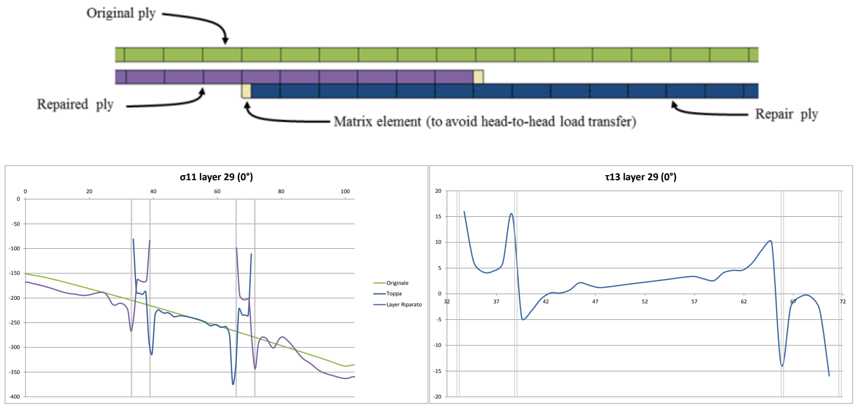

Figure 6. Fiber load and interface shear stress distribution for the most critical layer in the P80 SRM repaired skirt

Simulation shear stress distributions results are in good agreement with the analytical prediction, in terms of peaks values: positive Margin of safety, in terms of interlaminar stress and lamina stress, are guaranteed. Repair fibers also tend to be loaded like the corresponding original ones; peak values arise at the overlap ends. In conclusion, the numerical evaluation has shown that the repair patch is reliable.

3 Manufacturing of test articles

In order to validate the repair procedures implemented, two identical scaled cylinders were manufactured. The items represent the skirt of the P80 SRM and have a diameter of 400mm.
The first item represents the "reference undamaged Scaled Skirt" and the second one was damaged with an artificial damage by machining a 20x20mm hollow square with depth of 1/3 of the thickness, according to the simulation activities.
The layup was designed to reproduce the same P80 skirt lamination sequence but the overall number of plies was limited to 24 $[0_2;\pm45;90_2]_{2s}$.
The material was fully characterized but data cannot be published; in any case, the repair resin demonstrated to be fully compatible with original pre-preg since both interlaminar shear strength and adhesion between original and repaired layers were not affected by knock down factors.

3.1 Manufacturing of reference Undamaged Cylinder and Cylinder to be repaired

The two Cylinders were manufactured using Filament Winding process for the plies 90° (hoop) and hand layup for the plies 0° (Figure 7 A) and ±45° .
The cylinders were realized with the same high strength carbon fiber epoxy pre-preg tape currently used on the two P80 skirt.
The tool for the realization of cylinders was a metallic mandrel. The scaled cylinder was laminated on porous peel ply (Release Ease 234 TFP-HP, Airtech) in order to ensure the extraction from the mandrel after the cure.
The cure of the item was carried out in autoclave without added pressure. To compensate for the absence of pressure during the cure cycle, the two external layers in Kevlar were applied as hoop layers. Of Course, in order to separate the Kevlar form the CRFP item, the pourose peel ply and release film were applied (Figure 7 B, C).

After the cure, the cylinders was trimmed and prepared for the mechanical test (for the reference undamaged cylinder) and for repairing procedures (for cylinder to be repaired) (Figure 7 D).

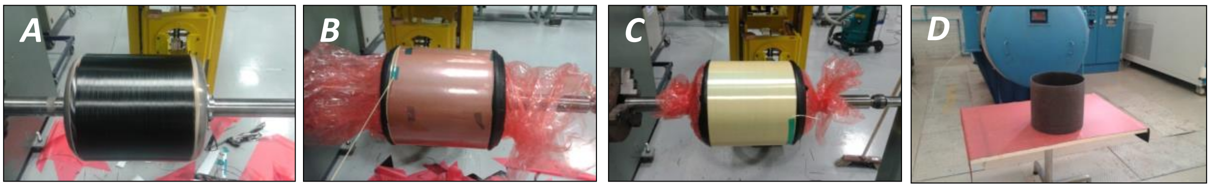

Figure 7. Filament winding of the hoop layers (A), Release film (B) and Kevlar winding (C), Undamaged Cylinder (D)

3.2 Repairing of the scaled Skirt

According to the implemented repair scheme, the following steps were carried out:

- Scarfing on damaged zone of the Scaled Cylinder
- Developing of repairing prepreg Tape made with a new epoxy resin formulation
- Hand layup of repairing patches
- Bagging and curing

As far as the scarfing, it was performed using a pneumatic cutter applied to the Filament Winding machine, in order to work with only four degrees of freedom, including the rotation of the mandrel.
The implemented repair patch schema foresees the removal of the damaged plies, layer by layer.
Removing a single layer was a challenge aspect, because it needs a very high accuracy of the “z axis” machine and high geometric precision of the item. Figure 8 shows the imperfection of the scarf due to reason said previously. In this case, the scarf was hand-optimized.

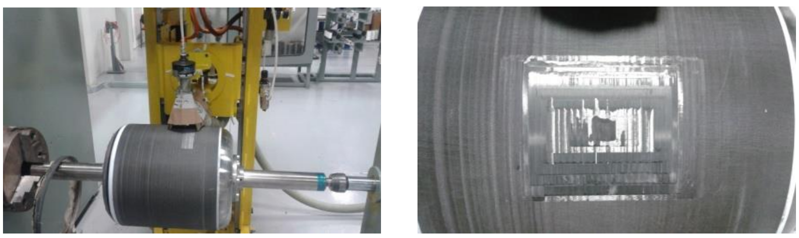

Figure 8. Stepped scarfing phase

Regarding the novel repairing tape prepreg, a new epoxy resin was optimized in order to match the SRM case repair requirements, in terms of process parameters and mechanical properties both neat resin and tape prepreg made with the same high strength dry fiber used for the P80 skirt. The formulation of new epoxy system are not presented in this paper.
The novel Tape prepreg was used to laminate the repairing patches by hand layup process. On the scarfed surface of the cylinder, an adhesive film (3M scotch weld, TMaf163/2) was applied, with the aim to ensure the adhesion between the repairing patch and the scarf on the cylinder. Then the plies of novel tape prepreg were cut and applied according to designed dimensions and orientations (Figure 9 A, B).
The vacuum bag was applied directly on the surface of the Cylinder (Figure 9 C). The cure cycle was optimized for the resin developed in the project. Figure 9 D shows the final repaired cylinder after the cure and trimming processes.

After the cure, the repaired cylinders were prepared for the mechanical test (potting) to be compared with the reference undamaged cylinder.

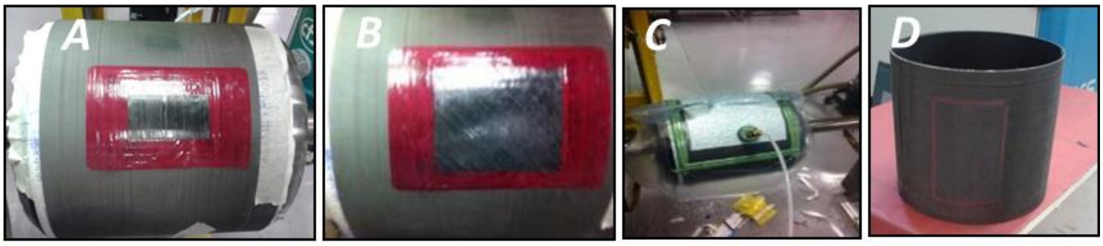

Figure 9. Hand lay-up of the repairing patch, vacuum bag and repaired scaled cylinder Skirt

4 Numerical results

A FE model was developed to predict the collapse compressive loads for undamaged and damaged cylinder.
The undamaged cylinder is modelled with shell elements and the stacking sequence is correctly addressed by the specific property card.
The cylinder was constrained in both displacements and rotation in both edges except for longitudinal displacements. Longitudinal compressive flux is applied to upper edge.
The stress component σ_{11} (fiber direction) is plotted in the internal and more external 0° cylinder laminas and reported in Figure 10**.**
The external compressive load at collapse is expected to be at least 2124 kN in case of defects absence, but the material used for the manufacturing, showed a lower compression strength [2]. Using updated allowables, based upon new experimental data performed on same batch material used to realize the scaled skirt, the expected collapse load was evaluated equal to 1140 kN.

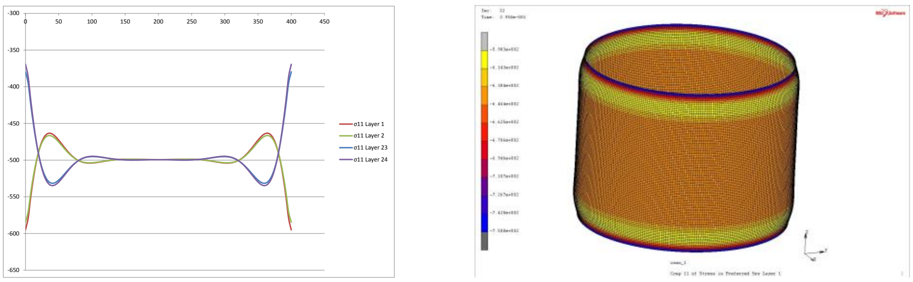

Figure 10. σ_{11} in inner and outer 0° ply and failure elements at 1140 kN

A FE model to simulate the repair was implemented applying a global local methodology as described previously.
In such case, any layer in the stacking sequence was modelled with brick element.
The repair scheme was designed in order to get the collapse of the structure at a value at least equal to the value determined for the undamaged structure.
The aim of the analysis was, also, to demonstrate that the interlaminar shear strength between damaged and repair plies is not exceed.
Figure 11 shows the σ_{11} stress distribution in the repair layers at 0°: R2, R3, R8 and R9. The maximum stress is always below allowable value.
In Figure 12 the stress level in the original 0° layers is reported; the allowable compressive strength was not exceeded in any location.

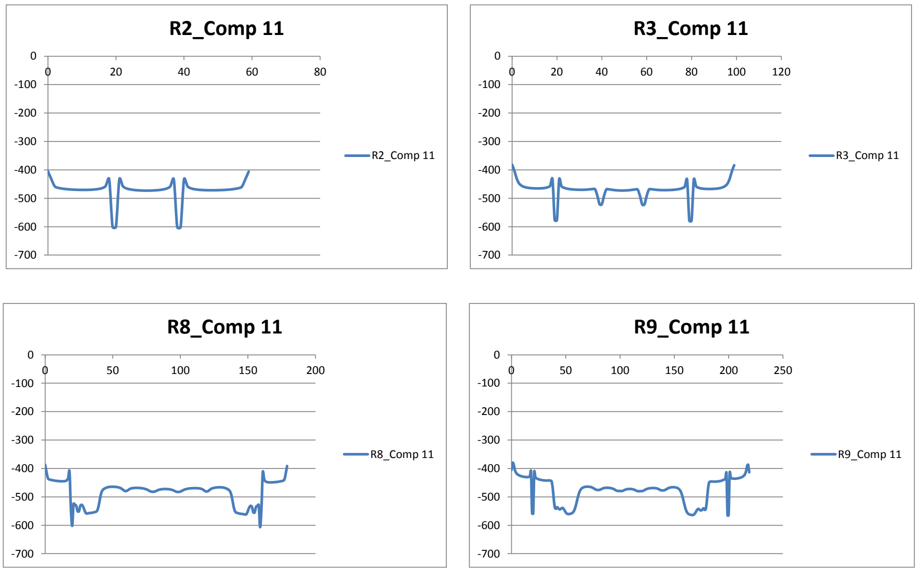

Figure 11. σ_{11} stress [MPa] in 0° Repair laminas

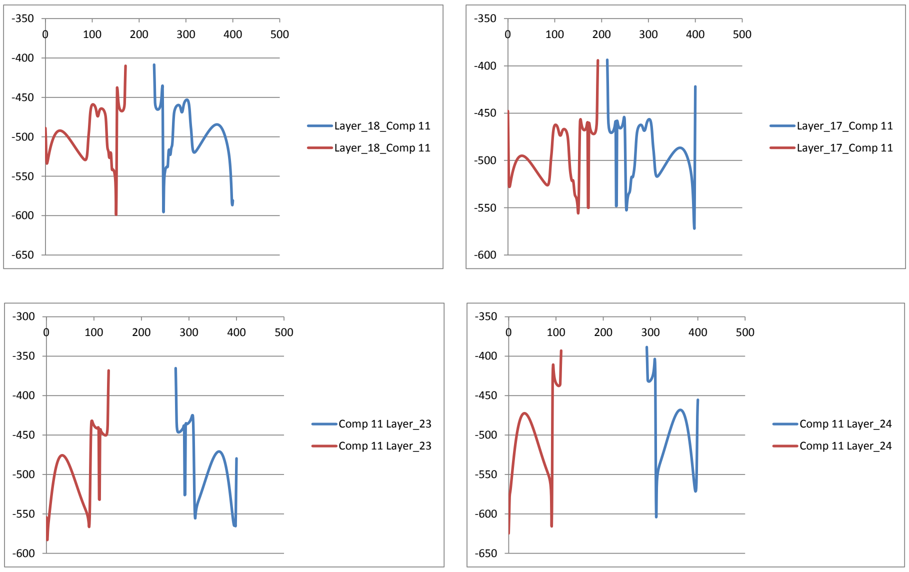

Figure 12. σ_{11} stress [MPa] in 0° original plies

5 Experimental-numerical correlation

Both undamaged and repaired cylinders were tested under compressive load up to total failure by means of servoidraulic machine ITALSIGMA with a capability of 3000kN in compression, and a maximum crosshead displacement equal to 75 mm.
The displacement/deformation field of the test cases were monitored by means of:

- Six LVDT (3 fixed on the rigid plates used to introduce the load, and 3 on the external layer of the cylinder **(**Figure 13 b, c)
- Six strain gauges (4 in axial direction, spaced of 45° each other; and 2 in tangential direction, stepped of 180° each other) (Figure 13, a).

For the repaired cylinder, both the two strain gauges (axial and tangential) and a LVDT were placed in the patch zone.

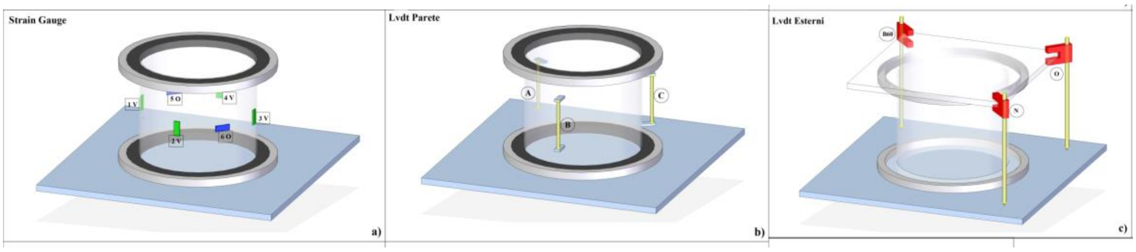

Figure 13. Strain gauges and LVDT locations

After a preload phase, performed to stabilize the structure and to check the right link of all strain gauges and LVDT, the test was executed up to collapse load.
Figure 14 shows the load vs. applied strain curve for undamaged and repaired structure. The maximum load reached for the undamaged cylinder was 914 kN, while the maximum load reached for the repaired test case was 1144 kN. The premature failure of the undamaged cylinder could be addressed to a not perfect parallelism of the two ends. In fact, after the failure, the damages were not equally distributed around the potting zone. Instead, the repaired cylinder ends were perfectly flatness and parallel. The experimental failure load is in excellent agreement with the estimated failure load.

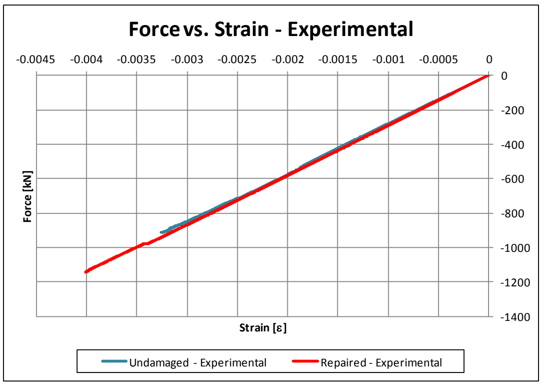

Figure 14. experimental compression test: load vs. applied strain curve

Figure 15 and Figure 16 show both cylinders before and after test, respectively. It is possible to note that both test articles failed at the same way. The inner and outer lamina, close to the potting zone, collapsed probably due to delamination and successive buckling induced by the high stresses in the constrained zone. After their failure, the remaining layers cannot support the load and so the entire structure collapsed. The repaired zone did not show any failure.

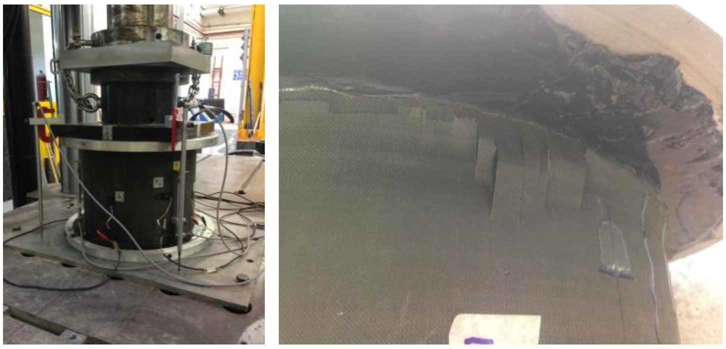

Figure 15. Compression Test of undamaged cylinder (reference)

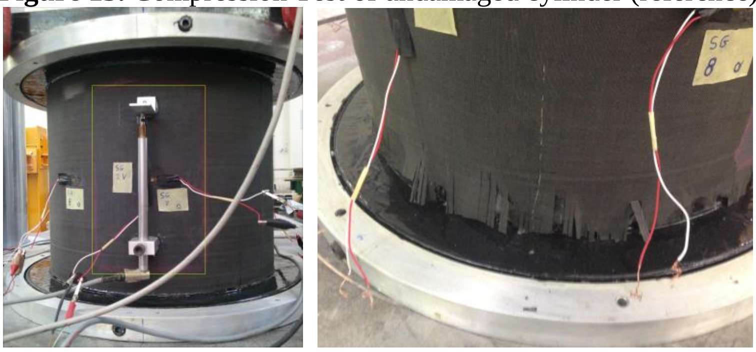

Figure 16. Compression Test of repaired cylinder

Figure 17 shows the comparison between numerical and experimental results both for undamaged and repaired cylinder.

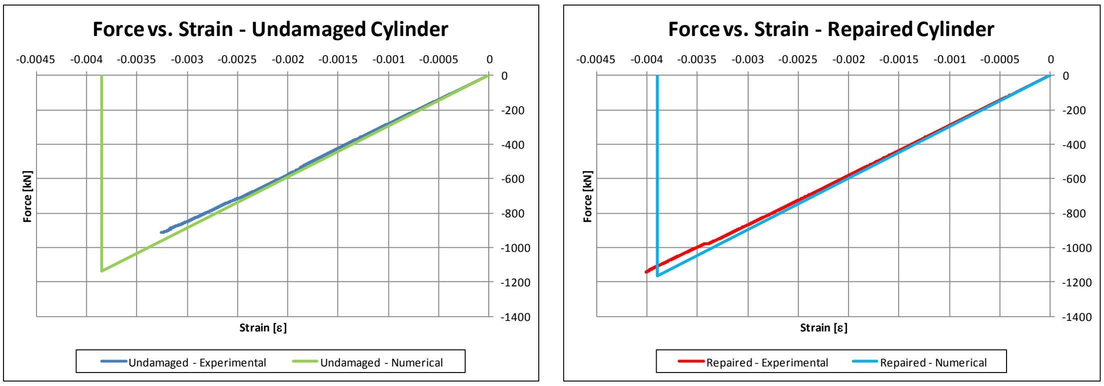

Figure 17. Comparison between numerical and experimental results

The difference between numerical and experimental results are neglictable for the repaired case, while are about 24% for undamaged case. However, this is not reliable; certainly, the experimental result is smaller than the numerical for the reason explained previously. More investigation will be performed using further experimental tests.

6 Conclusion

In the present work was presented a procedure to design and realize a bonded patch in order to repair damaged composite structure. The test articles consist in a cylinder representative of SRM P80 of VEGA launcher. The numerical investigation about the damage scenario induced by impact event was performed on coupons with real thickness, and on scaled thickness. The repairing, the experimental tests and the final numerical-experimental correlation was performed on the scaled model. The obtained results demonstrate that the repair procedure (design and manufacturing) is very reliable. The failure load related to the repaired cylinder is in excellent agreement with the estimate load, and with the numerical results. Therefore, the whole procedure, starting from the numerical sizing to the manufacturing process, is very robust. Due to some troubles related to undamaged experimental test, the failure load was quite less than the estimated load, for this reason in the next future new experimental tests will be performed to verify the capability of the undamaged cylinder.

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