PRIMARY PRINCIPAL COMPOSITE STRUCTURE REPAIR WITH MULTI-INSTRUMENTED TECHNOLOGICAL EVALUATOR TOOL BOX

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Abstract

This paper introduces a methodology to solve opened issues associated to “on field” large repair of primary principal structures for composites. If a repair is mandatory, it leads to a costly immobilization. Structural damage needs a “case by case” solution including design, calculation phases, damaged zone removal, patch construction, set-up and finishing. Furthermore composite solution needs to be considered with its real “industrial” variabilities and with a continuous link between all scales (from micro scale to structure scale). To address such challenges, Multi-Instrumented Technological Evaluators (MITEs) Toolbox is developed in order to restitute the representative working conditions of repair areas in industrial structures. Thanks to multi-axial modular test device, multi-axial loadings are chosen for placing the repair zone under a chosen representative strain fields. Results are discussed through comparison between experimental data and FE models results for several Multi-Instrumented Technological Evaluator types.

1 Introduction

1.1 Challenges about “on field” large repair of composite primary principal structures

“On field” large repair of composite primary principal structure is a very strategic issue for aeronautics. Obviously whatever the material (metallic or composite), Standard Repair Manual (SRM) does not cover large repairs. As far as composite solution is concerned, fuselage and wing cannot be dismantled (if any, anyway not in accordance with schedule for airline companies). Structural damage needs a “case by case” solution including design, calculation phases, damaged zone removal, patch construction, set-up and finishing. Everything needs to be controlled and approved by certification authorities. Large repair involves large complex patch including thickness variations, stiffeners and/or frames’ parts, opening frames. Obviously, the development and production of unitary complex primary structure as quick as possible is a great challenge!

Composite solution needs to be considered with its real “industrial” variabilities and with a continuous link between all scales (from micro scale to structure scale). A definition of the state of the fields is mandatory for “on field” large repairs of composite primary principal structures.

1.2 State of the fields: from a "black metal approach" to a "global vision" GOALS

The standard solutions for repair are based on "metallic" approaches. They lead to the use of doublers and a lot of rivets for linking repair patch and safe structure. For each rivet, a very precise hole performed "on field" is mandatory. Apart from weight rising, the consequence is a significant increase of time, risks then costs. Such standard approach can be used for composite but "safe/damaged" boundary is more difficult to identify. The patch manufacturing is touchiest and risks are higher during patch assembly. Process is longer and more costly than for metallic aircraft. For composite wing, it will be very extremely complex to certify. The standard approach has a lot of disadvantages and is not capable to take profit from composite possibilities and a global approach. As regards airworthiness requirements, it is crucial *to set up the right approach at the right level*.

The right approach means to be operational and to be certified. We have to promote a new methodology and to solve at the same time scientific issues, technological "bottle necks", economical strategic deals. The requirements are to be worldwide accepted by companies and certified by airworthiness authorities which are the Federal American Agency (FAA) and the European Aviation Safety Agency (EASA) as well. For some items of this global process (material removal, contaminant detection, bonding, NDT...), the Technology Readiness Levels (TRLs) are low (2 to 3). The standardization of key principles concerns TRLs lower than 2. Furthermore, it is impossible to ignore Original Equipment Manufacturers' competition (OEM) but *all of them* are interested having certified solutions to all generic main challenges.

The right level concerns the scientific, economic and technologic fields. Clément Ader Institute Laboratory (ICA) and Composites Expertise & Solutions Company (CES) worked on this Goal with some partners since 10 years. Many other scientific and industrial teams were involved on specific items since many tens of years. But today *there is no optimized composite solution*. It is mandatory to federate at the worldwide level: energies, knowledge, resources (manpower, funds, devices...) if we want to succeed. A new global certified method is required. It needs to be as standard as possible taking profit from a full bonded optimized interface. This is our unified thread [1].

Today as Boeing and Lockheed Martin, EADS Innovation Works Germany develops a continuous process chain for a fast, automatable and reproducible repair of CFRP and GFRP structures [2] for addressing applications as fuselages, rotor blades, wing… but they come across the same problems. As far as a Global Approach is concerned, our contribution is defined as GOALS proposal which means ***G****lobal pr****O****cess for in situ, full bonded, l****A****rge repair on principa****L*** *composite and multi material* ***S****tructures*. A synopsis of is shown Fig. 1.

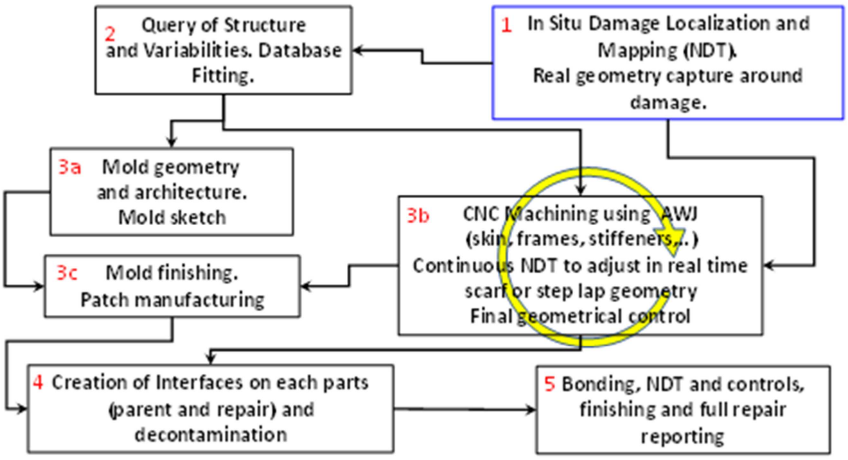


Figure 1. Different main steps illustrating the synopsis of our global approach called GOALS for "on field" large repairs of composite primary principal structures.

To address such challenges, Multi-Instrumented Technological Evaluators (MITE) Toolbox is developed in order to restitute the representative working conditions of repair areas in industrial structures.

2 Description of the MITE tool box

Thanks to a partnership begun in 2002 between ICA and CES, an original concept is proposed, called MITE tool box for Multi-Instrumented Technological Evaluator tool box. It leads to a test/calculation dialogue adapted to the particular case of composite structures from the design of composite structural parts. In fact, it deals with a set of complementary tools and methodologies. It involves three parts of equivalent importance: experimental, numerical and structural. The objective of this toolbox is to - numerically and with experimental tests - assess the response of a reduced size specimen under complex loading but containing the scales representative of the industrial structure. The MITE specimen is case by case created to put in situation issues introduced by a design singularity within a structure, more economic than the real industrial part. So it allows a statistical study opening the way to the variability consideration inherent to the material or to the process. The experimental part of MITE tool box is an original experimental set-up. It consists in a modular multi-axial testing machine described in Fig. 2 and Fig. 3.

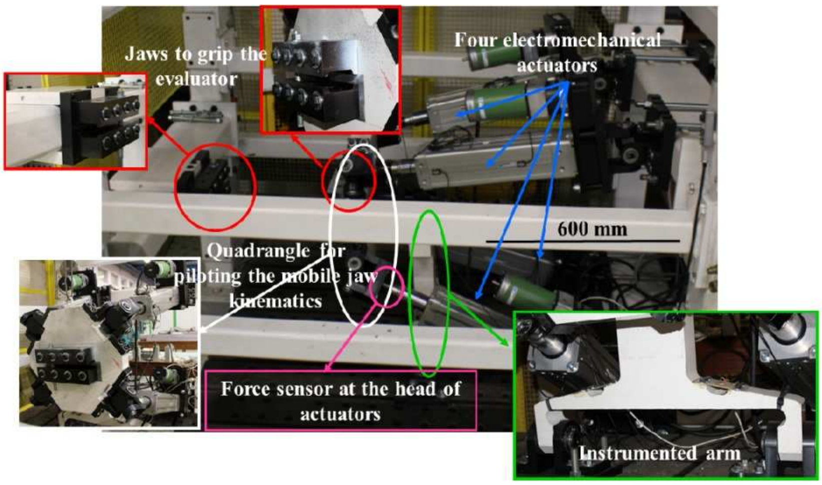
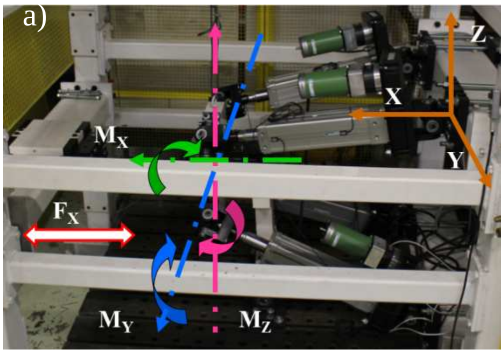


Figure 2. Experimental part of the MITE Tool box with different zooms of the modular multi axis testing machine with 4 electromechanical actuators.

The modular multi-axial testing machine is composed by 4 electromechanical actuators articulated at their attachment to a frame on one side. In their other extremity, the actuators are attached to a steel rectangle. Combined kinematics and associated loadings are given in Fig. 3 and applied to MITE specimen.



b)

Possible combined kinematics and associated loadings for the current geometry
Traction / compression along X axis with F_{max} = 140 kN, stroke Δ_{max} = ± 100 mm.
Bending along Z axis with M_{max} = 40 kN.m, α_{max} = ± 20°.
Torsion along X axis with M_{max} = 8 kN.m, α_{max} = ± 15°.
Bending along Y axis with M_{max} = 30 kN.m, α_{max} = ± 20°.

Figure 3. Modular multi axis set-up with a) possible kinematics/loadings and b) associated maximum values.

The numerical part MITE tool box concerns multi-scale FE models (cf. Fig. 4). The objective is to address fields similar - but not necessary identical - to those whom the composite material will see in the industrial structure. The identification of the kinematics to be applied (cf. Fig. 3) is carried out by means of simple FE models for a chosen damage in nature and localization as well (cf. Fig. 4). The test is thus realized with chosen in advance conditions and for wished modes of rupture (cf. Fig. 5), here in the center of the MITE [3].

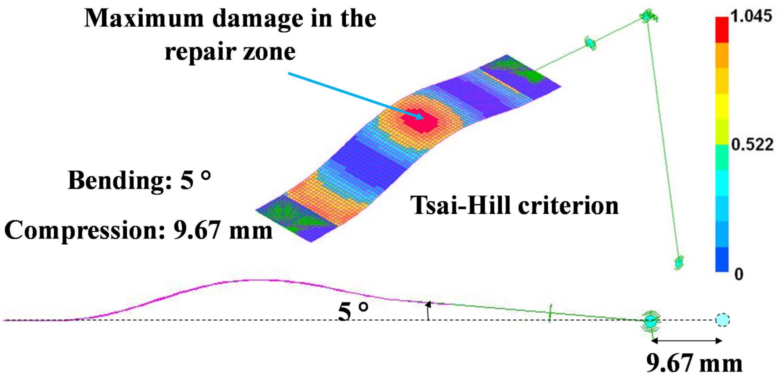


Figure 4. Numerical part of MITE tool box with simple FE models **(**thin composite shell F.E.) to identify a loading path (here [3] for a compression/bending combination) in accordance with expected damage at a chosen location (in the center of the MITE).

The structural part of MITE tool box is a technological evaluator equipped by a set of sensors allowing multi-scale instrumentation (cf. Fig. 5).

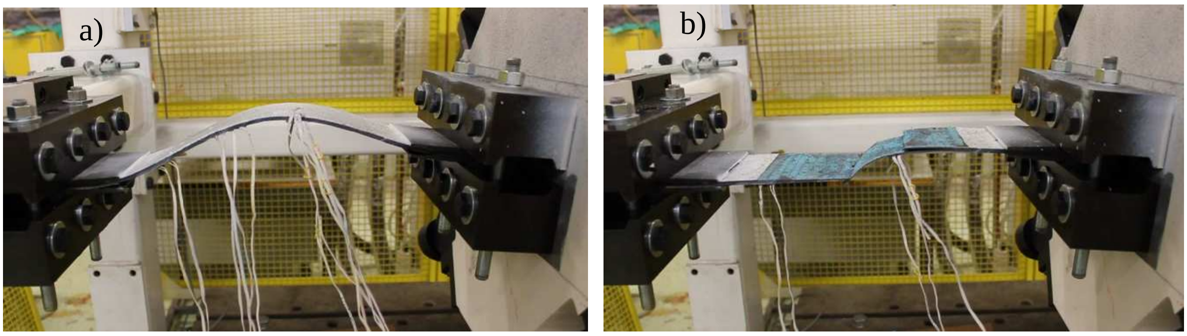


Figure 5. Structural part of the MITE tool box with a technological evaluator [3] equipped by a set of sensors allowing multi-scale instrumentation with a) during the test and b) after rupture.

In Fig. 5, the loading path chosen is a coupling between bending and compression in the repair zone (cf. Fig 4). The initial critical damage appears at the same location both in the safe and repaired zone of the repair MITE far from the jaws. For more details, the reader can refer to the paper [3]. The final goal is to validate the capacity of the numerical models to describe the involved phenomena and the possible couplings.

3 First added value of the MITE tool box

Placing the composite material in the representative working conditions is one of the main objectives of the MITE tool box to take profit from a composite solution. In this way, using simple loading paths with the classical experimental test device leads to handle unexpected situations. In Fig. 6, it is obvious that, for the tested repair MITE of [3], simple loading paths impose stress concentration the repair MITE's boundaries of but not in the zone of interest which is the location of the patch repair.

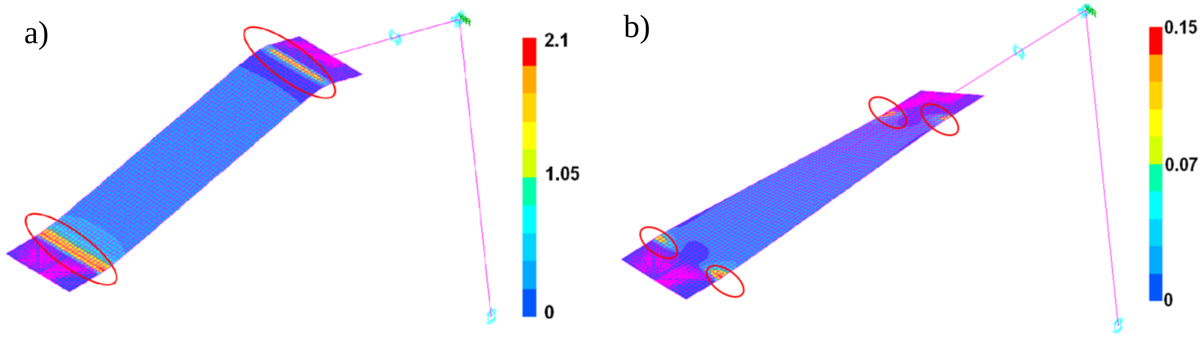


Figure 6. F.E. modeling of elementary tests leading to damage localization (Tsai-Hill criterion map) close to the MITE's jaws [3] with a) bending along Y axis (α = 5°) and b) torsion along X axis (α = 15°).

4 Example of the MITE box relevance for repair

4.1 Definition and FE modeling of repair technological evaluators with more singularities

MITE is a specimen which is the receptacle of different issues and singularities met in an industrial structure (as fuselage or wing) as variation of thickness, drop off area, zone of stiffener stop …

We propose such MITE specimen (more advanced that the one of [3]) as illustrated Fig. 7 made in HexPly® UD M21 T700GC.

There are a drop off of 12 plies between a thick zone of 30 plies and a thin zone of 18 plies (cf. Fig 7.b). The respected stacking sequences are mentioned in Fig. 7.b.

A stiffener is bonded with an adhesive film on the center of the MITE. Fig 7.c shows a cross section of the stiffener for the definition of the dimensions and the stacking sequences respectively the top, the bottom flange and the web.

We have chosen a zone of interest having to repair which is the stop stiffener area (cf. Fig. 7.a).

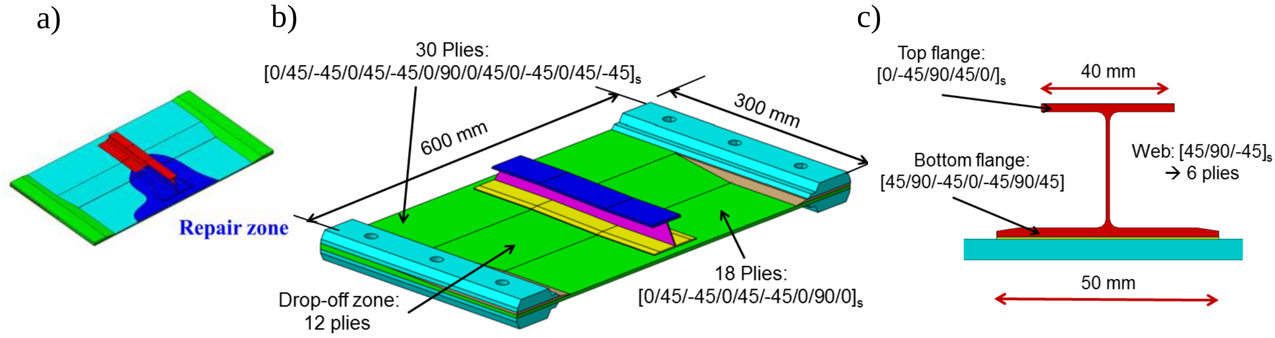


Figure 7. Advanced repair MITE with a) zone of interest (repair zone), b) plane dimensions and stacking sequences and c) cross section for the stiffener definition.

For identifying the loading path capable to submit a critical strain field to the zone of interest, FE Modeling is developed (cf. Fig. 8a) to restitute the degrees of freedom applied by the modular multi-axis test device (cf. Fig. 8c). The numerical modeling consists in composite shell elements with Mindlin hypothesis involving 16200 quadrangular elements of T29 type in Samcef® code (in respect the ratio length/width < 4) and 1488 cohesive elements to simulate strength of adhesive between flange and plate (with an adhesive film of 0.15 mm thick).

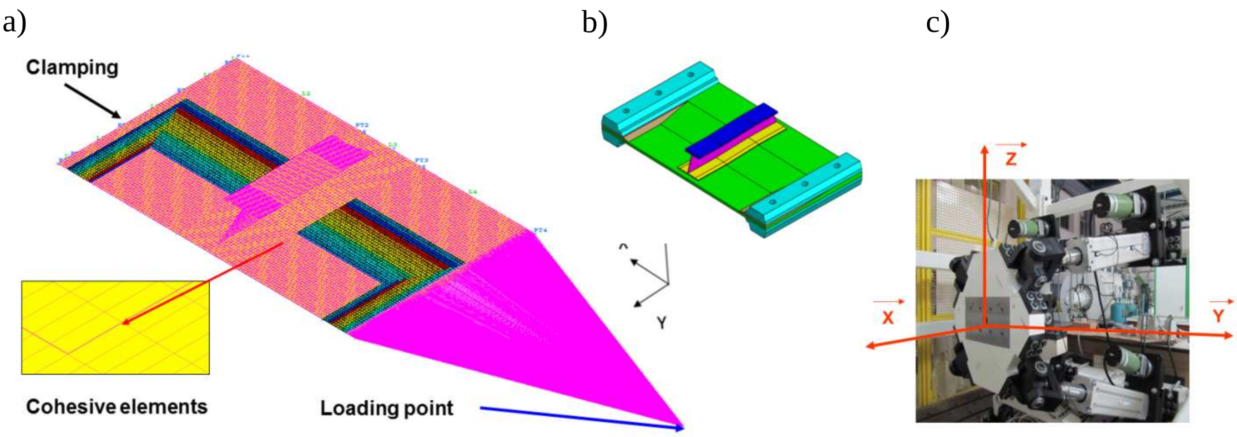


Figure 8. Advanced repair MITE with a) 2D FE modeling, b) CAD view and c) the mobile steel rectangle of the modular multi axis test machine modeled thanks to rigid beams linked to a loading point.

4.2 Identification of the loading path for submitting the repair zone to a critical state

Thanks to an optimization loop tool including in the MITE tool box the multi-axial loading identified is a combination of a bending along - Y axis (with 2.6° angle) with a torsion along - X axis (with 9.8° angle) and a compression along + X axis (with 4.3 mm translation). Fig. 9 represents Tsai Wu criterion in 45° upper ply of the bottom flange of the stiffener (cf. Fig. 9.a), debonding between stiffener and plate (cf. Fig. 9.b), Tsai Wu criterion in 0° upper ply of the plate (cf. Fig. 9.c) and in 0° lower ply of the plate (cf. Fig. 9.d). It is the proof that only the zone of interest will be submitted to a critical state thanks to such multi axial loading. It is noticed that the 0° lower ply of the plate has no risk to be damaged before the occurrence of damage in the zone of interest.

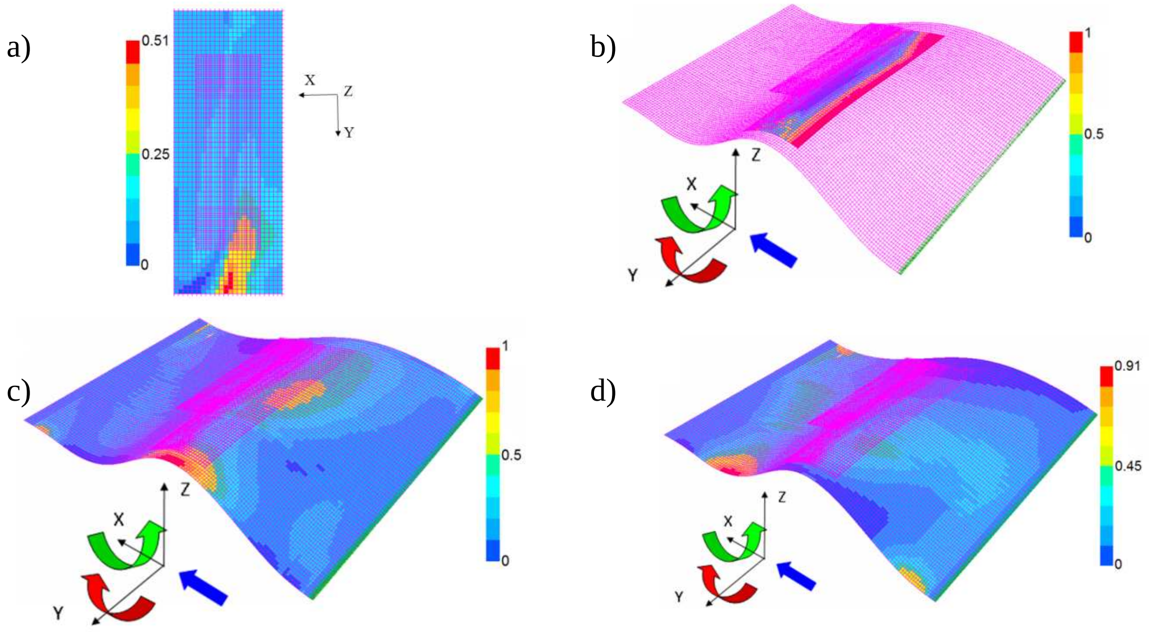


Figure 9. Final state of the MITE under a combination of bending with 2.6° angle along - Y axis, torsion with 9.8° angle along - X axis and compression with 4.3 mm translation along + X axis with a) Tsai Wu criterion in 45° upper ply of the bottom flange of the stiffener, b) debonding between stiffener and plate, c) Tsai Wu criterion in 0° upper ply of the plate and d) Tsai Wu criterion in 0° lower ply of the plate.

The loading path is optimized thanks to the multi axis modular set-up capability to verify if a critical state will never reached in any place of the repair MITE during the test. If the multi axial loading is applied with a sequential manner, it leads to issues illustrated Fig. 10. Two zones are checked respectively, zone #1 for the zone of interest and zone # 2 close to the boundaries of the repair MITE. The “a”, “b” and “c” letters are used to point out that the same final state is addressed whatever the studied loading path (Fig 10.d and Fig. 11.d). It is shown that zone #2 could be damaged with a sequential loading, after the 1st phase with bending along Y axis (cf. Fig. 10.a). Furthermore the compressive force along X axis could be higher than 50 kN which is important for the actuators (cf. Fig. 10.d).

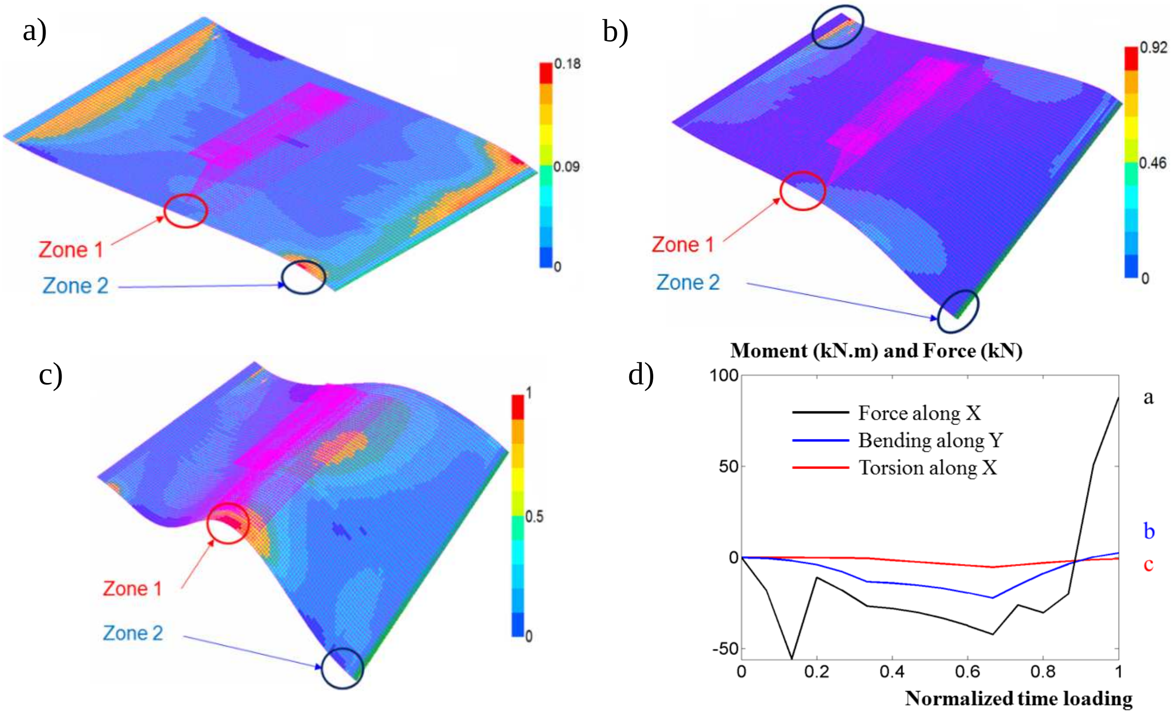


Figure 10. Sequential loading and Tsai Criterion in 0° upper ply of the plate respectively for a) the 1st phase with bending along Y axis, b) the 2nd phase with torsion along X axis, c) the 3rd phase with compression along X axis and d) evolution of each loading path.

Fig. 11 exhibits the results got from an optimized multi axial loading path which is simultaneous application of bending (with 2.6° angle along - Y axis), torsion (with 9.8° angle along - X axis) and compression (with 4.3 mm translation along + X axis).

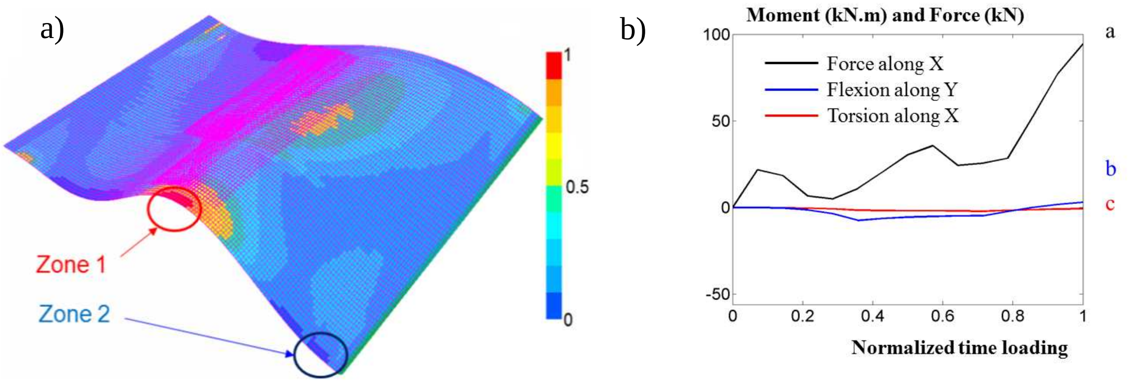


Figure 11. Optimized loading (simultaneous) with a) Tsai Criterion in 0° upper ply of the plate and b) evolution of each component of the optimized loading path.

Only the zone # 1 is submitted to a critical state (cf. Fig. 11.a) and the evolution each component of the loading path is better under controlled along the test than the sequential one (cf. Fig. 11.b), addressing the final state (marked by the “a”, “b” and “c” letters).
As far as the experimental part of the MITE tool box is concerned, the evolution of Tsai criterion in 0° upper ply of the plate along the test in the two studied zones (# 1 and # 2) is underlined the interest of the optimization of the loading (cf. Fig. 12). Fig. 12.a exhibits an overstress in zone # 2 (close to the boundaries of the repair MITE) while it is under controlled thanks to the optimized loading path (cf. Fig. 12.b).

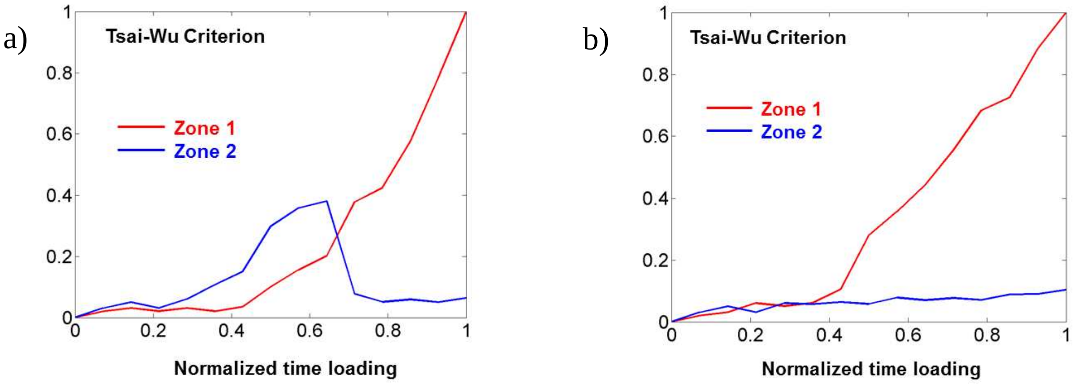


Figure 12. Evolution of Tsai Criterion with a) for the sequential loading and b) for the optimized loading.

5 Conclusions

Thanks to Multi-Instrumented Technological Evaluators Toolbox, it is possible to restitute representative working conditions of repaired area in industrial structures. This allows developing more efficient composite solutions in taking into consideration its real “industrial” variabilities and to set a continuous numerical link between all scales (from micro scale to structure scale) without using artifice like numerical zooms. Through this approach, issues are addressed coming from primary principal composite structure on the very strategic subject of “on field” large repair of primary principal structures for composites (as fuselage or wing) and this method could be the focus point of the GOALS program.

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