Studies on Shape Optimization of Repair Patches for Damaged Composites

STUDIES ON SHAPE OPTIMIZATION OF REPAIR PATCHES FOR DAMAGED COMPOSITES

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Abstract. *Due to the increasing development of health monitoring and damage detection techniques, the assessment of damage presence and its shape is a viable option to continuously evaluate the structural integrity of composite components. Along with such tool, one could employ repair patch techniques in order to restore, or locally improve, the originally designed strength of a damaged composite component. This approach would imply in the use of a composite repair patch capable of increasing the stiffness of a damaged component with minimal material addition, resulting in the minimization of costs with component replacements and extend the structures life. In this context, the present work exposes initial studies concerning simple repair shapes optimization applied to damaged composite materials. The main objective of this research is to propose an optimization procedure capable of specifying suitable patch shapes to be applied in a pre-assessed damaged area of a laminated component. The optimization formulation was defined considering as objective function the minimization of the error with respect to the structure first natural frequencies. Linear programming along with an interior point algorithm was employed in order to obtain an optimized repair patch shape. The analyzed model was a rectangular multilayered plate with a predefined damaged zone. Epoxi-carbon composite with transversely isotropic material behavior was considered for all components. A shell finite elements model was used to solve the associated modal problem.*

Keywords: *Repair patch, Laminate, Shape optimization, Modal analysis*

1 INTRODUCTION

The early applications of composite materials in military aircrafts lies in the 1960s, being extended to civil aircrafts during the following decade. After this point, more than two decades were needed to the civil aircraft manufactures starting to employ composites in significant levels. However, it was only after the '90s that the full potential of advanced composed materials began to be exploited by aerospace industry (Tsai, 2005). During this decade, carbon-reinforced polymer composites gained appliance in aircraft design for primary and secondary structural applications (Baker, 1999). In recent years, the increasing in the use of advanced composites for replacing traditional materials made it possible to accomplish remarkable achievements such as the groundbreaking design of aircrafts as the Boeing 787 (more than 50% of advanced composites in total weight), Airbus A350 and Bombardier CSeries (Katnam et al., 2013).

The tremendous increase in the use of composites experienced by the aviation industry, however, brought more challenges to light. The major advantages of the advanced composites relies on the high strength/mass ratio, superior resistance against corrosion and enhanced fatigue life (Jones, 1998; Baker et al., 2004; Barbero, 2010). However, when compared to metallic materials, the mechanical behavior and failure modes of composites are still not fully comprehended (Kumar & Hakeem, 2000). This is certainly an issue to be addressed in order to exploit the full potential of such materials. Consequently, inherent to the susceptibility to damage is the need to repair composite structures (Katnam et al., 2013).

Concerns relating the fast expansion in the use of advanced composites and the capability of the aerospace industry to deal with the demand for technology that supports this growth at healthy levels have been presented by the US Government Accountability Office (GAO, 2011). As showed by Davis (1995), the safety of composite aircraft will largely depend on, both, structural repair and maintenance. The increase in the structural applications for advanced composites unleashed an enormous demand for effective manufacturing processes and damage detection techniques. Without the complete fulfilling of this demands, an increase of manufacturing defects and, consequently, structural maintenance issues may arise. To circumvent such issues, the development of advanced repair techniques is needed (Katnam et al., 2013).

The pioneer works (Baker, 1978, 1984) developed in the Australian Research Laboratories (ARL) for Royal Australian Airforce (RAAF) were successful in employing composite repair patches to restore the mechanical strength of damaged aircraft elements. Nevertheless, those works (Baker et al., 1984; Baker & Jones, 1988) only covered metallic cracked components. The use of fiber reinforced repair patches applied to damaged composite structures is still very limited, by both aviation rules and certification, and technology development. Usually, only conventional rectangular geometries with predefined fiber orientation and stacking sequences are considered. In this context, the present work is aims to propose an optimization approach for repair patch shapes of damaged composite structures.

2 REPAIR OF DAMAGED COMPOSITE COMPONENTS

Structural repair of composite components aims to restore a damaged structure to its original condition (operational and structural). In order to achieve this status, the strength and stiffness of the damaged composite structure needs to be recovered to a condition as close as possible to its undamaged state (Baker & Jones, 1988), which is very challenging. Due to the widespread use of composites in aerospace industry and the importance of aircraft safety, the Maintenance, Repair and Overhaul (MRO) market is facing a fast increase in demand for repair techniques of secondary and primary structures and engine components (GAO, 2011). Moreover, the research area of composites repair is being leveraged by the development of modern health monitoring techniques, which are crucial for reliable assessment and further repair of damage.

2.1 Damage Detection

Due to the increasing development of health monitoring and damage detection techniques, the assessment of damage presence and its shape is a viable option to continuously evaluate the structural integrity of composite components. The detection of degradation along the operational lifetime of structures subjected to dynamic loads is highly desirable in order to minimize costs with component replacements and extend the structures life (Kashfuddoja & Ramji, 2013).

The practical application of non-destructive inspection methods for in-service investigation of composite components for structures such as aircrafts fuselage/wing and wind turbine blades is not a trivial task. However, recent and suitable non-destructive techniques of health monitoring and damage detection may allow the assessment of extent, location and degradation level of damage in composite components (Caminero et al., 2013). Such information is crucial in order to evaluate if a structural repair is a feasible solution, as replacing the entire component is not always cost-effective. Moreover, as the reduction in material strength depends on the type and size of damage, its accurate detection and quantification are essential for efficient structural maintenance and repair strategies.

2.2 Repair Techniques

Various traditional approache, such as mechanically fastened, injection, doubler, scarf based repairs, adhesive patches, among others, may be employed to repair damaged composite structures (Baker & Jones, 1988; Baker, 1999). However, these approaches are applied, mostly, to secondary components (Baker et al., 2015). Among those techniques, fiber-reinforced adhesive patches is, undoubtedly, the most promising and efficient one (Kumar & Hakeem, 2000). Nonetheless, the current state of art for adhesive composite repair patches is far away from optimal. One most present some drawbacks: non-aerodynamic rough surface; excessive mass gain; inducing of stress concentration (Cantwell & Morton, 1992; Rachid et al., 2012). Moreover, in the sense of fiber-reinforced adhesive patches, there is no consensus in the literature in terms of the most efficient repair patch parameters such as: shape, thickness, stacking sequence and fiber orientation.

Studies concerning the applicability of composite repair patches to damaged aircraft components took place in the ARL since the decade of 1970s (Baker, 1978). However it was only in the early 2000's that the repair patch techniques have been wielded aiming to achieve an optimization based patch. Along the last years, different approaches intended to propose the geometry patch capable to reduce the Stress Intensity Factor (SIF) at the tip of cracked metallic plates. In the great majority of the works presented in the literature, it is suggested the use of patch shapes capable to distribute a larger amount of material on the surroundings of the crack tip. Some of those works suggest the use of repairs with: skewed patch shape (Kumar & Hakeem, 2000); modified skewed patch shape obtained by optimization with genetic algorithms

(Brighenti et al., 2006); trapezoidal shape (Bouiadjra et al., 2011); arrow head or H-shaped patch (Rachid et al., 2012); bow tie patch shape (Bouchiba & Serier, 2016).

Despite the amount of repair patch shapes proposed in the literature, defining the best repair shape for restoring a specific damaged area in composite materials is still not trivial. The best repair patch needs to achieve the requirement of restoring a damaged component to its original designed stiffness state. However this must not be achieved by means of adding an excessive amount of mass, i.e., resulting in larger inertia, to the repaired component. Nevertheless, the repair patch shapes proposed in the literature are defined, in the great majority of the cases, aiming to reduce the SIF solely, which may not be the best strategy to approach such problem. One must note that there is no guarantee that the patch shape that minimizes the SIF of a damaged component will not significantly modify the structures stiffness.

A viable option to define an efficient repair patch shape is to evaluate the minimal patch area capable to increase the stiffness of a damaged component towards its original, undamaged, value. This situation may be treated as a modal analysis problem, where the modal response of the repaired component must be as similar as possible to the one from the undamaged structure. This is the intent of the present work.

3 PROBLEM DEFINITION AND OPTIMIZATION FORMULATION

Considering a scenario where one is capable of identifying the existence of a damage zone in a composite structure and able to evaluate the size and shape of the affected area, an optimization problem may be formulated to define the best repairing approach. In the present work, the geometry of study intends to reproduce the scenario of a composite panel employed in structures such as: aircrafts fuselage; wing skin; wind turbines blades; among others. The borders of this panels are commonly attached to its neighbors, which leads to the case of a fully clamped component. Therefore, the geometry of study was considered as a flat rectangular plate with dimensions $l \times l/2$. The plate consists in a three layered laminate with stacking sequence $[0, -45, 90]^{\circ}$. The lamina thickness, t_i, was considered as 1 mm. A centered rectangular damaged area was modeled with sizes $d/4 \times d$. The component is fully clamped at all four sides, as presented in Fig. 1.

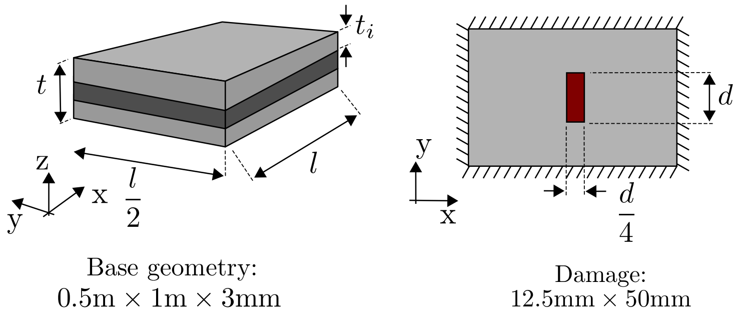


Figure 1: Geometry of study.

Four different, simple, geometries were tested as repair patch candidates, namely circular, square, elliptical and rectangular. The repair patch is modeled with a thickness, t_p, equal to 0.5mm. For all purposes, the repair patch was considered as a single lamina with predefined fiber orientation, ϕ, equal to $[0]^{\circ}$. Both repair patch and composite panel are considered as a Carbon Fiber Reinforced Polymer (CFRP) with transversely isotropic material behavior as presented in Tab. 1.

Table 1: Laminate mechanical properties.

CFRP (transversally isotropic).			
Young modulus	E_{xx}	147	GPa
	E_{yy}	9,8	GPa
Shear modulus	G_{xy}	2,35	GPa
	G_{yz}	3,3	GPa
Poisson ratio	ν_{xy}	0,405	
	ν_{yz}	0,4848	
Density	ρ	158	kg/m^3

The adhesive layer was taken as a perfect thin bonding lamina with negligible thickness and fully load-carrying. The epoxy-nitrile FM73M adhesive was considered with isotropic material behavior: Young modulus, E_{adh}, equal to 2,158 GPa; Poisson ratio, ν_{adh}, 0,35; and density, ρ_{adh}, of 1588 kg/m^3. The damaged area was modeled as a local strength loss. Its mechanical properties were considered as equal to the ones presented in Tab. 1 multiplied by a factor of 1×10^{-5}. This was applied to elasticity and shear modulus only, which implies in a strength loss of five orders of magnitude.

The optimization problem was formulated as the minimization of the error with respect to the repaired structures modal response compared to the undamaged one. This objective function is presented as

$$Error_f = \sqrt{\sum_{i=1}^{3} \left(\frac{f_i - \bar{f}_i}{\bar{f}_i} \right)^2}, \tag{1}$$

where f_i and $\bar{f}i$ are the i-th natural frequency of the the undamaged and repaired structures respectively. The design variable, x_i, represent geometrical parameters of each repair patch. The circular and square patches result in optimization problems with a single design variable: radius R, and square side l_s respectively. Analogously, the elliptical and rectangular patches have two design variables each: radius R_h and R_v for the elliptical geometry, and lengths l_h and l_v for the rectangular geometry.

The optimization problem may be stated as follows

$$\begin{aligned} \underset{x_i}{\text{minimize}} \quad & Error_f(x_i), \\ \text{subjected to} \quad & x_i \leq up_i, \\ & x_i \geq low_i, \end{aligned} \tag{2}$$

where up_i and low_i are side constraints applied to the design variables. For all cases, the lower and upper bounds were considered as $d/20$ and $l/2$ respectively. The optimization process is illustrated in the flowchart of Fig. 2.

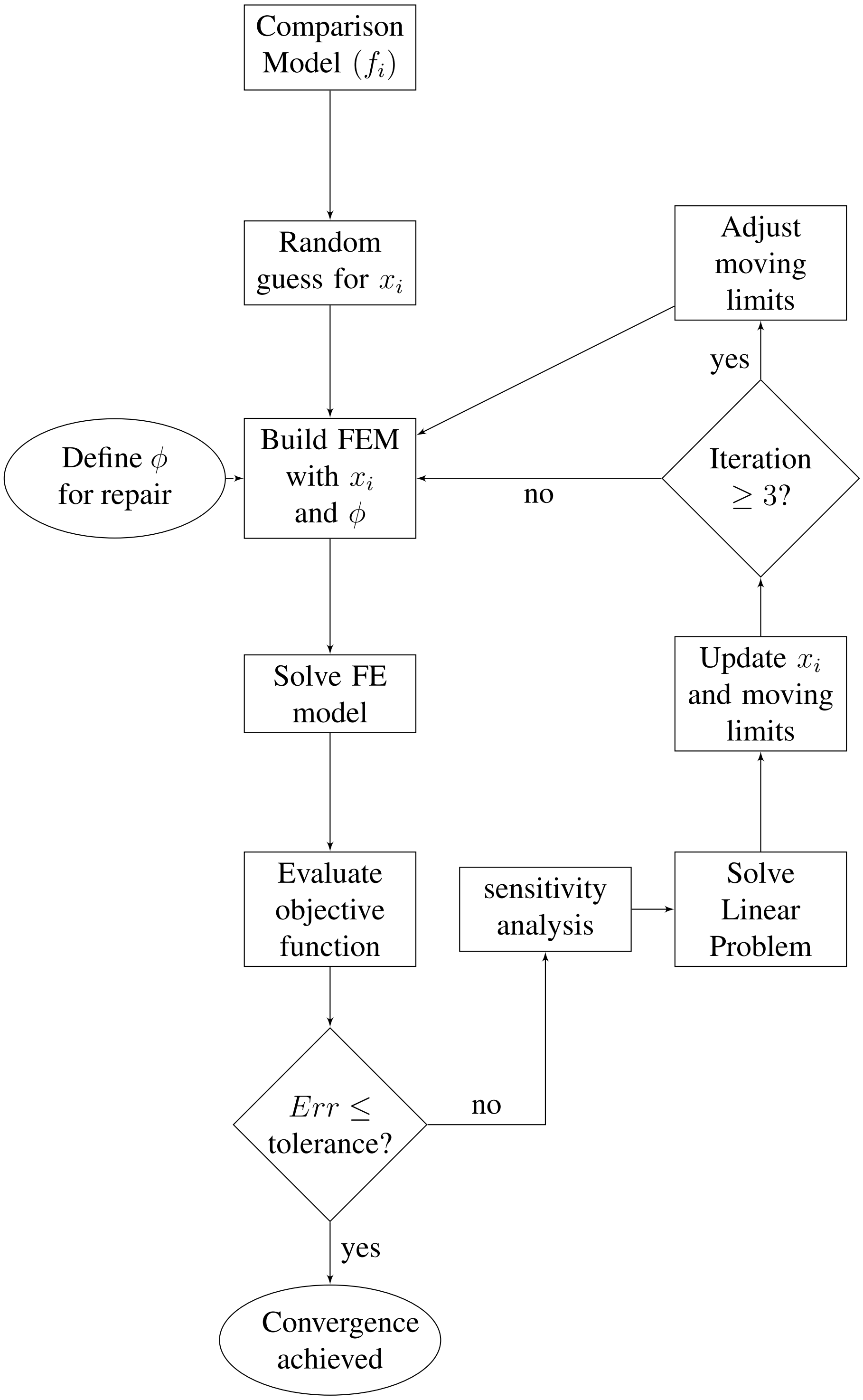


Figure 2: Optimization flowchart.

The optimization problem was solved employing Linear Programming, LP, along with interior point algorithm. A Taylor series expansion was employed to linearize the objective function of Eq. 1. The sensitivity analysis was performed by means of forward finite difference. The Finite Element Models, FEM, employed 8 node bi-quadratic shell elements with a maximum element size equal to $l/35$, defined after a mesh convergence analysis.

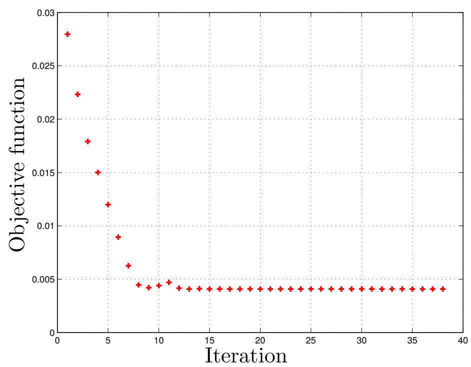
The majority of the optimization parameters presented in Fig. 2 were defined according to best practices proposed in the literature. The finite differences disturbance, Δx, was defined as 1×10^{-4}, as recommended by Arora (2011). The initial value (0.25) and bounds $(0.1 \longleftrightarrow 0.5)$ for moving limits (α) were defined as proposed by Nocedal & Wright (2006). A tool for updating the step length modifier, i.e., adjust moving limits, was employed considering past iterations data (Fonseca, 1997). The initial starting guess for design variables was randomly generated, the CPU time was used as seed.

4 PRELIMINARY RESULTS

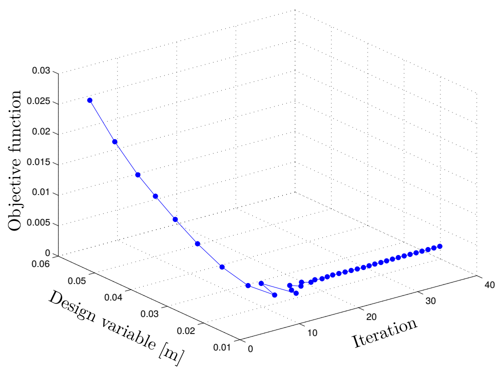
In the following sections, the results obtained for the four patch shape candidates are presented. Results are discussed in terms of total repair area and material distribution.

4.1 Circular and Square Repair Shapes

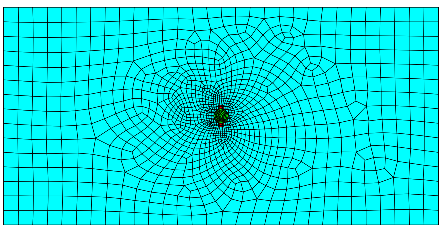
Considering the geometry of Fig. 1, the optimized circular repair patch shape obtained is presented in Fig. 3. Convergence curve, design variable evolution are presented as well.



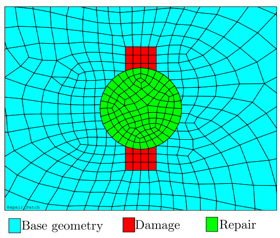
(a) Convergence curve.



(b) Optimization progress of the design variable.



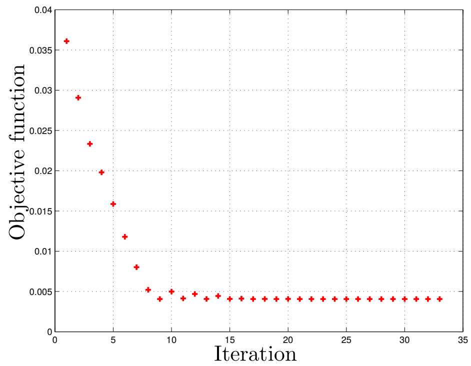
(c) Repaired geometry.



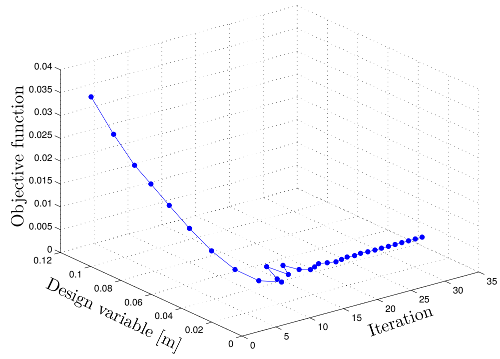
(d) Repair patch in detail, area $= 8.52$**cm**^{2}**.**

Figure 3: Optimum configuration with circular repair $R = 16.47$**mm.**

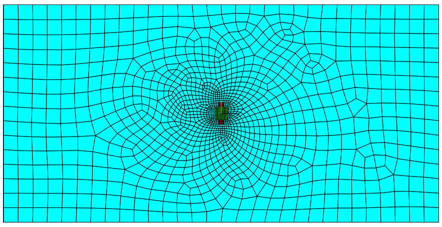
The circular repair shape that minimizes the objective function has a total area equal to 8.52cm^2. Note that the damage area was not fully covered by this patch. This indicates that a wider circle patch implies in excessive mass gain.



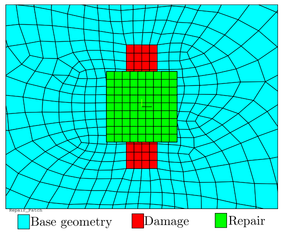
(a) Convergence curve.



(b) Optimization progress of the design variable.



(c) Repaired geometry.



(d) Repair patch in detail, area $= 8.14$cm^2.

Figure 4: Optimum configuration with square repair with side $l_r = 28.53$mm.

Analogously to the case of a circular repair patch, the optimization algorithm was applied to a square repair patch. The optimized configuration for this patch shape is presented in Fig. 4. Once more, the convergence curve and design variable evolution are presented as well.

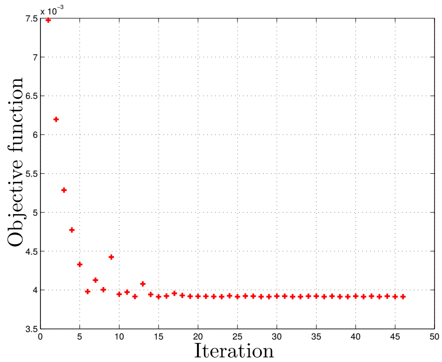
The square repair shape that minimizes the objective function has a total area equal to 8.14cm^2, which is approximately 4.5% less than the circular repair area. Similar to the results for the circular patch, the damage area was not fully covered by this repair geometry.

The length of damaged area covered by both repair patches, circular and square, was practically identical. Due to the geometrical restriction imposed by the predefined patch shapes, the complete damage overlay was not achieved. Once the objective function of Eq. 1 takes into account the modal response of the structure, the increasing of the component stiffness by means of material (repair) addition also impose the increment of inertia. This implies in the need of equilibrium between repaired components stiffness and mass. The lack of material distribution in the extremes of the damage area directly implies in stress concentration. However, considering that the employed optimization formulation does not focus on SIF reduction, this is an expected outcome.

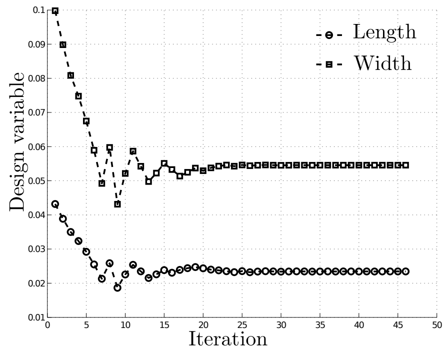
4.2 Rectangular and Elliptical Repair

The optimized elliptical and rectangular repair patch shapes obtained are presented in Fig. 5 and Fig 6 respectively. The results are presented encompassing the convergence curves and design variables evolution through optimization process. The repair patch shapes are presented in detail, along with the predefined damage area.

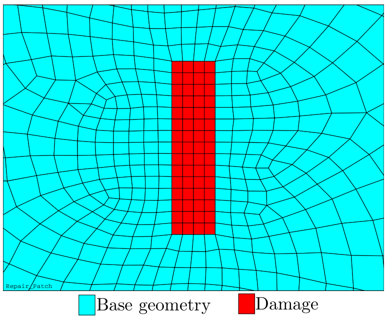
The elliptical repair shape that minimizes the objective function has a total area equal to 10.32cm^2, while the rectangular patch has an area of 8.54cm^2. Note that the damage area was



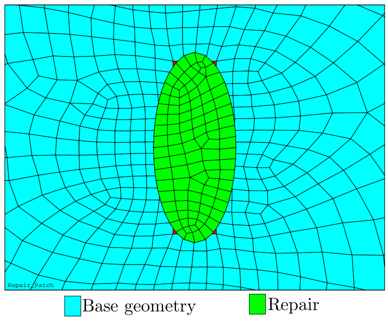
(a) Convergence curve.



(b) Optimization progress of the design variable.

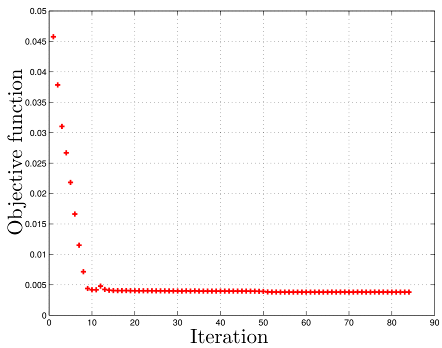


(c) Repaired geometry.

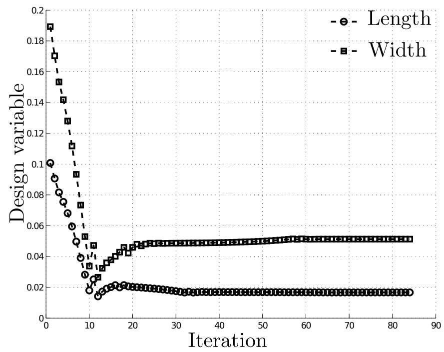


(d) Repair patch in detail, area 10.32**cm**^{2}**.**

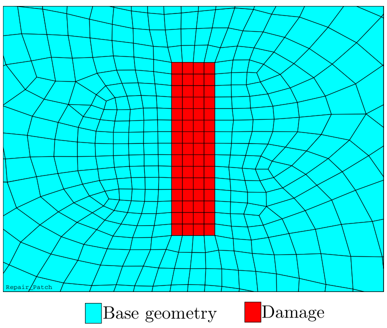
Figure 5: Optimum configuration with elliptical repair $R_h = 11.93$**mm and** $R_v = 27.54$**mm.**



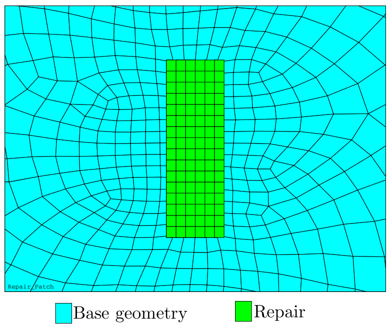
(a) Convergence curve.



(b) Repaired geometry.



(c) Damage in detail.



(d) Repair patch in detail, area 8.54**cm**^{2}**.**

Figure 6: Optimum configuration with rectangular repair with sides $l_h = 16.66$**mm and** $l_v = 51.26$**mm.**

fully covered by the rectangular patch. However, the elliptical patch did not overlapped the four edges of the damage area corners.

The geometry of the damage favors the rectangular repair shape and this, probably, is the main reason why the rectangular patch appears as the best patch candidate. However, this is an important indicative that damage regions with generic non-uniform shape, may only be efficiently repaired by patches with generic geometries as well. In other words, using a conventional patch to restore a realistic damage region would lead to repair material waste and excessive mass increment. Noteworthy, even the unconventional repair patches proposed in the literature, that prime for material distribution in the regions of stress concentration, may incorrectly restore a damaged component to a over/under-stiffened state.

5 FINAL REMARKS

The current work presented optimized conventional repair patch shapes to restore damaged composite panels with a predefined damage area. The optimization problem was formulated by means of mathematical programming and intended to achieve repaired configuration with a first natural frequencies response as similar as possible to the one of the undamaged component. Results showed that the more versatile the repair patch shape is, the better it will cover the damaged region, without material waste. For the damaged area considered herein, the rectangular patch presented the best repair option.

6 WORK CONTINUITY

The present work is an undergoing research, the preliminary results discussed are the basis for an attempt to formulate a optimum based technique to determine repair shapes for complex damaged areas in composites. The continuity of this work will encompass the definition of generic repair shapes and patch fibers orientation angle optimization. In order to do that, repair shapes employing a spline delimited contour will be used as the feasible domain for the optimization problem. Further research concerning the repair of curved surfaces is intended to be achieved as well. The future application of this techniques to a real problem application for aircraft structures is considered as a major goal.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

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