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OPTIMIZATION OF COMPOSITE PATCH REPAIR FOR INCLINED CRACK ON ALUMINUM PLATE USING GENETIC ALGORITHM

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Abstract

In this study, a composite patch repair will be designed for an aluminum plate with a central crack placed at 45 degrees to the applied unidirectional tensile load carried by the plate. In this state, the condition of loading is mixed mode. In the first step, behavior of the crack repaired by the composite patch under the applied tensile load is simulated by using ABAQUS commercial software. The crack growth process is modeled with the extended finite element method (XFEM) and the cohesive zone model (CZM) is used to model any damage progression in the adhesive of the composite patch repair. The shape of the five layer composite patch is assumed to be elliptical. For design optimization, the size of major and minor radius of the ellipse and the angle between the major axis and horizon are considered as design parameters. Then, using the genetic algorithm (GA), these design parameters will be found such that the weight of composite patch is minimum in presence of some constraints like load sustainability and maximum stress in the patch.

1 Introduction

These days, structural aging, specifically aging of aerospace structures, is one of the most important topics in structural science. Phenomenon like mechanical and thermal fatigue, corrosion, stress corrosion cracking, etc. normally age a structure and one of the most common effects of such phenomenon is discontinuity which appears as cracks. This strongly threatens the structure’s life and performance.

The common solution for crack repair is using metallic patch which has its side effects like increasing the weight of structure and strength reduction due to the mechanical connection of the patch and structure. However, composite bonded repair is applied as an alternative solution using adhesives which has its own advantages over metallic patches. Since life extension of aging aircraft, in contrast to regular repair, may involve using a number of patches, added weight and patches connection may make the life extension infeasible. So, knowing about the behavior of the crack under the bonded repair subjected to critical loading condition is of a great importance. Moreover, to genuinely control the added weight and to guarantee the optimum performance by the composite patches a multi-objective optimization process is inevitable. Therefore, optimization of composite patch repair has been considered by several researchers [1-4]. Kumar et al. [1] studied weight optimization of a two-sided symmetric composite patch that was used for repair of a cracked metal plate. They considered the SIF[1] parameter at crack tip of the sheet as a constraint and the plain-form shape of the patch and its thickness as design variables of the optimization. Yala et al. [2] considered minimization of SIF as the objective for optimization of composite patch repairs. The thickness of the patch, the thickness and the shear modulus of the adhesive were the three optimization variables in this study. Errouane et al. [3] developed a numerical model for optimal design of composite patch repair for

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[1] Stress Intensity Factor

cracked aluminum plates under tension. They considered geometrical parameters of the patch (e.g. height, width and thickness) and the adhesive thickness as the optimization parameters. The objective of their optimization was to reduce the stress concentration in the vicinity of the crack tip. Talebi et al. [4] (authors of this research) considered the configuration parameters of pre-designed composite patch repair by Okafor et al. [5] and optimized them with the aim of achieving the highest level of stability of crack growth in aluminum in presence of some constraints like weight, load sustainability, shear stress in the adhesive layer and maximum stress in the patch. They used nonlinear fracture mechanics concepts in calculating the stability of crack in the cracked aluminum plate. The current team in another research [6] simulated the patch which was designed by Okafor et al. [5] incorporating XFEM and CZM capabilities of ABAQUS commercial software to include the dynamics of the crack propagation. This study could clearly show the propagation and progression of damages in the aluminum and adhesive material. Also, with the simulation performed they could succeed to develop a general calibration technique for the adhesive properties used in modeling with the experimental data published by Okafor et al. [5]. Ramji et al. [7] also carried out an optimization study on a symmetrical composite patch with considering design variables such as patch thickness, patch layup configuration, and patch shape which can influence the performance of composite repair for SIF reduction. Moreover, they considered circle, rectangle, square, ellipse and octagon patch shapes in their study. The important issue in this study was that the crack was assumed inclined with respect to the loading axis. But, they did not consider crack growth in the optimization process, what will be investigated in the present study. Inclined crack caused the condition of loading switch to mixed mode. The existence of inclined crack in the plate which was repaired with the composite patch, have been considered in the several researches [8-11]. Bouiadjra et al. [8] used the finite element method to analysis the behaviour of repaired cracks with bonded composite patches in mode I and mixed mode by computing the stress intensity factors at the crack tip. They highlighted the effects of the patch size and the adhesive properties on the stress intensity factors variation. Sun et al. [9] proposed a finite element analysis to investigate the fracture toughness of the cracked cylindrical shell patched by a single-sided bonded composite patch. They assumed that the crack was in any direction and considered the mixed mode of crack. Their results showed the significant influence of curvature of the cylindrical shell on the total energy release rate of an inclined crack bridged by a bonded composite patch repair. Ayatollahi et al. [10] used a three-dimensional finite element model of the single sided repaired specimen to study the effect of composite patching on the crack tip parameters (KI, KII and T-stress). They predicted the fracture initiation angle and the fracture strength of repaired crack by using the generalized maximum tangential stress criterion. Also, they investigated the effects of composite laminate configuration and adhesive properties on the performance of bonded composite patch. They showed that parameters like mode mixing, patch thickness and properties of film adhesive can influence significantly the crack tip parameters and hence the fracture strength of the repaired specimens under mixed mode loading conditions. Ouinas et al. [11] applied the finite element method to analyses the central crack’s behaviour repaired by a boron/epoxy composite patch. They analysed the influence of the materials properties on the values of the fracture parameters which calculated for a plate subjected to a traction containing an inclined center crack. Their results showed that the quality of the patch material and its geometry, play an essential role on the distribution of the stress concentration at the vicinity and the crack tip. The novelties of this study is the optimization of the composite patch repair for the damaged aluminum plate with inclined center crack by simulation of its growth and propagation from the beginning of loading up to the point of complete failure. In order to achieve the above mentioned aims, the optimization process is performed by developing an interface between genetic algorithm available in MATLAB and ABAQUS software.

2 Finite Element Modeling

The aluminum plate configuration is a rectangular with dimensions of 177.8×76.2×1.6 mm (7×3×0.063 in) which consists of an inclined center crack with length of 25.4 mm (1 in) and angle of 45 degree with respect to the X-axis (θ) as shown in Fig. 1. The crack is repaired with an elliptical 5 ply unidirectional Boron-Epoxy patch with the thickness of 0.132 mm (0.0052 in). The patch is bonded to the Al plate with a 0.18 mm (0.007 in) thick layer of FM-73 adhesive [6]. The 8-noded nonlinear 24 DOF solid element (C3D8R) is used for meshing the Al plate and the composite patch and the cohesive element (COH8R) is used for meshing the adhesive material [12].

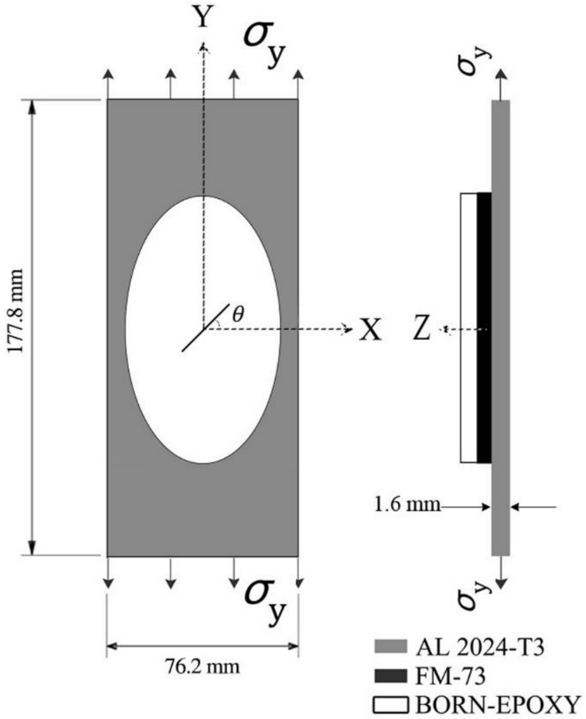


Fig. 1: Geometry of aluminum plate and patch.

As for the loading and boundary conditions, to simulate the tensile load a 10 mm displacement in the Y-direction is applied to the plate while the nodes on one end of the plate are restricted in all 3 directions and the nodes on the other end are just restricted in X and Z directions.

Table-1 presents the properties of Al 2024-73 plate and Table-2 provides the properties of the Boron/Epoxy composite, respectively.

Table-1. Properties of Aluminum 2024-T3

E (GPa)	ν	Fracture Toughness $(MPa*\sqrt{m})$	Density (kg/m^3)
69.64 [a]	0.32 [a]	24.5 [b]	2770 [b]

[a] Okafor et al. [5].
[b] Bauccio [13].

Table-2. Material properties of boron-epoxy

E_1 (GPa)	E_2,E_3 (GPa)	ν_{12},ν_{13}	ν_{23}	G_{12},G_{13} (GPa)	G_{23} (GPa)	Density (kg/m^3)
195.12[a]	25.44[a]	0.168[a]	0.035[a]	7.24[a]	4.94[a]	2000[b]

[a] Okafor et al. [5].
[b] Baker et al. [14].

Table-3. Properties of FM-73

E (GPa)	α Penalty parameter	υ	G_{IC} (kJ/m^2)	G_{IIC} G_{IIIC} (kJ/m^2)	$T_{n,max}$ (MPa)	$T_{s,max}$ (MPa)	η
2.2[b]	0.278[a]	0.32[b]	1.4[c]	1.29[a]	49[c]	19.79[a]	2.0[c]

[a] Talebi et al. [6].
[b] Okafor et al. [5].
[c] Sugiman et al. [15].

3 Simulation

Here, the simulation process is divided into four stages. In Stage-1, for FEM model verification, the behavior of Al plate without crack is simulated up to and beyond the plastic deformation. Fig. 2 show the load-displacement curve of the aluminum plate acceptably matches with the experimental results obtained from Okafor et al. [5]. For more information about this section refer to another research of the current team [6].

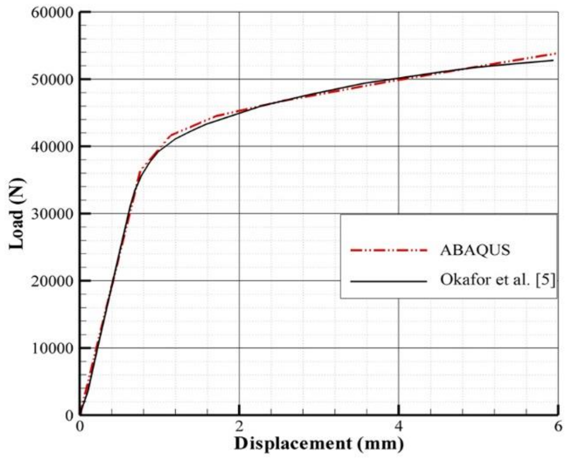


Fig. 2: Load-displacement curve for aluminum plate.

The XFEM simulation of crack growth of the pre-cracked Aluminum plate is performed in stage-2. The stress distributions in the aluminum plate along with the crack propagation estimated by XFEM approach in different steps of loading are shown in Fig. 3. Here, it should be explained that the load sustainability of aluminum plate is expected to increase after the crack rotation. Therefore, the load-displacement curves for $\theta = 0°$ and $\theta = 45°$ are shown in the Fig. 4. For more information about XFEM refer to Khoei [16] and Talebi et al. [6]. Stage-3 involves simulation of the repaired pre-cracked Aluminum plate with a composite patch. In this stage, the CZM capability of ABAQUS is used to simulation of progressive damage in the adhesive layer. It is an important stage of the simulation, because the parameters of CZM Influence on the maximum load carrying capacity of the plate and crack propagation in the aluminum plate. It is considered in another work of the current team [6]. The results of the crack growth simulation and the progression of damage in CZM are shown in Fig. 5. In this figure (i.e. 5(a) and 5(b)), the stress and crack situation in the plate repaired with the composite patch at three time point steps are shown. Also, progression of damage in CZM is shown in Fig. 5(c). The comparison of load-displacement curves for stage-2 and stage-3 are shown in Fig. 6.

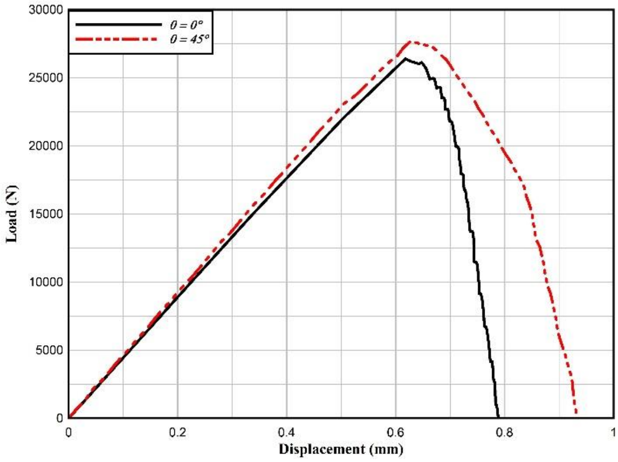


Fig. 4. Load-displacement ($\theta = 0°$ and $\theta = 45°$).

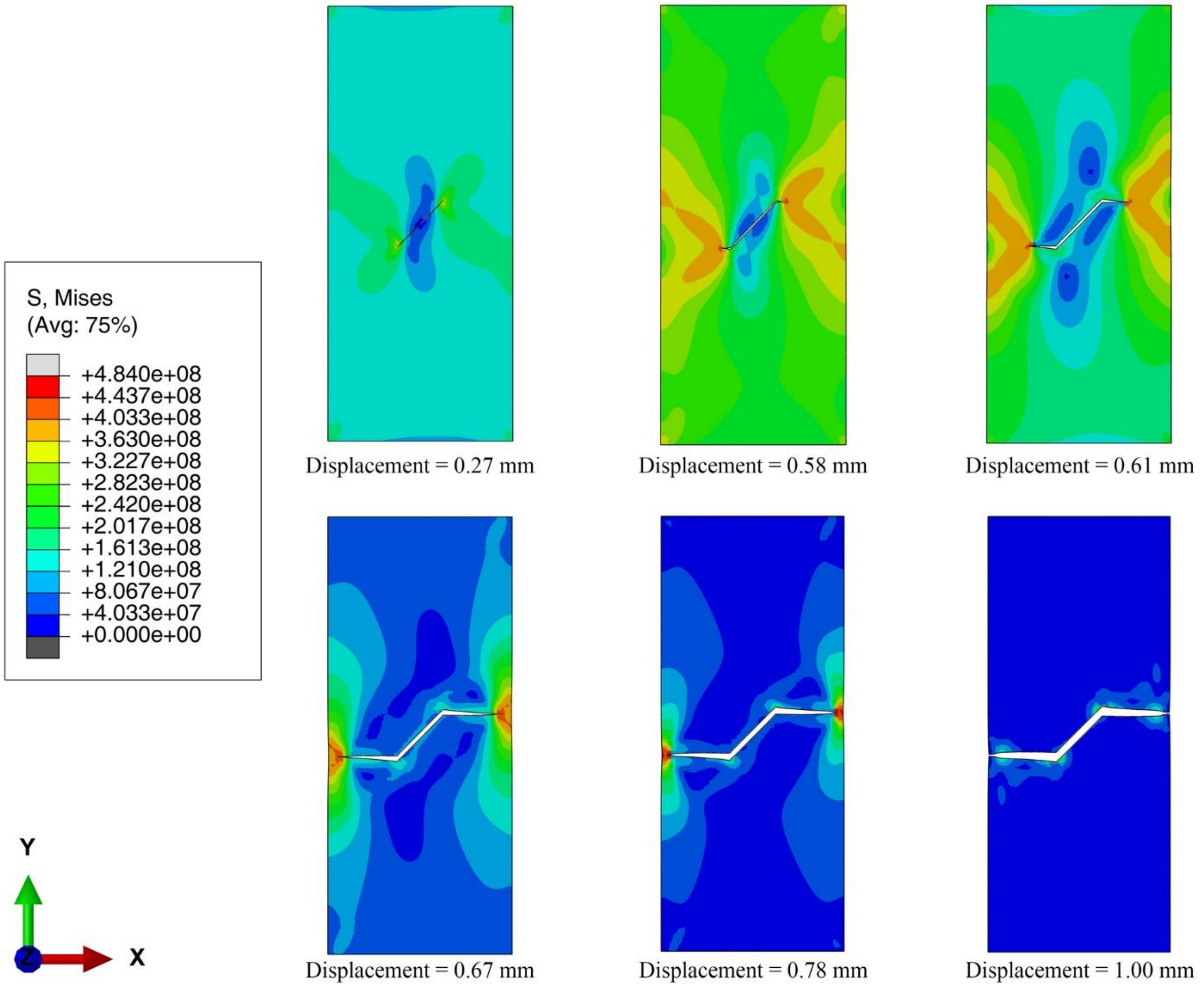
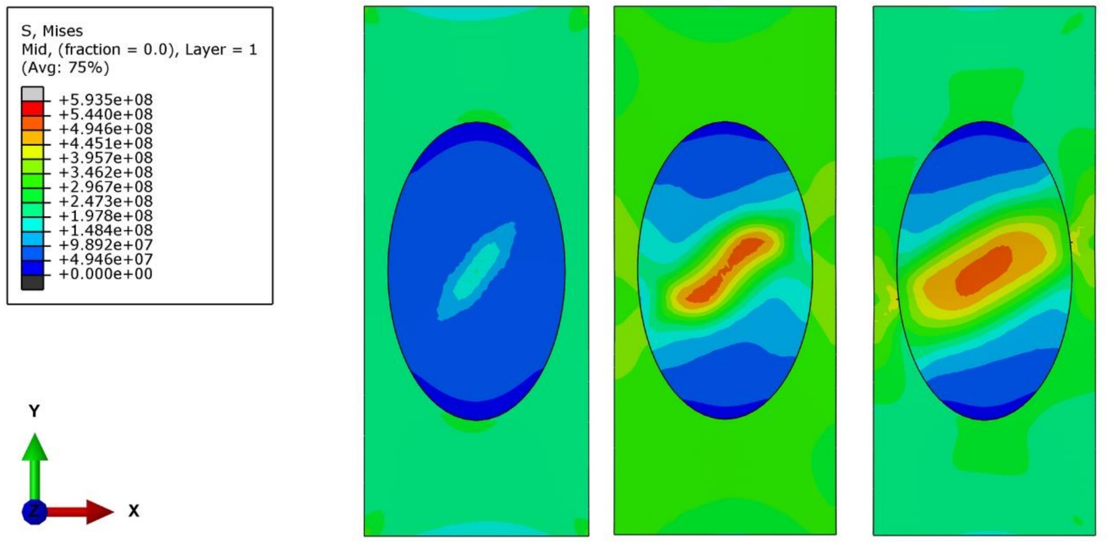


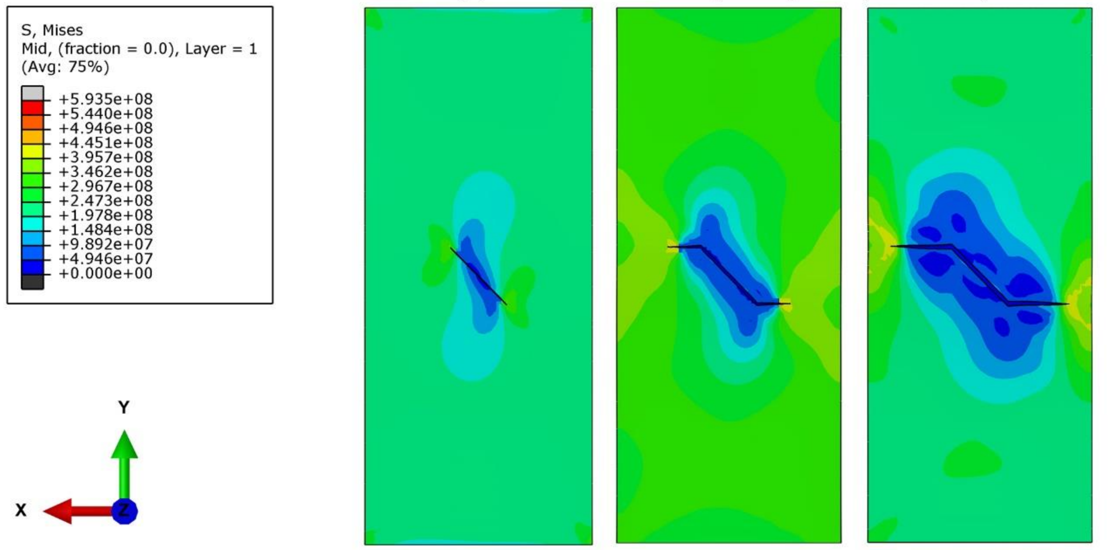
Fig. 3. Stress distribution and crack propagation with XFEM approach in cracked AL plate.

(a): Plate with the composite patch (front view)



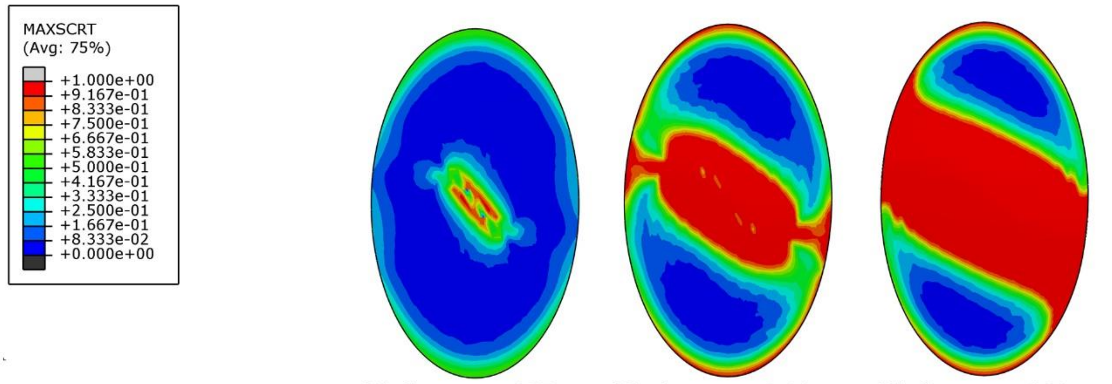
Displacement= 0.57 mm Displacement= 1.16 mm Displacement= 1.21 mm

(b): Plate with the composite patch (back view)



Displacement= 0.57 mm Displacement= 1.16 mm Displacement= 1.21 mm

(c): Progressive damage in CZM



Displacement= 0.57 mm Displacement= 1.16 mm Displacement= 1.21 mm

Fig. 5. Results of the crack growth simulation and the progression of damage in CZM.

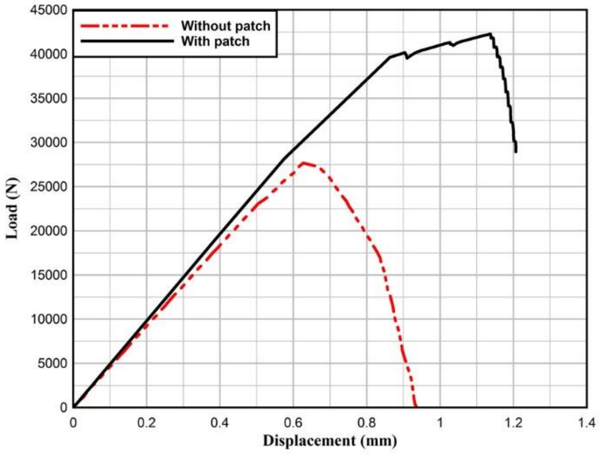


Fig. 6. Load-displacement curves for stage-2 and stage-3.

4 Optimization process

In this paper, the optimization process is performed using the genetic algorithm (GA). This is done using the GA module of MATLAB commercial software which is linked to the ABAQUS software [17]. The objective here is the minimization in the weight of composite patch in presence of some constraints like load sustainability and maximum stress in the patch. In other words, the maximum tensile load that plate can sustain not to be less than *38 kN* and the maximum stress in the patch should be less than *680 MPa*. These values are related to the patch designed by Okafor et al. [5]. The searching population is considered to be composed of 20 individuals (chromosomes) and the type of the input to the fitness function is Double Vector. The selection function type is Stochastic uniform and the type of crossover function is Scattered.

The verified model from the previous section was modified for parametric optimization study. In this paper, the 3 independent configuration parameters of the patch are investigated. Parameters 1 and 2 are the size of major and minor radius of the ellipse and parameter 3 is β (the angle between the major axis of ellipse and horizon). These parameters are shown in the Fig. 7. Variation of parameters 1 and 2 influence on weight, load sustainability and maximum stress in the patch. But, variation of parameter 3 only influence on load sustainability and maximum stress in the patch and does not influence on weight of the patch.

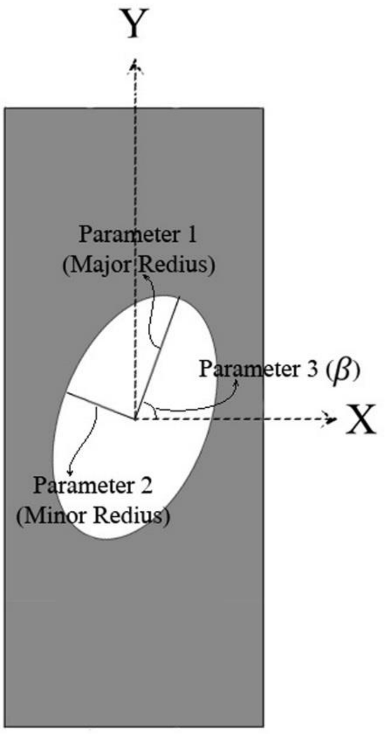


Fig. 7. Geometry parameters of patch for optimization.

The flowchart of the optimization process is shown in the Fig. 8. In this process, after creation of random parameters value, patch configuration constrain is checked. The configuration parameters of the patch should be chosen such that geometry of patch is possible and unique. If this constrain is satisfy, model will be run in ABAQUS. After complete ABAQUS run, the crack growth and other two constrains i.e. maximum load carried by the assembly and maximum stress in the patch will be checked. If these constrains are satisfy, then weight of the patch will be calculated. After calculation of weight, one cycle of process is completed. However, this process should be done several times, and finally determine the lowest value of weight.

In optimization process, plots of the best fitness and the mean fitness obtained in each generation are shown in Fig. 9. As shown in this figure, the optimization process converges after 17 generations.

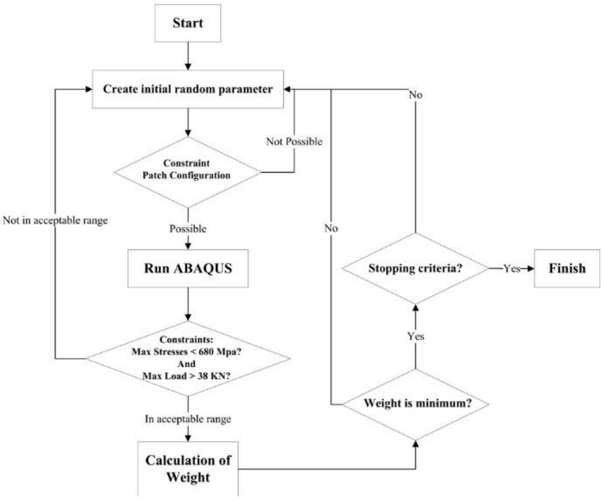


Fig. 8. Flowchart of the GA optimization process.

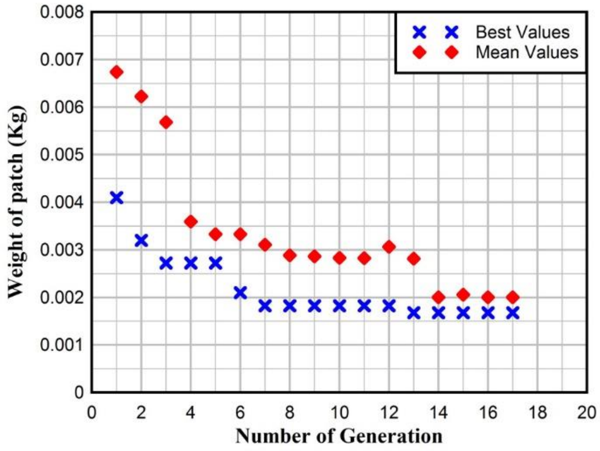


Fig. 9: Optimization process.

The results of optimization for the best geometry parameters are given in the Table-4. The optimum patch geometry that is achieved by the GA optimization process is shown in Fig. 10.

Table-4. Optimization results.

P. 1 (m)	*P. 2 (m)*	*P. 3 (degree)*	*Maximum load (N)*	*Maximum stress in patch (MPa)*	*Weight (g)*
0.0302	0.0134	137.5	38004	553.28	1.68

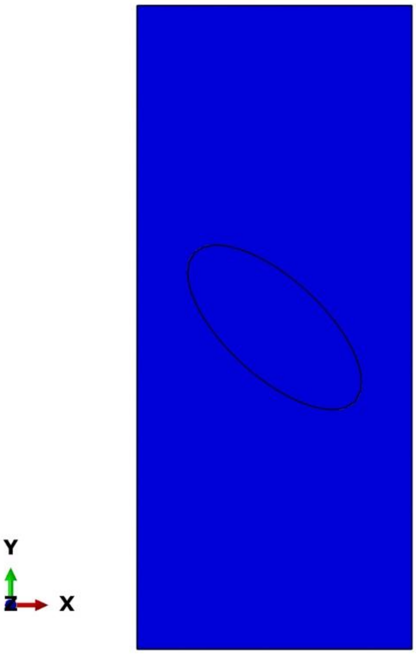


Fig. 10. Geometry of optimum patch.

5 Conclusion

In this paper, the objective of optimization is achieving to minimum weight of the composite patch repair for damaged aluminum plate with inclined center crack in presence of constrain on sustainable load and maximum stress in the patch. For this purpose, the FEM simulation of the adhesively bonded composite patch repair of cracked aluminum aircraft panels with the concept of CZM and XFEM has been carried out successfully from the beginning of loading up to the point of complete failure. The crack propagation in the aluminum plate and the damage progression in the adhesive have been simulated simultaneously.

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