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Investigation of Adhesive Humidity Absorption and Optimization of Composite Patch Repair in a Cracked Ship Plate

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Abstract— **Repairing cracked ship plates using composite patches is one of the best solutions to recover the material properties, strength, and fatigue. One of the most critical things that affects repair efficiency is the humidity absorption of the adhesive. In this study, the humidity absorption of aged adhesive is investigated. The mechanical properties of aged adhesive adekit A140 epoxy are used in this study using the finite element method to analyze the behavior of fracture mechanic parameters. The stress intensity factor of mixed-mode crack is investigated in different immersion times. The material properties of the aged adhesive are taken from the experimental work of the previous research. The optimization of the patch using the genetic algorithm is performed to find the best patch in critical conditions. The obtained results show that the water absorption in different immersion times affected the repaired ship plate's stress intensity factor.**

Keywords—Bonded composite repair; finite element method, fracture mechanic; genetic algorithm; adhesive humidity absorption

I. INTRODUCTION

Metal materials are prone to be cracked because of their characteristics. There are many methods to repair cracked metal, and the common thing that people use today is metal patch repair. However, it has many side effects, like increasing the weight of the main structure, and being more problem-prone because of high stresses at the fastener, which increases the Stress Intensity Factors (SIF) [1,2]. Compared to metal patch and other repair methods, the composite patch is recommended for it has many benefits [3]. The first advantage of composite repair is the large load transfer area; bonded repair with composites is much stiffer than mechanical joints. Other benefits are that it seals the interface, reduces corrosion leakage, reduces repair time and lower cost, is lightweight, and causes minimal damage to the main structure [2]. This repair aims to restore the damaged structure to its original condition, and even the repair will make the structure better and stronger in terms of strength and stiffness.

One of the applications of composite repairs is shipbuilding structures repair [4]. Ships worldwide have various sizes and types and different specifications and characteristics. The different structural parts and details of a steel ship are subjected to plenty of stacking conditions during the vessel's operational life. The type and magnitude of this loading condition have various conditions because of the wave's stochastic nature, which makes the loading applied to a marine structure [5]. As a result, it causes multiple types of local deformations, defects, failures, and cracks in the ship structures. In addition, corrosion is also a factor that increases those problems. One of the most important things to be considered in composite patch repair is the humidity absorption by the adhesive because it affects the fracture mechanic parameters. Previous researchers reported that adhesive humidity absorption affects the values of J-Integral [6,7].

Many researchers have investigated composite patch repair in many fields since decades ago. Among the numerical analysis, Finite Element Method (FEM) is one of the best methods because of its accuracy and versatility. FEM is applied for fracture mechanic analysis, especially in the composite repair field [8]. Various optimization works have been applied, and one of the most accurate and straightforward methods is the Genetic Algorithm (GA) method, which previous researchers have performed [9,10]. However, not much work exists in the literature regarding the adhesive humidity absorption effect and the optimization for ship plates using both methods, especially for applied mixed-loading (Inclined crack angle in many degrees). This research aims to find the effect of adhesive humidity absorption on the patch performance and the optimum patches for different inclined angles with efficient parameters, especially for a cracked ship plate, using the GA and FEM.

II. PROBLEM DEFINITION AND MODEL VALIDATION

The geometry of the panel is considered 2400mm x 800mm x10mm, and the three different inclined angles are investigated $\beta = 30^{o}$, 45^{o}, and 60^{o}. In the last part of this work, optimization is performed. Fig. 1 shows the schematic problem. The applied boundary conditions are commonly used for the composite patch repair investigation in various cases and have been applied by Karr et al. in ship plating applications [4]. The displacements applied at the plate's two ends are restrained perpendicular to the load, and the plate can move freely in the Y direction. The tensile stress is applied in the Y direction at the two ends of the plate. The crack angle is defined as β with 2a crack length. The applied tensile load is considered to be 100 MPa. The geometrical dimensions are defined in the figure below (Fig. 1).

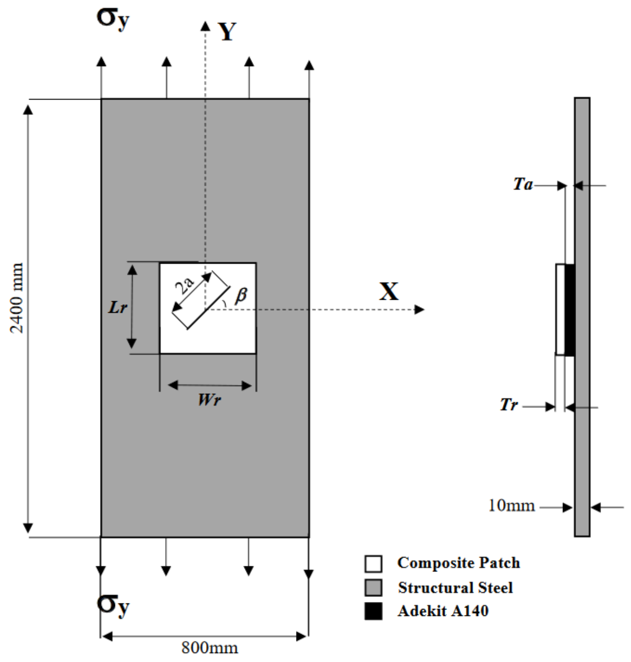

Fig. 1. Geometry of defined problem

The structural steel, composite patch, and adhesive are modeled and meshed with C3D8R elements. These elements are solid quadratic eight-node elements with reduced integration. The crack modeling is done using the contour integral method. Some previous works reported the 3D FEM and modeling with this type of elements and crack modeling method [3,11]. The panel, adhesive, and composite overlays are assembled by applying constraints to the model. To assemble these parts, tie contact (surface-to-surface constraint) is applied. Surface-to-surface interactions can define the contact between two different deformable surfaces and create the translational degree of freedom same for the two surfaces [12].

Table 1 Material Properties

Material	E_1	E_2	E_3	G_{12}	G_{13}	G_{23}	V_{12}	V_{13}	V_{23}
Boron-Epoxy [a]	208.1	25.44	25.44	7.24	7.24	4.94	0.1677	0.1677	0.035
Carbon Epoxy [a]	134	10.3	10.3	5.5	5.5	2.3	0.33	0.33	0.53
Glass-Epoxy [a]	27.82	5.83	5.83	2.56	2.56	2.24	0.31	0.31	0.41
Graphite-Epoxy [a]	172.4	10.34	10.34	4.82	4.82	3.10	0.3	0.3	0.18
Adhesive Adekit [b]	2.47	-	-	-	-	-	0.3	-	-
Structural Steel [c]	205.8	-	-	-	-	-	0.3	-	-

[a] Mohammady S, 2020
[b] Rezgani et al., 2017
[c] Rahbar and Zarookian, 2014

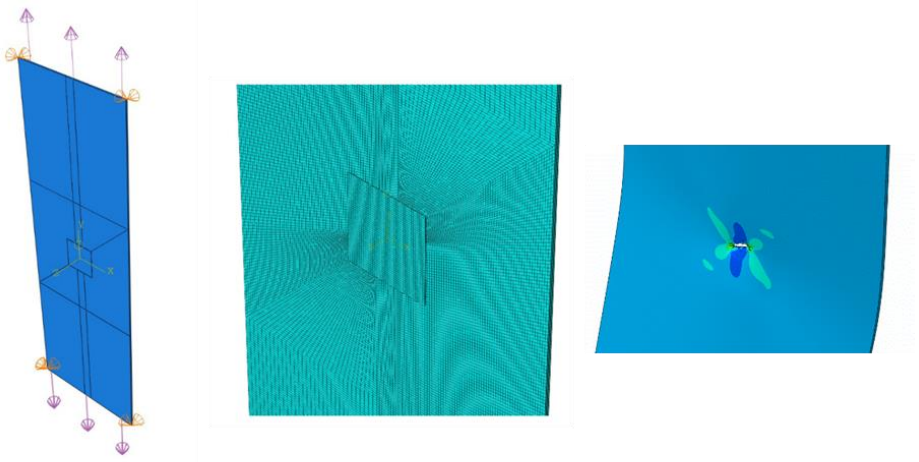

Fig. 2. Finite Element Analysis illustration created with ABAQUS software (Modeling, Meshing and FEM result)

The material properties of the FEM modeling are presented in Table 1. The main panel is the ship's structural steel which is mainly used for the ship's main structural parts [13]. The adhesive in this investigation is considered to be adhesive adekit A140. The composite repair materials are boron-epoxy, carbon-epoxy, glass-epoxy, and graphite-epoxy, with the fiber orientation considered to be in line with the applied tensile load. The next part discusses the model validation of this study. Before further investigation and the main problem are studied, validation is necessary to ensure that the given results are valid and trusted.

The analytical and numerical solution results for the stress intensity factor are compared [2]. The SIF is the only significant parameter that allows knowing the state of stress and deformation in any crackhead. For a central crack solicited in opening mode, the relation between the far applied stress on the plate (σ) and the stress intensity factor K_I and K_{II} are as follows:

$$K_I = \sigma \sqrt{\pi a} \cos^2\beta \qquad (1)$$

$$K_{II} = \sigma \sqrt{\pi a} \cos\beta \sin\beta \qquad (2)$$

In this work, the modeling validation is done to investigate the previously determined conditions. The SIF in both modes I and II through the panel thickness are obtained. The results are converged and show that the numerical and the analytic models lead to practically the same results in various applied stress to the plate. The figures below (Fig. 3) show the results of the studies. Those behaviors show that the model developed in this study and the boundary conditions imposed are reliable and allow a better mechanical behavior analysis of the cracked structure that is repaired with a composite patch. These conditions will be retained in this work and allow reliable composite patch repair modeling analyses.

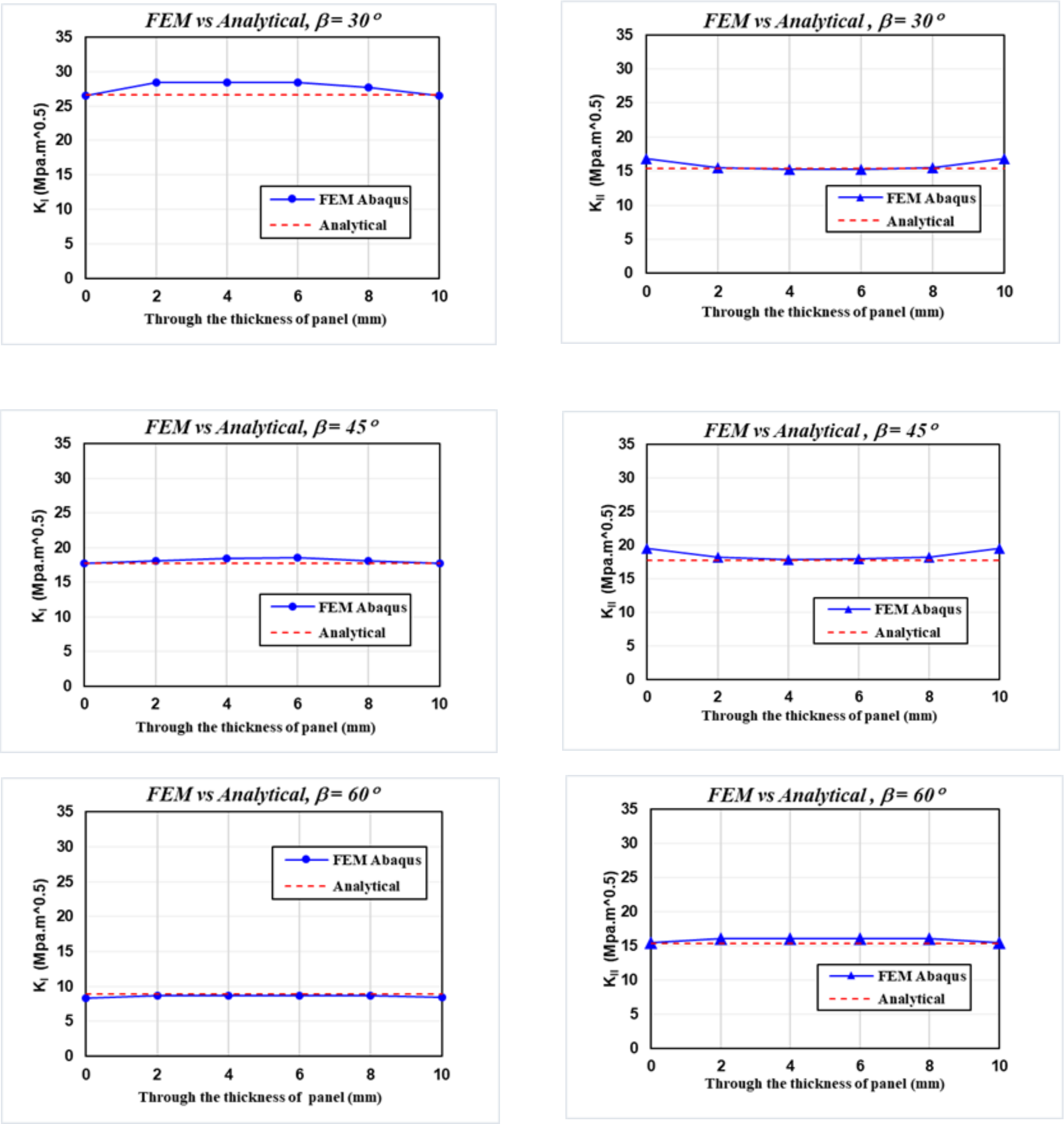

Fig. 3. Analytical vs numerical results

III. INVESTIGATION OF ADHESIVE HUMIDITY ABSORPTION EFFECT OF THE ADHESIVE ON THE PATCH PERFORMANCE

The humidity absorption of the adhesive is one of the essential things that should be considered because it has significant effects on the fracture mechanics parameters such as the J-integral and SIF [7]. The experimental study of the humidity absorption effect on the adhesive adekit 1410 has been done by Oudad et al. The study showed that humidity absorption has many effects on the adhesive material properties at various immersion times [6]. In this work, the results of the experimental work are taken from previous research to investigate the humidity absorption effects on the mixed-mode crack.

Sixty specimens of adhesive adekit 1410 were aged before. These adhesive specimens were immersed in distilled water tanks inside an enclosure maintained under a temperature 30°C. Before the test, these specimens were weighed. After the immersion, these specimens were weighed again to know the water mass absorbed by the adhesive during various immersion times. The level of water absorption is given below:

$$M(\%) = M_t - M_0/M_t \qquad (3)$$

After the test is performed, the change in the adhesive's material properties is obtained. Those curves show that the young modulus and yield stress decreased on different days of immersion (Fig. 5). The longer the immersion day is, the young modulus decreases. The yield stresses of the aged adhesive have the same behavior as well. After the data of those material properties are obtained, the material property of each adhesive is used to analyze the fracture mechanics behavior with FEM.

Fig. 4. Adhesive specimen

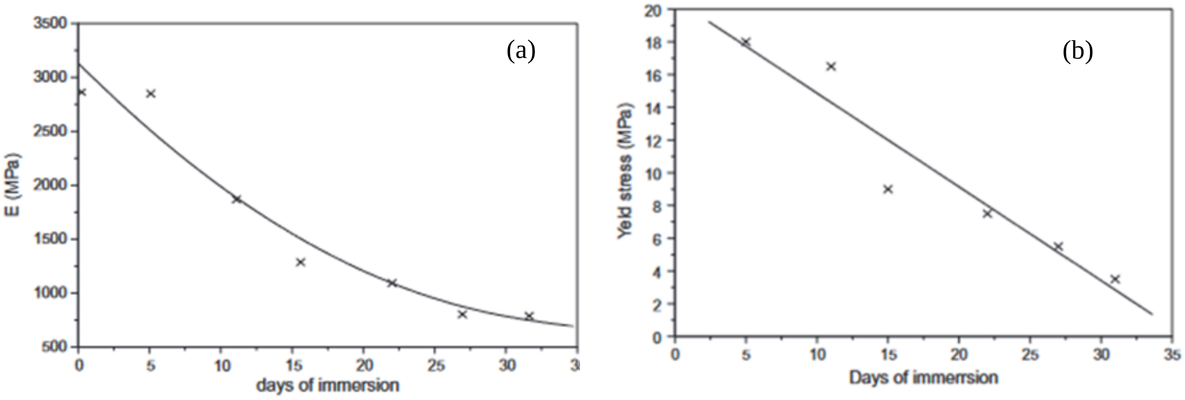

Fig. 5. (a) Young modulus vs days of immersions (b) Yield stress vs days of immersion

IV. FEM RESULTS IN STRESS INTENSITY FACTOR MODES I AND II IN DIFFERENT IMMERSION TIMES

In This part, the numerical FEM is conducted to study the effects of adhesive aging in different immersion times on the composite repair performance in ship structural steel. This method is conducted using ABAQUS software. The K_I and K_{II} were computed to study the repair efficiency in terms of the humidity absorption effect of the adhesive. The geometry of the plate is 2400 mm x 800mm x 10mm. The patch dimension is 200mm x 200mm x 2mm using boron-epoxy composite. The adhesive thickness is considered 0.8 mm in different immersion times for 0 days, 5 days, 12 days, 16 days, 23 days, 28 days, and 32 days. The plate is subjected to a remote uniaxial tensile load 100 MPa.

Previous research reported that adhesive aging reduces fracture mechanic parameters like J-Integral [6,7]. There is a lack of resources for the effect of the adhesive humidity absorption in different immersion times in terms of K_I and K_{II} for inclined cracks. The problem was studied, and the results of K_I and K_{II} were obtained. Fig. 6 shows SIF K_I and K_{II} results for inclined angle 30°. In case of K_I, when the crack size is longer, K_I increases. For the 0 to 5 days immersion time, K_I does not increase significantly, and the values between them are almost the same. From 5 to 12 days, the K_I increases around 2% and continues to increase until 32 days, with higher K_I. In this case, the values constantly increase from low to high values. In case of K_{II}, the trend of different immersion times is the same as in the KI. It gradually increases by 3-4% between every immersion time from 0 to 32 days. The average SIF K_{II} has some variations when the crack growth increases and decreases in various crack sizes, and in all immersion times, the variations of SIF have almost the same values.

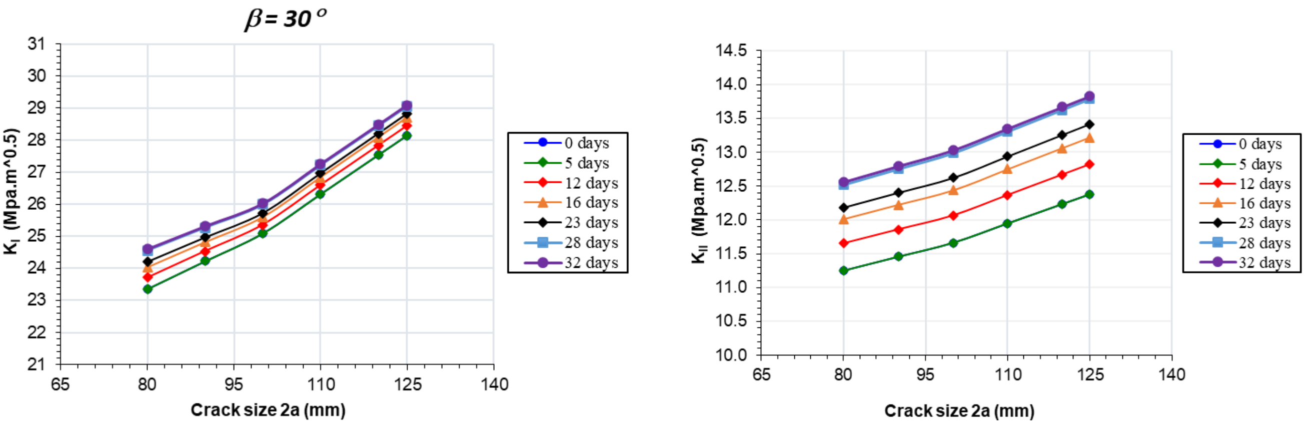

Fig. 6. SIF Modes I and II β=30° inclined angles in different immersion times

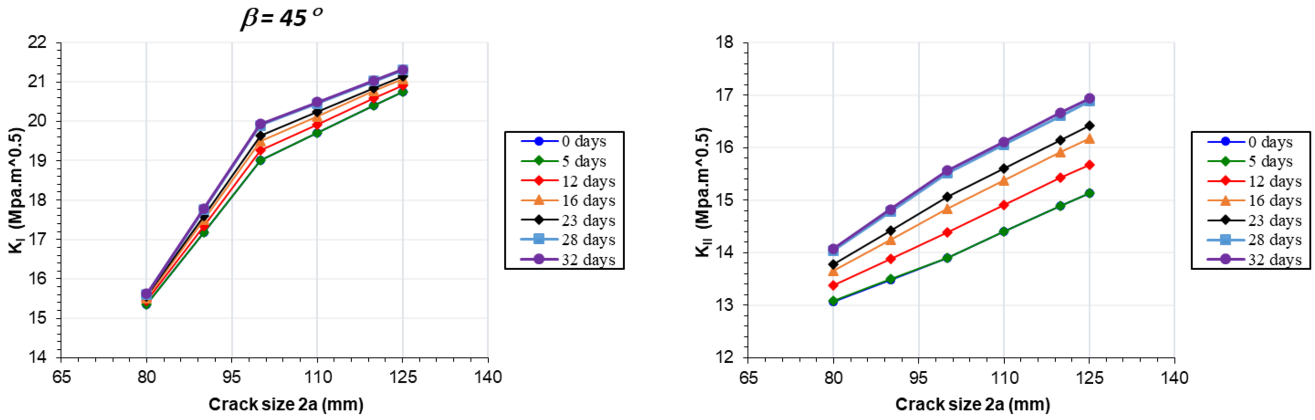

Fig. 7. SIF Modes I and II β=45° inclined angles in different immersion times

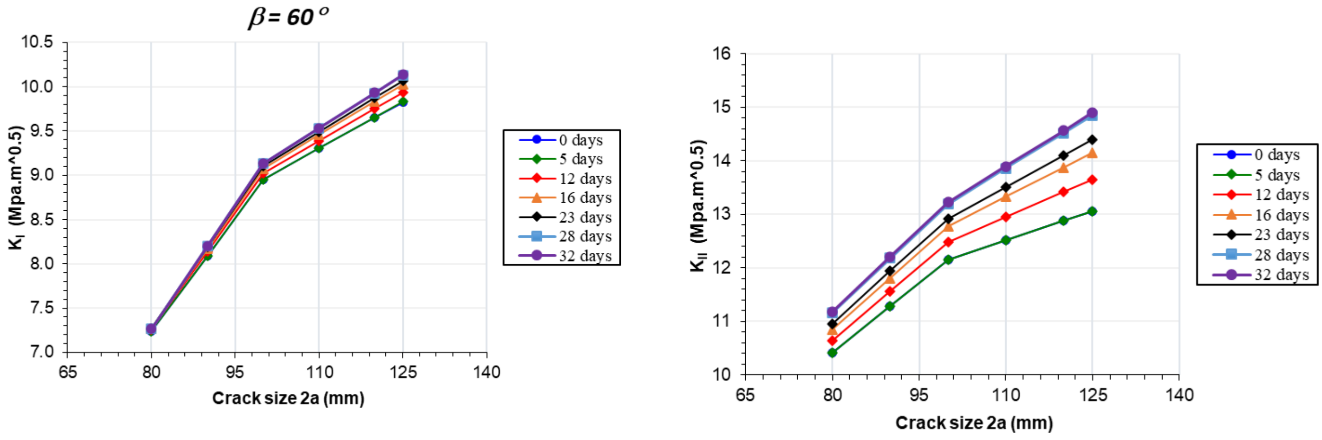

Fig. 8. SIF Modes I and II β=60° inclined angles in different immersion times

Fig. 7 and 8 show the SIF modes I and II for 45° and 60°, respectively. The results show that K_I and K_{II} values have the same trend as the inclined angle 30°. The K_I values increase while the crack grows, and when the adhesive ages longer, the K_I values are higher. The K_{II} values have the same behavior, but when the immersion time of the adhesive is longer, all of them increase. The FEM results agree with the previous research that the humidity absorption in various immersion times affects the fracture mechanic parameters [6,7]. In this section, it is evident that the SIF, both K_I and K_{II} change while the immersion time is longer. The FEM results presented that the efficiency of the composite repair is strongly affected by the humidity absorption by the adhesive. The adhesive adekit A140 material property change so that it affects the SIF results. Fig. 9 shows the increase of SIF in different immersion times. It can be concluded that the repair is more efficient when the humidity absorption decreases in the case of the different inclined angles of the cracks.

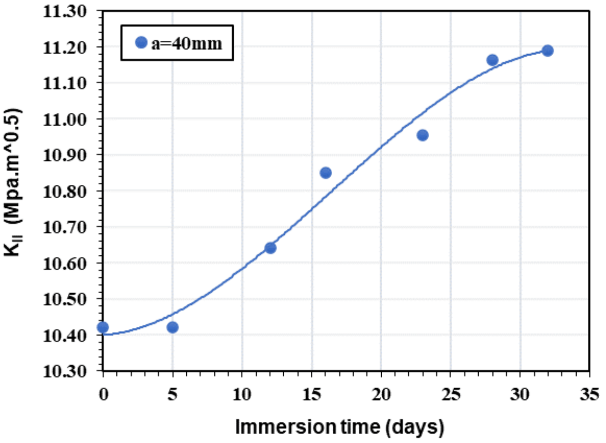

Fig. 9. SIF mode II vs. immersion time (β = 60°)

V. FEM RESULTS FOR DIFFERENT PATCH MATERIALS

This section investigates the effect of different patch materials on the patch performance at different immersion times. Firstly, the patch materials are considered to be boron-epoxy, carbon-epoxy, glass-epoxy, and graphite-epoxy, and the adhesive material is adekit A140. The dimension of the patch is 200mm x 200mm x 2mm, and the adhesive thickness is 0.8mm. The crack size is considered to be 80mm. Fig. 10 shows the 30° inclined angle results in modes I and II. Boron-epoxy's K_I is the lowest in different immersion times compared to the other patch materials. From 0 to 32 days, it gradually increases up to 5.3%. Glass-epoxy has the highest K_I values, followed by carbon-epoxy and graphite-epoxy, which are lower and have almost the same K_I values. Those values have the same trend, increasing up to 5%. K_{II} results have the same trends as the K_I, increasing gradually from 0 to 32 days, around 11.6%. Boron-epoxy has the lowest SIF, glass-epoxy has the highest SIF, while carbon-epoxy and graphite-epoxy are in the middle, almost having the same K_{II} values.

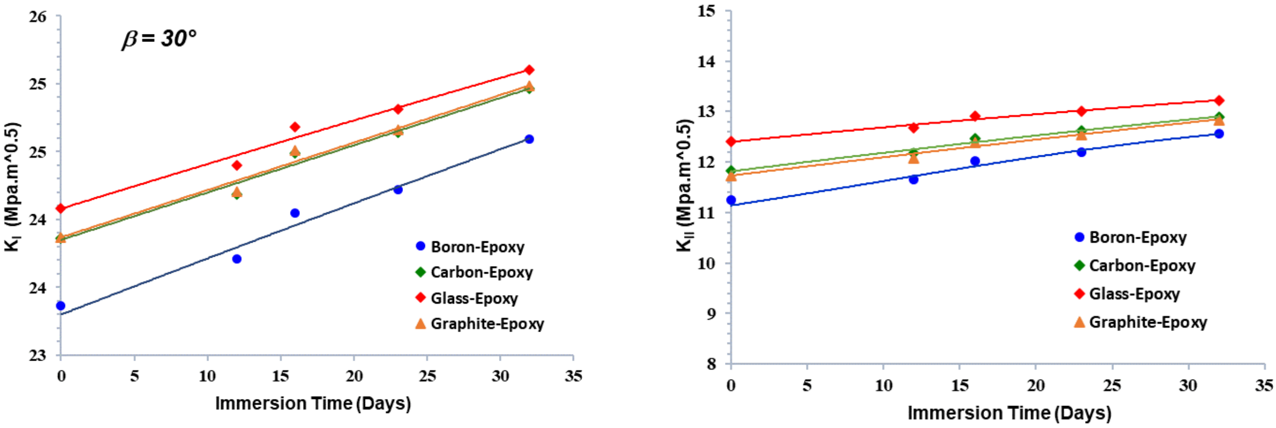

Fig. 10. SIF modes I and II vs immersion time in terms of different patch materials (β = 30°)

Fig. 11 shows the results of 45° both modes I and II. The average SIF mode I is lower compared to 30° inclined angle while Mode II is higher. In mode I SIF, all of the patch materials increase when the immersion time is longer. Boron-epoxy still has the lowest SIF average compared to the other patch materials. The values of boron-epoxy's K_I increased by 1.69% from 0 days until 32 days. Glass-epoxy has the highest K_I values, followed by carbon-epoxy and graphite-epoxy. All the patch material's K_I increased when the immersion time is longer. The K_{II} results have the same behavior as the K_I, but the glass-epoxy has the higher K_{II}, while boron-epoxy still has the lowest results compared to the others. Those values increase by around 7.72%. Fig. 12 shows the results for 60° inclined angle. The SIF results, modes I and II increase when the immersion times increase. This behavior is similar to the 30° and 45° inclined angles. However, the other patch material has different results for K_I. Glass-epoxy has the lowest mode I SIF, while boron-epoxy has the highest values. Graphite-epoxy and carbon-epoxy are in the middle. The increases in the SIF are not too significant when the immersion time is longer. For example, graphite-epoxy from 7.21 MPa√m to 7.25 MPa√m while the other inclined angles increase significantly. The K_{II} results have similar behavior to K_I, increasing when the immersion time is longer. Fig. 12 shows that boron-epoxy's K_{II} has the lowest values, and glass-epoxy has the highest ones. Carbon-epoxy and graphite-epoxy have the same behavior; those values are between boron-epoxy and glass-epoxy.

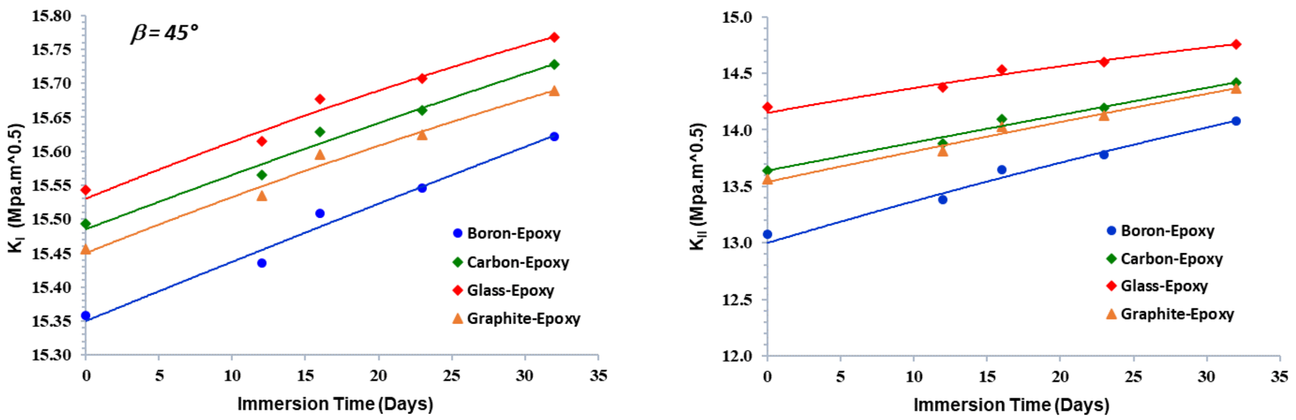

Fig. 11. SIF vs immersion time in terms of different patch materials (β = 45°)

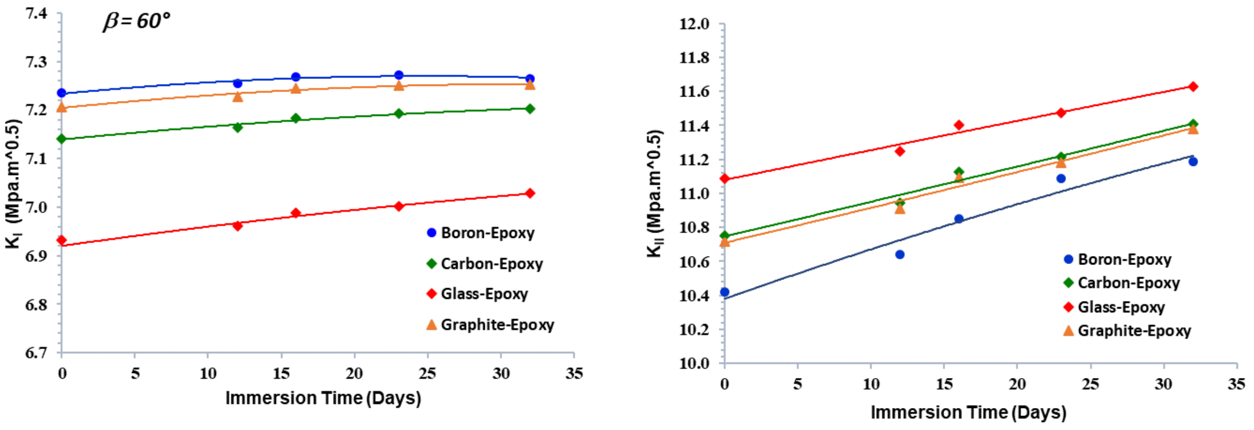

Fig. 12. SIF vs immersion time in terms of different patch materials (β = 45°)

Fig. 13 presents the study of SIF modes I and II for different inclined angles in different immersion times. It shows the SIF results comparison in a material (e.g. boron-epoxy). It presented that in mode I, 30° inclined angle has the highest value, followed by 45° and 60°. For mode II, 45° has the highest SIF while 30° and 60° almost have the same values. All the patch materials used have the same behavior in terms of longer immersion time. When the immersion time increases, the SIF modes I and II also increase. This condition affects repair efficiency and durability. Therefore, choosing the material of the patch is an essential thing to do by considering the crack conditions. For instance, choosing boron-epoxy is a good solution to repair 45° and 30° because it is presented that this material has the lowest SIF in both modes I and II. Previous research reported that humidity absorption in a normal crack is critical when repairing a cracked plate because it affects the material properties and increases fracture mechanic parameters [6]. In this study, the behavior of the inclined crack is investigated, and it showed that the SIF in both modes I and II increased. In addition, the material selection to get the most efficient patch in certain conditions is obtained by investigating the patch effect in different immersion times. This aging condition is in a normal distilled water temperature; it needs further research to study and investigate various temperature effects on repair efficiency.

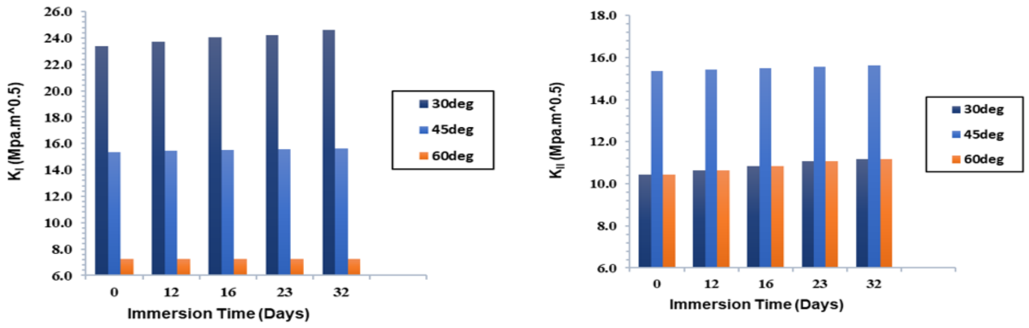

Fig. 13. SIF Modes I and II in terms of different inclined angles (boron-epoxy)

VI. OPTIMIZATION USING GENETIC ALGORITHM METHOD

The GA optimization process is performed to obtain the optimal design of the ship structural steel composite repair of central cracks under mixed-mode loading. The optimization is performed for single-sided repair. The objective is to determine the minimum mode I SIF. The search population is considered to be six individuals (chromosomes). The maximum number of generations is considered to be 20. This value of maximum generations is the same as previous composite patch optimization in aircraft applications reported by previous researchers [6]. There are various selection methods in GA optimization [13]. In this work, the selection uses the rank method to determine the best parents, with a selection rate of 20%. The type of crossover is a one-point crossover with a crossover rate of 20%. The mutation rate that is applied is 11% of the total chromosomes. The range of the design variables is 200mm to 800mm for the patch width, 200mm to 600mm for the patch length, and 2mm to 8mm for the patch thickness. Previous researchers reported the range of the composite patch design in their works, and the patch length reached up to lr/lp ratio = 0.5, and the wr/wp ratio = 1 [14]. The patch thickness for composite application in the marine industry varies from 1mm to 30mm [5]. The design variables that are determined in this work are in an acceptable range for the composite patch repair based on the reported research, especially in marine applications. The design variables of the composite patch, which are applied for the optimization parameters, affect the value of SIF [14]. Fig.14 shows the flowchart of GA optimization in conjunction with ABAQUS, and Fig. 15 shows the optimization process.

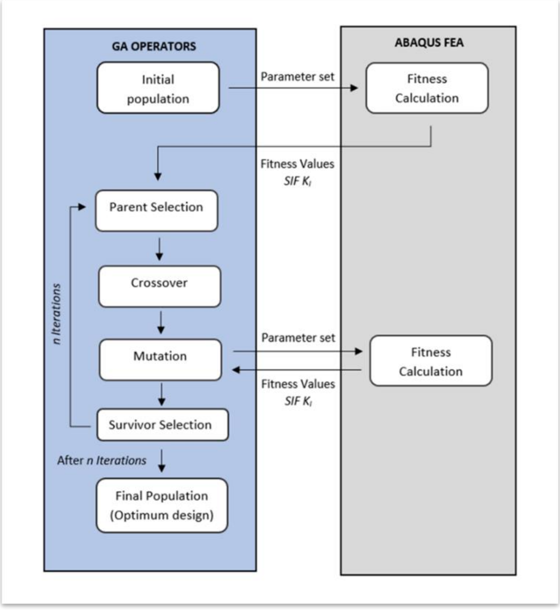

Fig. 14. Flow chart of GA optimization in conjunction with ABAQUS

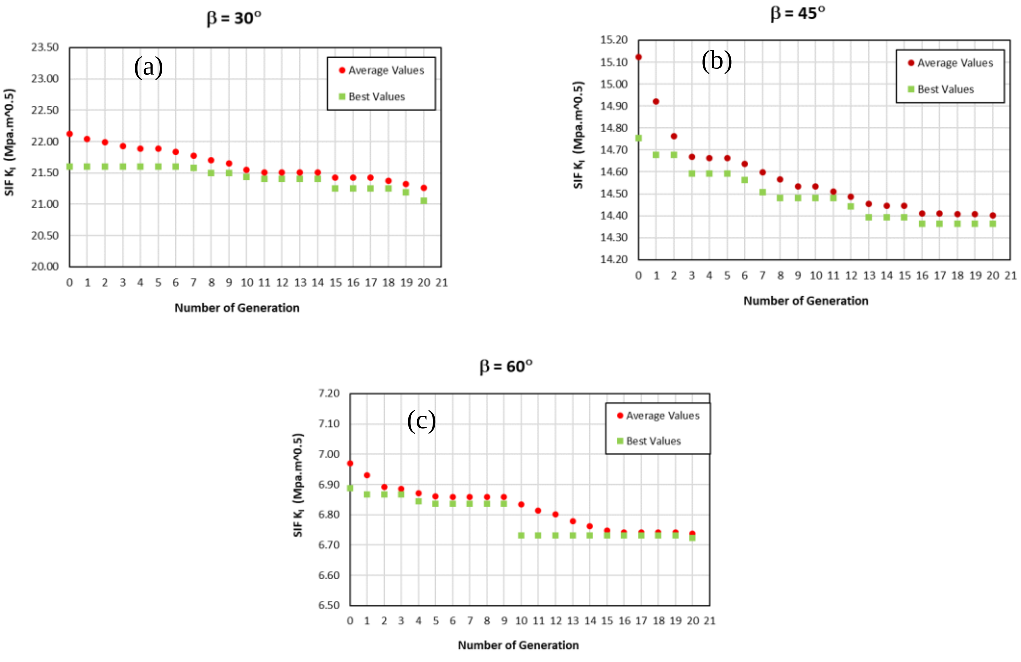

Fig. 15. GA optimization process (a) 30° (b) 45° (c) 60°

The optimization work is performed using GA, and the results are obtained for the optimum geometry in all inclined angles. The optimum design for 30° is 212mm x 275mm x 7.2mm, for 45° is 221mm x 546mm x 6.4mm, and for 60° is 297mm x 417mm x 7.7mm. Table 2 shows the SIF reduction in both modes I and II. The optimum geometry of 30° inclined angle reduces the SIF modes I and II by 5.3% and 8.47%, respectively. The optimum geometry of 45° and 60° reduces SIF mode I by 1.7% and 3.4%, respectively, while for mode II, the SIF by 2.71% and 2.44%, respectively. Fig.16 shows the modeling of the optimum design in terms of different inclined angles. The optimized patch configuration improves repair efficiency in terms of SIF reduction. This condition agrees with the research that reported that the optimization work improves the repair efficiency by reducing the SIF modes I and II [14].

Table 2 Comparison of SIF with and without optimum patch configuration

Angle (β)	**Condition**	***SIF*** K_I ***(MPa√m)***	***SIF*** K_{II} ***(MPa√m)***
30°	Without optimized patch	22.24	11.34
	With optimized patch	21.06	10.38
	Difference (%)	5.3%	8.47%
45°	Without optimized patch	14.68	12.15
	With optimized patch	14.42	11.82
	Difference (%)	1.7%	2.71%
60°	Without optimized patch	6.95	9.42
	With optimized patch	6.71	9.19
	Difference (%)	3.4%	2.44%

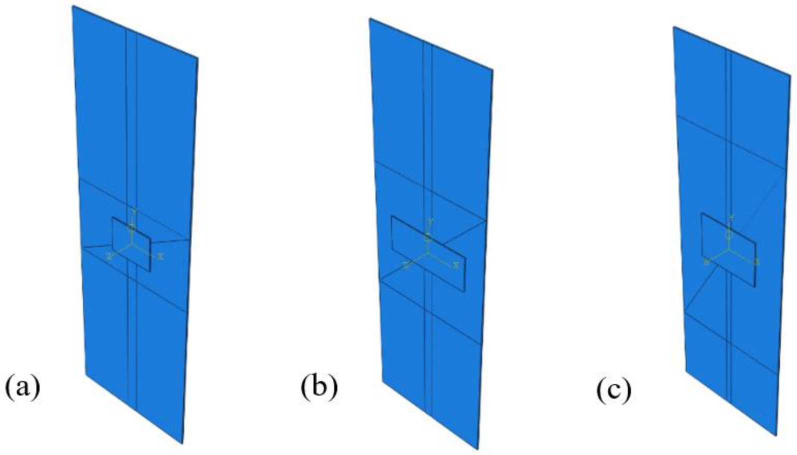

Fig. 16. Optimum patch designs using GA. (a) 30° crack angle (b) 45° crack angle (c) 60° degree crack angle

VII. OPTIMUM PATCH PERFORMANCE STUDY IN DIFFERENT IMMERSION TIMES OF ADHESIVE HUMIDITY ABSORPTION

Table 3 shows the comparison between the optimum patch designs and initial designs. Generally, the optimum designs reduce the K_I values in different immersion times of the adhesive. For 30° inclined angle, the reduction of SIF is almost the same as the condition before the immersion. The value is up to 5.8%. The performance of the optimum patch for 45° inclined angle decreases as the immersion time is longer. The reduction value is 1.88% in 0 days of immersion, and it becomes 0.2% in 32 days of immersion. There is no K_I value of optimum designs that is higher than the unoptimized. In terms of 60° inclined angle, the performance of the optimum design decrease as the immersion time is longer. The reduction value starts from 3.56% in 0 days of immersion and 1.88% in 32 days. K_I values of the optimum patch design are lower compared to the unoptimized patch designs even though the reduction decreased in some conditions, but there is no K_I value that is higher than the unoptimized designs in all inclined angles.

The behavior of mode II is the same as the SIF mode I in terms of different immersion times of the adhesive; the optimum designs reduce the SIF values. For 30° inclined angle, the performance of K_{II} is lower as the immersion time is longer. The reduction is 8.47% in 0 days of immersion and decreases gradually to 5.36% in 32 days. The performance of the optimum patch at 45° inclined angle decreases as the immersion time is longer. The reduction value is 2.84% in 0 days of immersion and 1.15% in 32 days. For 60°, The performance of the optimum design decrease when the immersion time is longer. The reduction value starts from 2.45% in 0 days of immersion and decreases to 1.88% in 32 days. K_{II} values of the optimum patch designs are lower compared to the unoptimized patch designs, even though the reduction decreases when the immersion time is longer, but there is no K_{II} value that is higher than the unoptimized designs in all inclined angles. Therefore, In the case of SIF modes I and II, the optimum patch design improves the repair efficiency in different inclined angles and immersion times of the adhesive.

Table 3 . SIF mode I reduction of optimum design in terms of adhesive humidity absorption in different immersion times.

β	Immersion time	K_I ($Mpa\sqrt{m}$)			K_{II} ($Mpa\sqrt{m}$)		
		Initial design	**Optimum**	**difference (%)**	**Initial design**	**Optimum**	**difference (%)**
30°	**0 days**	22.39	21.09	5.81%	11.24	10.29	8.47%
	5 days	22.40	21.10	5.81%	11.25	10.30	8.46%
	12 days	22.61	21.28	5.85%	11.64	10.72	7.86%
	16 days	22.80	21.48	5.81%	11.99	11.13	7.14%
	23 days	22.91	21.59	5.75%	12.15	11.34	6.72%
	28 days	23.12	21.84	5.53%	12.47	11.75	5.75%
	32 days	23.14	21.87	5.49%	12.51	11.80	5.63%
45°	**0 days**	14.66	14.39	1.88%	12.09	11.75	2.84%
	5 days	14.66	14.39	1.88%	12.09	11.75	2.84%
	12 days	14.73	14.53	1.38%	12.38	12.09	2.30%
	16 days	14.80	14.66	0.95%	12.64	12.41	1.77%
	23 days	14.83	14.72	0.73%	12.76	12.57	1.53%
	28 days	14.90	14.86	0.26%	13.02	12.87	1.18%
	32 days	14.90	14.87	0.20%	13.05	12.90	1.15%
60°	**0 days**	6.95	6.70	3.56%	9.38	9.15	2.45%
	5 days	6.95	6.70	3.56%	9.38	9.15	2.45%
	12 days	6.97	6.74	3.22%	9.57	9.36	2.17%
	16 days	6.98	6.79	2.82%	9.75	9.55	1.99%
	23 days	6.99	6.81	2.57%	9.84	9.65	1.94%
	28 days	6.99	6.85	1.94%	10.02	9.83	1.88%
	32 days	6.99	6.86	1.88%	10.04	9.86	1.88%

VIII. CONCLUSIONS

According to the study in this paper we can conclude:

- For all inclined angles investigated, the adhesive's humidity absorption significantly affects the repair efficiency. As the immersion time is longer, the SIF in modes I and II Increase. Therefore, patch efficiency decreases when the immersion time is longer.
- For all inclined angles investigated, in all immersion times of the adhesive, the SIF in both modes I and II increases significantly as the crack length increases. Therefore, patch efficiency decreases when the crack size increases.
- In case of different patch materials, the SIF in both modes I and II relatively increase as the immersion time is longer. Therefore, for all patch materials, the repair efficiency reduces when the immersion times is longer.
- In general, in different inclined angles, SIF in modes I and II of the patch materials such as boron-epoxy, graphite-epoxy, carbon-epoxy, and glass-epoxy increases slightly from 0 to 32 days.
- Boron-epoxy and glass-epoxy have the highest and lowest efficiency, respectively, based on SIF modes I and II values in different immersion times for 30° and 45° inclined angles. Even though boron-epoxy has the most significant increases, its values in 0 to 32 days are the lowest compared to the others. Graphite-epoxy and carbon-Epoxy almost have the same behavior. For 60° inclined angle in all immersion times, in mode I, Glass-epoxy and boron-epoxy have the highest and lowest patch efficiency, respectively, while in mode II boron-epoxy has the highest and glass-epoxy has the lowest SIF. Carbon-epoxy and graphite-epoxy are in the middle and have almost the same behavior.
- The optimal geometries (lr x wr x tr) of the composite patch for ship structural steel using GA are as follows; 212mm x 275mm x 7.2mm (30° angle), 221mm x 546mm x 6.4mm (45° angle), and 297mm x 417mm x 7.7mm (60° angle). Those optimal geometries practically reduce the SIF in both modes I and II. Therefore, the optimum designs improve the patch efficiency for ship structural steel.
- For different immersion times and all inclined angles, from 0 to 32 days, the optimum designs constantly improve the repair efficiency in both modes I and II. No SIF values of the optimized design are higher than the unoptimized design. Therefore, optimum design performance constantly makes the patch more efficient.

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