



ARTICLE

Mechanical Behavior of Patched Steel Panels at Elevated Temperatures

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ABSTRACT

Preventive maintenance is an accepted practice in engineering to keep the structural reliability of ship hulls at the highest possible level. Designers ensure a longer period in between the consecutive maintenance of ship hull parts to optimize expenditure. This is relevant in view of the difficulty in reaching farthest corners in ballast tanks, fuel storage tanks, cofferdams etc. Prior maintenance of the deck and hull parts save a considerable amount of the owner's budget. A portable technology like patching becomes more handy and economic. Performance of both unpatched and patched samples during dynamic loading conditions being examined in the present investigation. The high strength steel panels with a dimension of 70mm×15mm×3mm were edge cracked for lengths of 4mm and 7mm, with width of 1mm for both. The edge cracked high strength steel panels are repaired with composite patches using GFRP (glass fiber reinforced plastic), CFRP (carbon fiber reinforced plastic) and AFRP (aramid fiber reinforced plastic). The patching was done by 3 and 5 layered and impact tested by Charpy impact tester at ranges of high temperatures. The amount of energy absorbed in the impact is converted to dynamic fracture toughness values and compared for evaluating the performance of FRP (fiber reinforced plastics). Finite element analysis was done for evaluating the stress intensity factors at different types of patching and testing conditions. Comparatively the AFRP patched samples showed better dynamic fracture toughness values at different temperatures.

1. Introduction

Steel and aluminum are widely used in marine applications. Marine structures constructed using these metals will be subjected to dynamic and fatigue loadings under different environmental conditions. Because of continuous exposure of the structure in marine atmosphere cracks may develop and lead to catastrophic

failure of the entire structure. The fracture control in structural components is one of the most important areas which require detailed study. Understanding the characteristics of failures from previous case studies can deepen the knowledge in building a safe and reliable structure. There is always scope for a question of how to increase the materials performance in different operating conditions. The

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protection of materials in a marine environment is always a challenge to both to the designer and operator. Two types of approaches are adopted, which are permanent and temporary repair methods. In permanent repair solutions, a designer should accommodate major or minor modification in the design by reinstalling or removing some parts of a structure after the crack confirmation. Temporary repair solutions use traditional industrial practices like re-welding over the crack, riveting or drilling hole near the crack tip for arresting crack growth and grinding off the cracks. These are effective up to a certain extent, but the welding or grinding of soft metals will make it unfit for structural applications. The method composite patching can be done with low cost, ease of portability and ready to use for repairs. The composite patching can be used for repairing micro to macro-cracks. Patching is useful in effective maintenance of decks and other superstructures of ships and offshore structures subjected to different environmental conditions.

The inspiration for the present work is derived from the literature reviews and innovative findings till date. The investigators in the early 70s^[5,6] studied the behavior of metals subjected to dynamic loading and different environmental conditions. The designers and analysts understood the importance of mechanical behavior of metals and started studying the characteristics and reasons for failures. A few authors^[8,9,12] found it uneconomical in bringing major modifications for the existing structures i.e., permanent modifications. They started suggesting the repair schemes for the existing structures and developed the traditional repairing methods. The traditional methods showed limitations such as time-consuming and sometimes non-effective in arresting the crack growth. Therefore in mid-80s industries shifted to composite materials for repairing structural components. Designers started proposing composites in the fundamental design considerations^[7]. The structural components repaired using composite patches showed improvement in duty cycles^[10]. Professional bodies like IACS (International Association of Classification Societies) and TSCF (Tanker Structure Co-Operative Forum) recognized composite for repairing of crack as industrial practices^[11].

In the early 90s^[13,14] industries emphasized improving the quality of repair by considering factors such as the location of the crack, factor for crack growth etc. Many procedures were proposed by ASTM (American Society of Testing Methods) for applicability of the composites in repairing the corroded cracked parts. After patching the cracked metals corroded less and showed an increase in duty cycles. In the late 90s and early 2000s, the corridors of material technology witnessed the use of composite op-

timium patch thickness which can have a significant effect on crack trajectories^[15,16]. The fiber orientations will help in arresting the mixed mode crack leading to increased reliability.

Even though composites showed promising in repairing of cracked panels, studies showed that care to be taken while production processes. Many researchers pointed out that debonding as the primary reason leading to failures because of rupture with the substrate^[18]. Debonding occurs due to the bending of specimens, manufacturing defects or high peel stress near the patched area and the combination of all these. Industries always had a concern towards the application of composites in impact testing because of these limitations. Different types of FRP used showed an impact on the energy absorption capacity of the repaired components^[19,20]. The different number of patch layers influenced improving energy absorption capacity.

The composites showed a limitation to humidity and ultraviolet radiations during their duty cycles. Aging of composites is responsible for the reduction in mechanical properties and may lead to catastrophic failures^[21]. Some researchers adopted different types of filler materials and testing procedures for evaluating the performance of composites^[22,23]. Finite element analysis was used for analyzing the stress intensity factor at different moisture and temperature conditions. Attention was paid in analyzing the crack growth behavior considering different adhesive properties, a geometry of the patch and its influence on reducing the stress intensity factor^[24-26]. An attempt was made recently by testing the samples at low temperatures and it was observed that different types and orientation of fibers in FRPs showed influence on dynamic fracture toughness of the repaired samples^[27]. At low temperatures, the patched samples were able to maintain the dynamic fracture toughness values without much variation and that was true even at cryogenic conditions. In one of the mechanical tests, it was observed that the patching could reduce the stress field around the crack^[28]. Optimization of mechanical properties and geometric parameters of patches will affect the performance of damaged structures^[29].

An attempt has been made in present work to repair structural components of high strength steel. Steel patched samples were tested for high temperatures; energy absorption at the respective temperatures was noted and later converted to dynamic fracture toughness values. The behavior of the composite patched panels at different temperatures along with variation in fracture toughness was observed. Corresponding stress intensity factor values were found for different crack lengths using finite element analysis. This exercise was performed for with and without patches at different temperatures.

2. Experimental and Numerical Works

2.1 Experimental Details

The Charpy impact test was carried out on the high strength steel patched samples using three different types of composite materials, widely used as structural components. Tables 1 and 2 shows the properties of patch and substrate materials taken for the study. The test piece is a rectangular bar of dimension 70mm×15mm×3mm, with a crack length of 4mm at the center and crack width 1mm. The same test piece with 7mm crack length also used figures 1(a) and 1(b) are relevant to this discussion. The samples were patched by hand layup process using bidirectional GFRP, AFRP and CFRP and later pressure were applied.

Three layers and five layers patches were prepared according to ASTM D2093. After preparing the patches were allowed for 48hrs curing before testing. The dimensions of the patches are 30 mm×10 mm dimensions are considered in such a way that notch is covered completely concerning Khallili et al. [19]. The number of plies is considered based on fracture toughness values from mechanical testing. The stiffness ratio (SR) is calculated based on the equation [19];

$$SR = \frac{E_p t_p}{E_s t_s} \quad (1)$$

Where E is Young's modulus, t is the

thickness, subscript p and s stand for patch and substrate properties. SR ratios of different types of FRPs are shown in table 3.

The patch thicknesses are different for different types of FRPs shown in table 3. Araldite 2015 was used as an epoxy resin for patches of FRPs to the substrate. The area around the notch of a substrate is roughened by scrubbing, for better bonding of FRPs to the metal surface. The bond line thickness is insignificant because just we have applied one layer, and no pressure for bonding was applied, and the patch is double-sided. Figure 1(c) shows the patched crack on the sample. The samples were tested at temperatures of 30°C, 100°C, and 250°C. The samples absorbed a certain amount of energy before it broke and later the influence of temperature on the dynamic fracture toughness were noted.

For converting the Charpy values (Impact values) to K_{Ic} (Fracture toughness) as per Novak-Rolfe ASTM STP 466 (1970)

$$\left(\frac{K_{Ic}}{\sigma_y} \right)^2 = 5 \left(\frac{\text{Charpy values}}{\sigma_y - 0.05} \right) \quad (2)$$

Where, fracture toughness K_{Ic} in MPa√m, Charpy values in joules, σ_y yield strength of the substrate material in MPa.

Followed by experiment the simulation is done using FRANC 2D/L for plane layered structures. The stress intensity factors for different crack length at different temperatures were simulated using FRANC software.

The equation (2) is used for arriving at the stress intensity values at different crack lengths and comparing with FRANC values for validation. For single edged notched bend sample, equation as per Anderson [2]

Table 1. Mechanical properties of tested materials

Type of material	Young's modulus E (GPa)	Poisson's ratio ν	Density ρ(g/cc)	Yield strength σ _y (MPa)	Co-efficient of thermal expansion α (/°C)
High strength steel	210	0.3	7.8	353.4	11.6×10 ⁻⁶

Table 2. Mechanical properties of composite materials

Type of composite	Young's modulus E ₁ (GPa)	Young's modulus E ₂ (GPa)	G ₁₂ (GPa)	Poisson's ratio ν	α (strain/K)	β (strain/K)	Density ρ(g/cc)	Volume fraction
GFRP (E- glass)	25	25	4	0.2	11.6	0.03	1.6	0.5
CFRP(300 GSM)	70	70	5	0.1	2.1	0.07	1.9	0.6
AFRP (29)	30	30	5	0.2	7.4	0.07	1.4	0.4

Table 3. Mechanical properties of tested materials

Type of FRP	Stiffness ratio of different layers		Thickness of layers (in mm)		Mass of layers (in gm)	
	3 layers	5 layers	3 layers	5 layers	3 layers	5 layers
GFRP	0.015	0.025	0.39	0.65	0.245	0.4017
CFRP	0.0566	0.094	0.51	0.85	0.244	0.408
AFRP	0.0165	0.0273	0.345	0.575	0.1449	0.2415

$$K_I = \frac{P}{B\sqrt{W}} f\left(\frac{a}{w}\right)$$

$$f\left(\frac{a}{w}\right) = \frac{3 \frac{s}{w} \sqrt{\frac{a}{w}}}{2 \left(1 + 2 \frac{a}{w}\right) \left(1 - \frac{a}{w}\right)^{\frac{3}{2}}} \left[1.99 - \frac{a}{w} \left(1 - \frac{a}{w}\right) \left\{ 2.15 - 3.93 \left(\frac{a}{w}\right) + 2.7 \left(\frac{a}{w}\right)^2 \right\} \right]$$

Where K_I is a stress intensity factor, and w length and width of crack, B breadth, P load, S length of the sample, $f(a/w)$ correction factor.

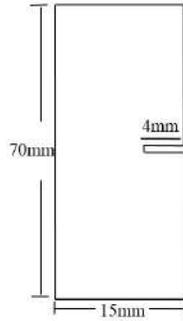


Figure 1. (a) 4mm cracked panel

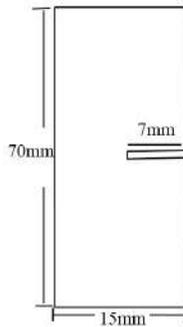


Figure 1. (b) 7mm cracked panel.

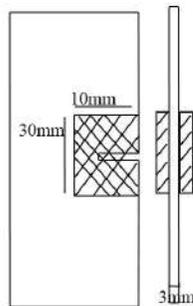


Figure 1. (c) Patch dimensions

Figure 1(a) and 1 (b) illustrates the dimensions of cracked panels prepared as per ASTM D 2093 and in figure 1 (c) shows the patch dimensions along with thickness.

(3) Figure 1 (d) consists of patched and unpatched samples before testing or after testing which is destructive.

Figure 1(e) shows the description of the testing device, the samples after patching are mechanically tested. The samples are placed on the sample holder, and the pendulum hits the sample shown in figure 1(f). The energy absorbed by the sample is indicated by the device.

The notched sample is kept with the crack tip facing the pendulum, and corresponding reading are noted.



Figure 1. (d) Patched and unpatched samples



Figure 1. (e) Charpy impact tester

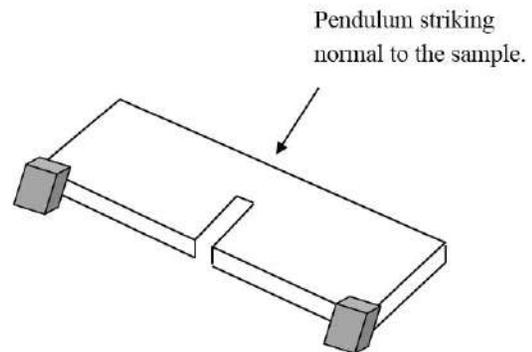


Figure 1. (f) Position of sample



Figure 1. (g) Samples after the tests



Figure 1. (h) Samples exposed to a temperature of 250°C beyond

The figures 1 (d) and 1 (g) illustrates the patched and unpatched samples which were tested at different temperatures. Only 5 layered AFRP found bending and observed the right amount of energy compared to 3 and 5 layered GFRP and CFRP and even 3 layered AFRP patched samples. The unidirectional laminates with different layers are obstructing the growth of the crack. The patching is effective in closing the width of the crack and lessens the stress at the crack tip and further growth of crack is stopped. Debonding is one of the major problems during tests and normally starts from the edges. Care is to be taken during manufacture as the debonding can lead to failure of a sample with less energy absorbed. The samples tested at different temperatures were able to retain the fracture toughness values at certain temperatures. Even after exposing to high temperature, a slight change in color of the patch is observed without affecting the fracture toughness of the sample. But up to 250°C, the patched samples retained their strength and beyond this temperature, patches lost their original appearance that is derivated from figure 1 (h). Five layers AFRP patched samples are found bent as a result of fibers crossing each fiber, while other patched samples failed by fiber pullouts.

2.2 Simulation Details

The modeling is done by CASCA for initial meshing, the input for FRANC 2D/L is created. The input file is fed

into FRANC software for estimating the stress intensity factors for different crack lengths. The material properties, boundary conditions, and analysis typesetting can be performed by FRANC software. The winged edge data structure is used in the design and analyses of FRANC 2D/L software. The winged data structure consists of vertices, faces and edges have main entities. These entities represent finite nodes and elements, the data structure contains adjacency information. This reduces the time required for finite element analysis and the adjacency defines the structural boundaries. Adjacency helps in deleting the elements during the crack propagation without deleting the edges and helps in recomputing the stiffness matrices. The software uses eight and six node elements with quadratic shape function by performing an elastic analysis. The stress singularity near the crack tips can be computed by moving six nodes to the quarter point locations. During analyzing coated samples the interface elements have relied upon to represent contact between surfaces. A relationship for defining the surface tractions are integrated for nodal loads during the dynamic relaxation solution. The linear elastic fracture analysis concepts are used for calculating stress intensity factors using displacement correlation or modified crack closure methods. During the crack propagation, the automatic remeshing strategy is adapted to delete the elements vicinity of the crack tip. Move the crack tip and then insert the trial mesh for connecting to the new crack of existing mesh. The dynamic relaxation solver is performed for damping solution until all the motion stops. During each iteration, the external load vector is calculated and the matrix multiplication is performed and subtracted along with the damping terms. As the acceleration and velocity terms approach zero, static equilibrium is achieved by balancing internal forces and external ones. The solution scheme is stable and will converge after many iterations depending on eigenvalues.

3. Results and Discussions

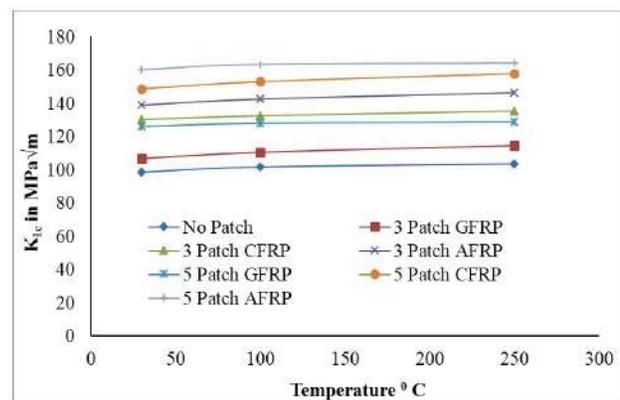


Figure 2. 4mm cracked panels fracture toughness against temperature

Figure 2 illustrates the fracture toughness of the 4mm cracked panels with and without a patch for different numbers of layers, types of patches at different temperatures. The variation in fracture toughness is observed for different types of patches. The fracture toughness is constant for particular patching.

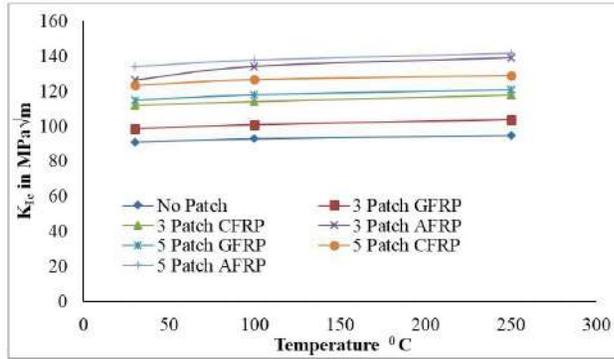


Figure 3. 7mm cracked panels fracture toughness against temperature

The observation for fracture toughness for the 7mm cracked panel is shown in figure 3 the trend of variation is similar to that in figure 2. However, there is a difference in fracture toughness values. Due to an increase in crack length value of 7mm the patch dimensions are unchanged therefore a decrease in toughness values. At a certain temperature, the fracture toughness of the patched samples was maintained without much difference, beyond which the fracture toughness decreased drastically. However, fire element retardant ingredients can be added to the composite so that the patching will maintain the mechanical properties like fracture toughness at higher temperatures.

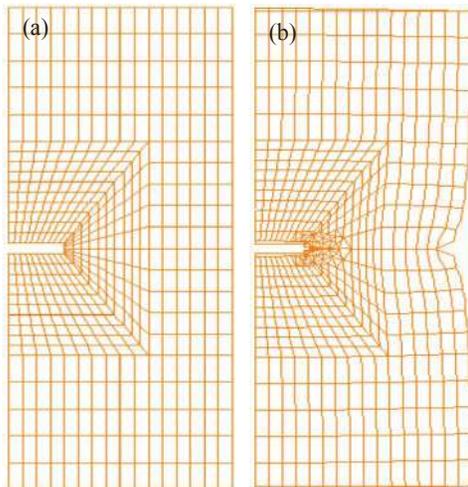


Figure 4. (a) Sample before cracking

Figure 4. (b) Initiation of crack

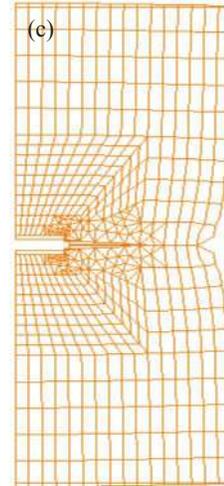


Figure 4. (c) Propagation of crack

Figure 4(a) illustrates unpatched samples before cracking and figures 4(b) shows its initiation. Figure 4(c) shows the propagation of the crack.

Figure 4(d) illustrates the fully grown crack along with the sample deformation because of no resistance for the crack growth and sample fails. Simulation of patched samples shows increment in energy absorption and obstruction for the growth of crack compared to unpatched samples illustrated in figure 4(e). Figure 4(f) shows the remeshing in the patched sample along with crack growth. The patching along with a number of layers is having an impact on the crack growth and reduced stress intensity near crack tip.

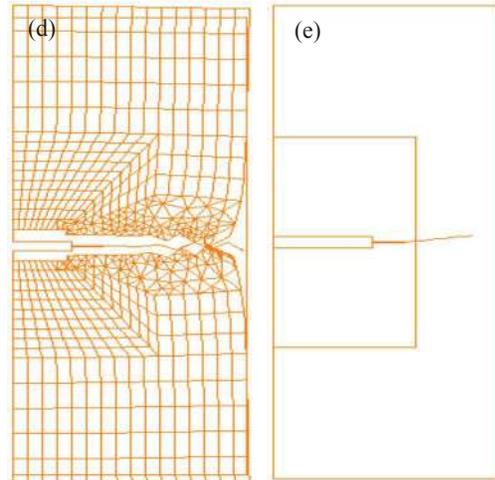


Figure 4. (d) Fully developed crack

Figure 4. (e) Patched sample along with crack

The validation of stress intensity factor between analytical values as per equation (2) and FRANC 2D/Lare shown in figures 5(a) and 5(b) for 4mm and 7mm cracked panels respectively. The analytical and FRANC values are calculated for different crack lengths and compared, a good

agreement can be observed.

The FRANC 2D/L analysis for different crack lengths and temperatures are shown in the following figures. Steel patched samples tested at high temperature shows an increase in K_I values for unpatched compared to patched ones. The K_I values vary for different types and layers of patched samples.

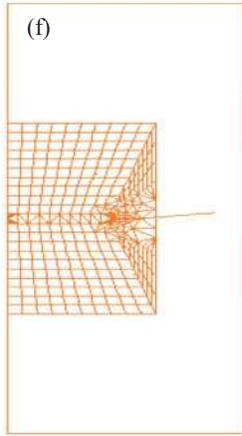


Figure 4. (f) Patched sample with further crack growth

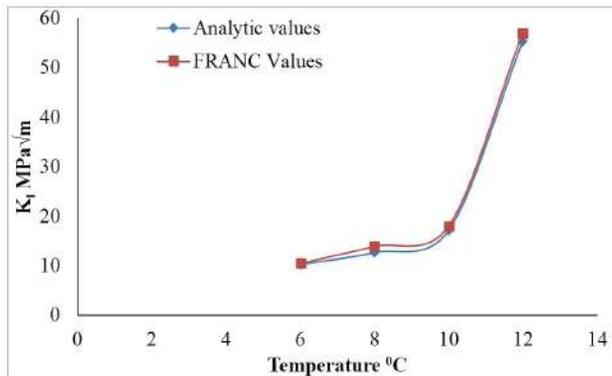


Figure 5. (a) Comparison of stress intensity factor for 4mm cracked panels

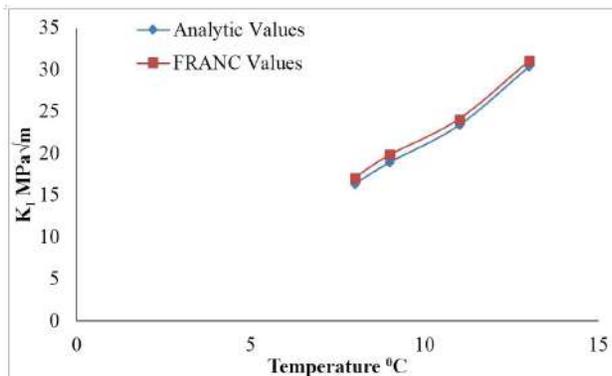


Figure 5. (b) Comparison of stress intensity factor for 7mm cracked panels

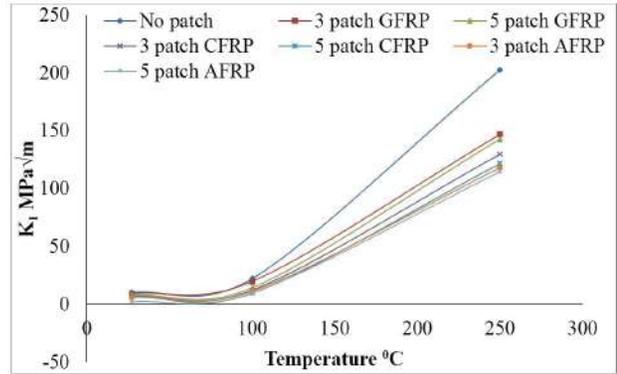


Figure 6. K_I against temperature for an increase in crack length from 4mm to 6mm

Comparatively the increase in patch layers shows a decrement in K_I values, offering obstruction for crack bridging.

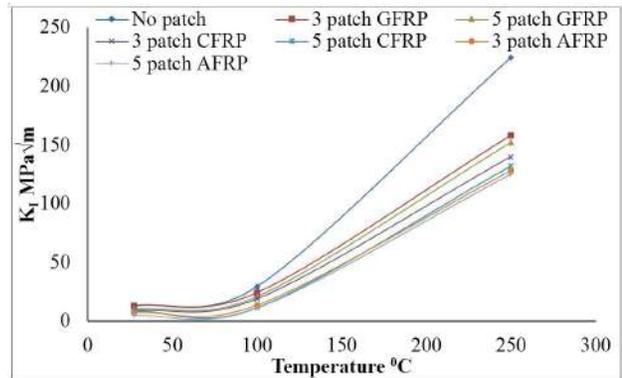


Figure 7. K_I against temperature for an increase in crack length from 4mm to 8mm

Further in figure 7 the increment in crack length made K_I rise in value and variation is similar to figure 6 with high K_I values. As per figure 8, the crack neared the end of patch boundary leading to a sudden increase in K_I value. The dimension of patching has an influence on the K_I values and as the crack near the end of patch, area showed a striking effect on crack bridging phenomenon.

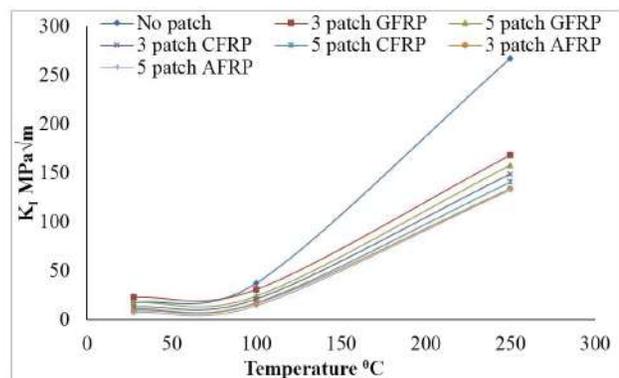


Figure 8. K_I against temperature for an increase in crack length from 4mm to 10mm

Therefore the crack bridging is occurring easily without much obstruction for crack growth.

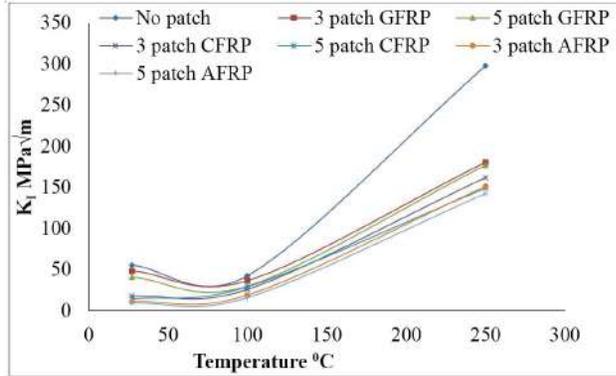


Figure 9. K_I Against temperature for increase in crack length from 4mm to 12mm

The crack after crossing the patched area shooting up in stress intensity factor can be seen in figure 9. In patched sample the crack after crossing the patched area there is a small variation in stress intensity values. Except in 5 layered patch there is an increase in fracture toughness and reduced stress intensity values. The increase in patching layers has shown a promise in case of repairing macro-cracks.

In 7mm cracked steel patched samples a further increase in K_I value is seen in figure 10. With increase in crack length and keeping patch dimensions same, there is an increase in stress intensity values from 7mm cracks. The variation in patch dimensions can influence the crack growth resistance.

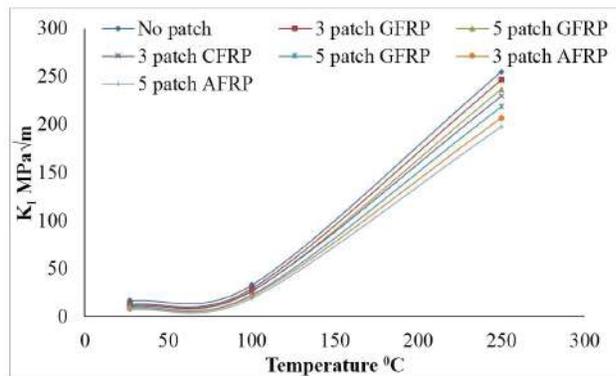


Figure 10. K_I Against temperature for an increase in crack length from 7mm to 8mm

In 7mm cracked panels an increase in stress intensity values can be observed as predicted and this is in comparison with 4mm cracked panels in figure 10. The crack length increment in the patched sample there will be minimal effect on stress intensity values.

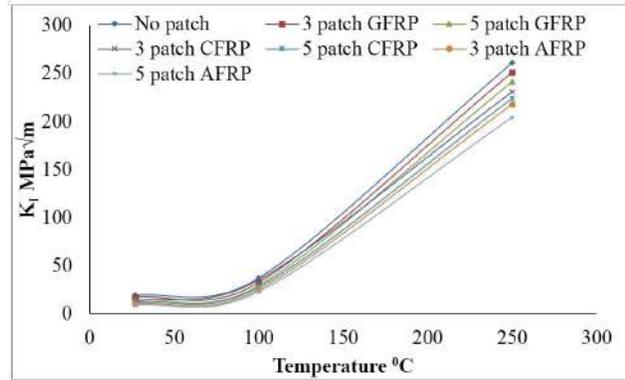


Figure 11. K_I Against temperature for an increase in crack length from 7mm to 9mm

There was a relative difference in growth in K_I value as the crack neared the patch boundary and it is shown in figure 11. Again the increase in crack length reduced the stress intensity value difference in unpatched and patched conditions. The increase in a number of patch layers has a minimal effect on the fracture behavior and stress intensity values.

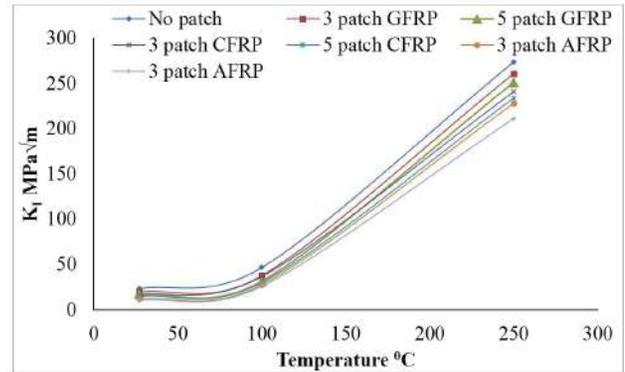


Figure 12. K_I Against temperature for an increase in crack length from 7mm to 11mm

Figure 12 and 13 shows the K_I values at a higher temperature for longer crack length. At lower temperature, it is non-linear and at high temperature say 100°C it is almost linear.

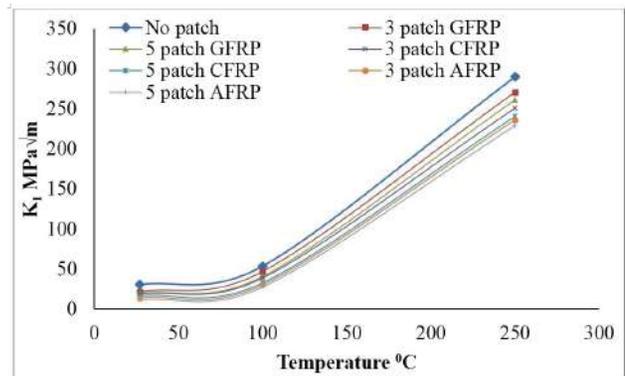


Figure 13. K_I Against temperature for an increase in crack length from 7mm to 13mm

The non-linear increase in the value of stress intensity against temperature is observed. However, the patches are ineffective at such high temperatures. Therefore the dimensions of patch play a key role in arresting or offering a resistances for the crack to grow. The AFRP patched samples at high temperatures were able to increase in DFT values compared to GFRP, and CFRP patched samples. Experimental investigation along with simulation showed the influence of temperature on the dynamic fracture toughness of the patched samples. The 5 layered AFRP patched samples were found to bend and absorb a good amount of energy. The crack bridging is not occurring effectively in 5 layered AFRP samples compared to other patched samples. The crack tip is getting blunted after crossing each fiber in 5 layered AFRP; in other samples, this phenomenon cannot be observed. The energy required for crack propagation is observed by fibers in the case of 5 layered AFRP patches; while the other patched samples are broken by fiber pullouts. The temperature is playing an important role in ductility transition of the patched samples. Unidirectional composite patches exhibited superior properties at different temperatures when compared to bidirectional composites. The patched samples depending on a number of layers are able to withstand for certain temperatures. At say 30°C and 100°C with sample showing a gradual loss in the fracture toughness of patched samples. While at 250°C a sudden reduction in effectiveness can be observed. From the trend of figure 13 it can be inferred that a temperature of roughly 175°C is the safe limit for the patches to be relied upon. There is always a scope for arriving at an optimum patch area at different crack lengths.

4. Summary and Conclusions

The high strength steel samples were cut to 70mm×15mm×3mm, edged crack of 4mm and 7mm at the centre. The 3 and 5 layers patching was done using GFRP, CFRP and AFRP and impact tested by Charpy for evaluating dynamic fracture toughness values. The application of composite patch for repairing crack is found regarding the crack growth and stress intensity factor. Therefore increases the life of the structure to perform well in certain demanding condition to overcome the challenges. The performance of composites in different temperatures and environmental conditions still remains as a challenge; an attempt is to reconfirm the effectiveness of composites at high temperatures. The following conclusions are arrived at:

※As the temperature of marine hulls is near to the medium in which it floats, the technology is found suitable. If the temperature is high say 250°C, due to some reasons, the patches are found ineffective.

※The 5 layered AFRP patches proved excellent compared to other types and layers of patches because of more energy absorption.

※While characterizing the fractured samples it was observed that in 3-layered and 5-layered patched samples of GFRP, CFRP and only 3-layered AFRP samples cracked by fiber pullout.

※The 5-layered AFRP were found bending leading to de-bonding of patches but no fiber pullouts beyond 3- the layer of the patch.

※AFRP can be used effectively in repairing of macro-cracks compared to other types of composite patches.

※The stress intensity factor of crack found drastically increasing after crossing patched area compared to crack inside repaired area using patch.

※The patch dimensions will have an influence on the arresting or resistance for crack.

※The behavior of crack inside and outside the patch area along with stress intensity factor is measured at elevated temperatures by finite element analysis using FRANC 2D/L.

※Selection of filler materials can really influence the performance of FRPs particularly at high temperature applications.

Author Contributions:

S. Surendran. Was the research guide for the second author. This is an unpublished script part of the research done in the Dept. of Ocean Engineering, IIT Madras.

G L Manjunath. He is good in experimental works and has got experience in computer simulation too. FRANC 2D was extensively used for computer simulation and a number of samples were tested. This paper shows the repair of metals and joints using composite patches.

S. K Lee is a collaborator from Pusan National University, Busan, S. Korea.

Conflict of Interest. There is no conflict of interest for this work.

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