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Improving the Transient Thermal Fatigue Life of a Gas Turbine Casing by Drilling Stop Holes and Inserting Pins into Them

H. Bazvandi, E. Poursaeidi*

Department of Mechanical Engineering, University of Zanjan, Zanjan, Iran

ABSTRACT: Gas turbines casings are susceptible to cracking at the edge of the eccentric pin hole. This paper describes the improvement of the transient thermal fatigue life of gas turbines casings through the application of pins. The repair technology under consideration involved drilling a number of holes in the gas turbines casing along the crack and inserting pins into them. The crack position and direction were determined using non-destructive tests. A series of finite element models were developed and tested in AStM-A395 elastic-perfectly plastic ductile cast iron. In some specimens, holes were drilled near the crack tips. Pins were inserted into the holes in some cases. Abaqus software finite element package and Zencrack fracture mechanics code were used for modeling. The efficiency of crack repair by the installation of pins was investigated along with the effect of the number of pins on crack repair efficiency. The result shows that the insertion of pins into holes drilled in the vicinity of the crack tips is an effective method of retarding crack growth in a gas turbine casing.

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1- Introduction

The most important role of a gas turbine casing is taking turbine rotor with an axial symmetry and the inhibition of elements such as nozzles and shroud segments in its fixed position with a total high weight. In 1998, the damages of fatigue and creep in the GE-F6 blades were investigated [1]. Mestanek analyzed low cycle fatigue of the last stage steam turbine blade by using the elastic and elastic-plastic finite element methods. The results showed that the elastic-plastic finite element method was more accurate [2]. Cheong and Karstensen [3], studied fatigue crack growth in a steam turbine casing and used fracture mechanics to calculate the fatigue life of the casing [3]. Hole edge cracks have been observed in industrial components similar to gas turbine casing [4]. Gas turbine is subjected to severe thermal loads. Mariusz [5] analyzed numerically the effects of variable heat transfer coefficients and material properties on thermal stresses using the finite element method on a cylinder model. Bao [6] examined the thermal stress and fatigue fracture of a single tube for a solar tower molten salt receiver; the temperature distribution of the tube was simulated and the thermal stress was calculated by solving stress equations. Then, the minimum heat flux formula was derived when the damage occurred on the wall based on the yield criterion and heat conduction equation. Wang [7] explored glass crack initiation under thermal loads to determine the correlation between temperature change and crack initiation. They carried out a series of experiments for float and Low-E glasses under uniform radiation conditions. Chang [8] analyzed the thermal fatigue of district heating pipes. Various crack arrest technologies have been proposed based on the reduction of the stress concentration caused by a damage. Drilling holes in the tip of a crack is often employed for repairs [9, 10] to remove the geometric singularity caused by a crack tip. This drilling delays crack growth while the new crack is initiated. The size of the hole was found to influence the number of cycles to the occurrence of a new crack [10]. However, strength considerations for the structural component may constrain the maximal diameter of the crack arrest hole. Modifications of this method may include drilling the hole ahead of the crack tip or drilling a number of holes surrounding the crack tip [11]. The insertion of pins into crack arrest holes was studied theoretically by combining finite element analysis and the Coffin-Manson equation for fatigue-life estimation [12]. The numerical analysis demonstrated that this method provides better results than the expansion of a hole alone. An experimental study demonstrated that the expanded and filled crack arrest holes and composite patches are two of the most efficient crack retardation methods [13]. The authors have previously reported on the investigation of a crack detected on the edge of an eccentric pin hole in a GE Frame 9 gas turbine casing and transient thermal fatigue life under elastic-perfectly plastic and linear elastic material behavior [14]. The primary objective of this research was to develop models for repairing cracked gas turbine casings by drilling stop holes along the crack and inserting pins into the holes.

Corresponding author, E-mail: epsaeidi@znu.ac.ir

2- Turbine Casing

Turbine casing operation is similar to that of pressure vessels that tolerate hot gas pressure caused by products of combustion. Another vital role of the turbine casing is its ability to tolerate the failure of its moving parts such as turbine blades, such that if there is a high centrifugal force and failure occurrence, then there should be no possibility that the casing of the turbine is damaged by piercing. Nonetheless, due to the relatively large thickness of different parts of the casing, its vulnerability to the high temperature gradient between internal and external surfaces (creating mechanical and thermal fatigue) is much more than that of any other static or dynamic load. Chemical analysis of the turbine casing material is fully defined in Table 1 [14]. These results showed a good correlation with AStM A395 that is a kind of ductile cast iron. Table 2 shows mechanical properties of the AStM A395 ductile cast iron [14]. It is necessary to determine the boundary conditions to analyze the casing. The most important boundary condition is the temperature distribution on the surface of the casing. A previous study [14] measured the inner surface temperature using a number of thermocouples installed on the casing. In that research, ten type K thermocouples that measured temperatures ranging from 0 to 1100 °C were installed at ten positions on the turbine casing and were connected to a paperless recorder to record temperatures inside the casing (Fig. 1). The position of the crack on the casing surface was investigated using non-destructive tests [14]. Fig. 2 shows a sample crack determined by penetrant testing.

3- Crack Growth Analysis

Paris's law [15] was used to calculate crack growth as:

$$\frac{da}{dN} = C(\Delta K)^n \tag{1}$$

Where C and n are material properties. Stress intensity factors K_I, K_{II} and K_{III} play an important role in fracture mechanics, characterizing the influence of load or deformation on the magnitude of the crack-tip stress and strain fields and measuring the propensity for crack propagation or the crack driving forces. Furthermore, the stress intensity can be related to the energy release rate (the J-integral) [16]:

$$J = \frac{1}{\bar{E}}\left(K_I^2 + K_{II}^2\right) + \frac{1}{G}K_{III}^2 \tag{2}$$

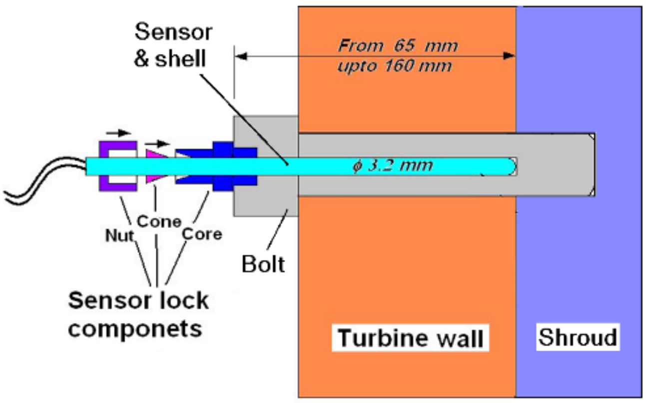


Fig. 1. Installation of thermocouples inside the turbine casing

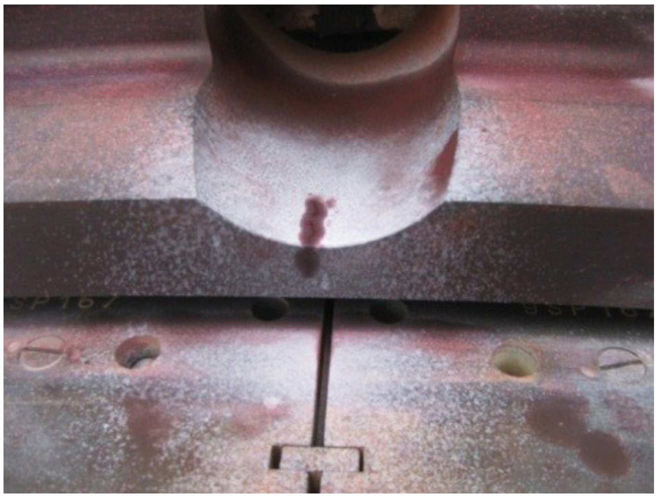


Fig. 2. PT test from crack corner at the eccentric pin hole of casing [14]

Where $\bar{E}=E$ for plane stress and $\bar{E}=E/(1-\vartheta^2)$ for the plane strain. The J-integral is widely accepted as a fracture mechanics parameter for both linear and nonlinear material responses. It is related to the energy release associated with crack growth and is a measure of the intensity of deformation at a notch or crack tip, especially for nonlinear materials. If the material response is linear, it can be related to the stress intensity factors. Because of the importance of the J-integral in the assessment of flaws, its accurate numerical evaluation is vital to the practical application of fracture mechanics in designing calculations. In the context of quasi-static analysis, the J-integral [16] is defined as:

$$J = \lim_{\Gamma \to 0} \int_A \lambda(s)\, n.H.q dA \tag{3}$$

Where Γ is a contour beginning on the bottom crack surface and ending on the top surface, as shown in Fig. 3, the limit $\Gamma \to 0$ indicates that Γ shrinks onto the crack tip, q is a unit vector in the virtual crack extension direction, and n is the outward normal to Γ. H [16] is presented by:

$$H = \left(WI - \sigma \frac{\partial u}{\partial x}\right) \tag{4}$$

For elastic material behavior, W is the elastic strain energy; for elastic-plastic or elastic-viscoplastic material behavior, W is defined as the elastic strain energy density plus the plastic dissipation, thus representing the strain energy in an equivalent elastic material. This implies that the J-integral calculation is suitable only for monotonic loading of elastic-plastic materials.

Table 1. Chemical analysis results of casing [14]

Element	C	Si	Mn	Al	Cu	Ni	V	Cr	Mg	Ti	Co	Fe
W%	3.344	2.7	0.136	0.016	0.351	0.082	0.044	0.12	0.057	0.038	0.033	Balance

Table 2. Mechanical properties of the ASTM- A395 ductile cast iron [14]

Hardness (Brinell)	Tensile strength, ultimate (MPa)	Tensile strength, yield (MPa)	Modulus of elasticity (GPa)	Poisson's ratio
167	461	329	169	0.29

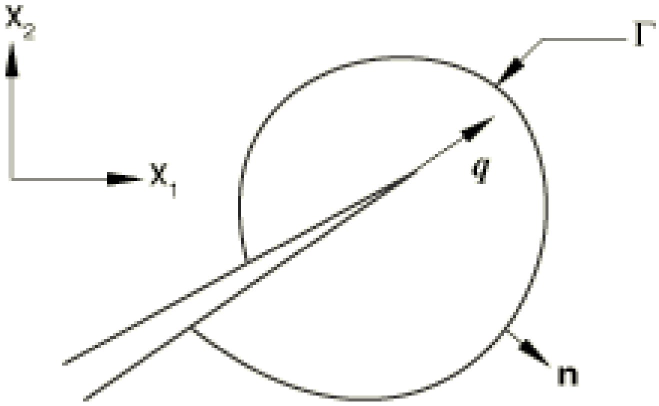


Fig. 3. Crack-tip region as *Γ*→0

4- Crack Growth Retardation

4- 1- Repair modeling

Crack repair process by drilling stop holes and inserting pins into them allows permanently repairing a crack without welding. The cracked metal is replaced with metal stitching pins installed by drilling a hole and tapping the pin into the hole to draw the sides of the crack together. This results in a continuous row of interlocking stitching pins to create a strong, pressure-tight repair. This metal stitching method is employed mostly on cast iron components but can be effective on other machinable metals such as ductile iron, steel, aluminum, and bronze castings. The cracked metal was replaced with cast master pins (Fig. 4). The experiment was performed on a sample stitching pin and a conventional bolt to show the difference between them (Fig. 5) [17]. The strain gauge used for measurement of the displacement in the conducted experiment. The experimental results showed that the displacement was negative for the cast master pins and positive for the conventional bolts (Table 3). Experimental results obtained by other authors [17] were used to verify the validity of the numerical modeling. The longitudinal and transverse displacement of the inner surface of the stitching pin hole was calculated by Abaqus software (Figs. 6, 7). The results showed that the calculated results were in a good agreement with the experimental results (Table 4).

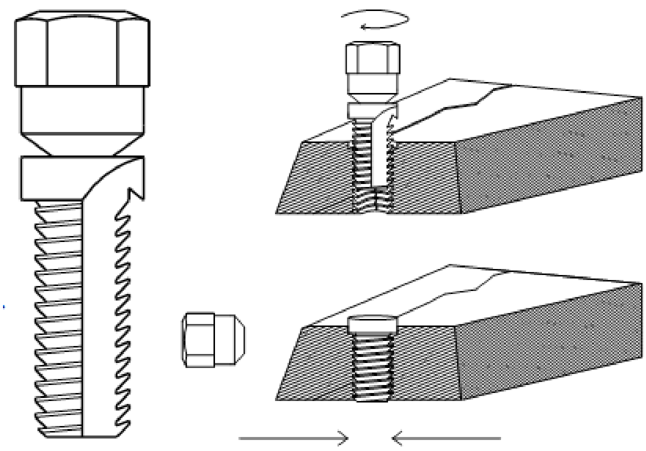


Fig. 4. Cast master pins

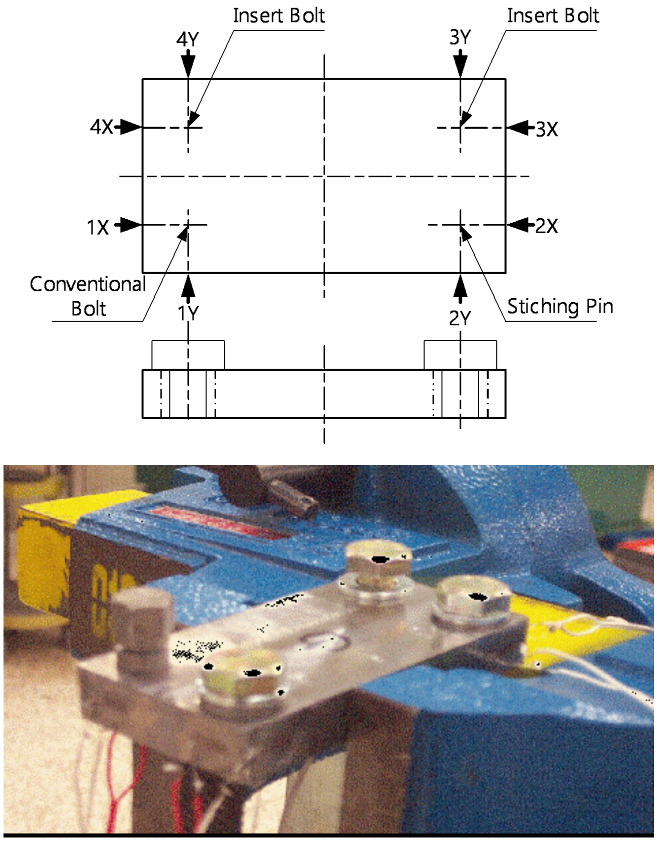


Fig. 5. Experimental procedure (80 ×160 ×25.4 mm) [17]

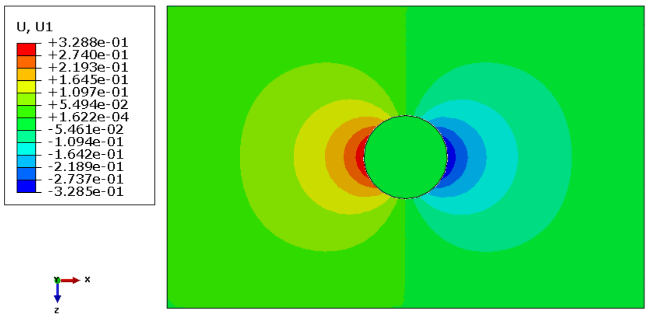


Fig. 6. Longitudinal displacement in vicinity of pin hole (mm)

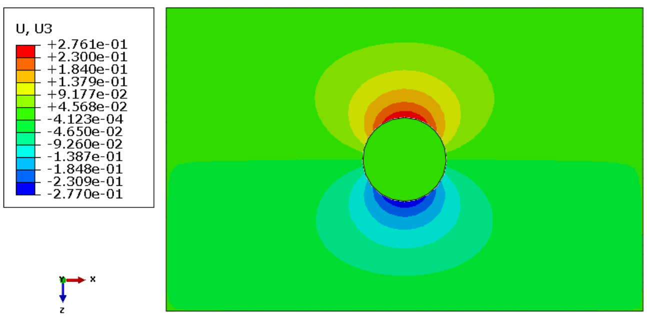


Fig. 7. Transverse displacement in vicinity of pin hole (mm)

Table 3. Displacement in longitudinal and transverse direction [17]

No.	1X	1Y	2X	2Y	3X	3Y	4X	4Y
Displacement (μm)	+3.800	+3.760	-326	-274	-547	-563	-587	-568

Table 4. Displacement in longitudinal and transverse direction for the stitching pin

Displacement	Longitudinal	Transverse
The experimental results (μm)	-326	-274
The numerical results (μm)	-328	-277

4- 2- Crack growth retardation of gas turbine casing

The fracture mechanics model was first developed and applied to the analysis of the efficiency of crack repair by the installation of pins during loading of the cracked part. The CT specimen represented a structural part made of a sheet of AStM-A395 elastic-perfectly-plastic ductile cast iron (Fig. 8).

The growth of the crack was analyzed under cyclic loading of constant amplitude at a load ratio of $R=(P_{min}/P_{max})=0$ where P_{max} and P_{min} are the maximal and minimal loads, respectively. Duplex steel pins were employed in the repair (Table 5). In the first step, the CT specimen was analyzed before the repair (Fig. 9). In the next steps, 2, 3, and 4 pins were applied to the CT specimens (Fig. 10). The results of the calculations for mode I maximum stress intensity factor are shown in Table 6. Comparison of the mode I maximum stress intensity factor values indicates that after the installation of four pins, the mode I maximum stress intensity factor was less than the threshold value and the crack was arrested. In a previous study by the authors [14], a crack detected on the edge of an eccentric pin hole of a gas turbine casing was investigated for transient thermal fatigue life under elastic-perfectly-plastic conditions. Calculation of the stress distribution in the casing represents a transient thermal-structural coupled problem. Most structural problems concern the description of how a structure behaves as it is loaded and moves from its reference configuration. Thus, the positions of a point are often compared in the current (deformed) configuration and a reference configuration is usually chosen as the configuration when the structure is unloaded or, in the case of geotechnical problems when the model is subjected only to geostatic stresses. A set of nonlinear elements for asymmetric loading of axisymmetric models is available, and linear infinite elements in two and three dimensions can be used to model unbounded domains. The solid element library includes isoparametric elements: quadrilaterals in two dimensions and bricks (hexahedra) in three dimensions. These isoparametric elements are generally preferred for most cases because they are usually the more cost-effective of the elements that are provided in Abaqus. The casing was meshed using a 3D 8-node thermally-coupled brick element (Fig. 11). Several points on the casing were chosen in order to check the results

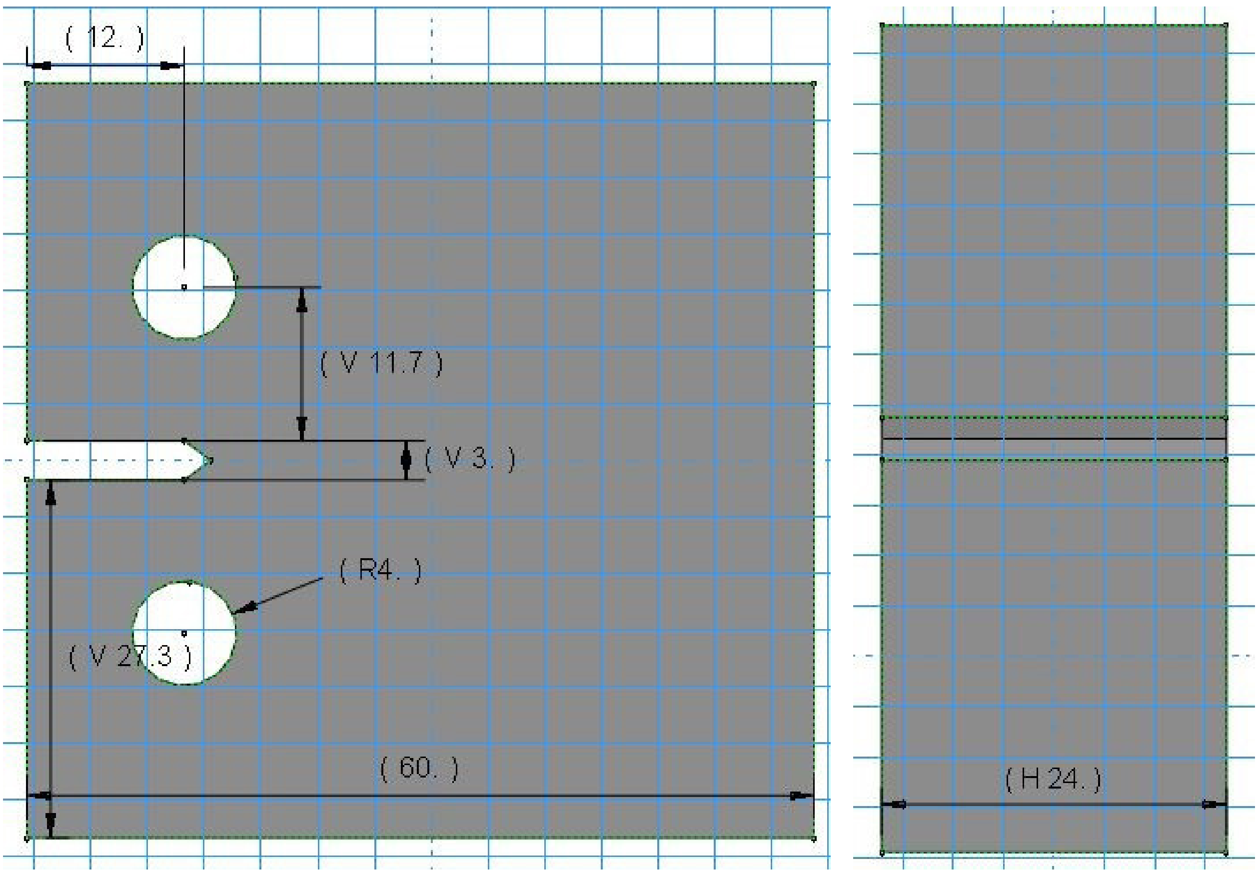


Fig. 8. CT specimen geometry (mm)

of mesh independency The same points were chosen in the other mesh sizes to investigate mesh independency, and the stress results are reported in Table 7. These points are shown in Fig. 12, it is noteworthy that the value of the stress is magnified in fine mesh and there is less difference between them. Finally, a mesh size of 0.014 (m) was used. The previous results indicated that the crack growth up 6.06 mm (Fig. 13). The crack was repaired by the installation of pins to prevent crack growth up to the forecast value (6.06 mm) and to prevent further growth under critical and unpredictable circumstances. As in the previous work [14], the cracks were simulated using Zencrack [18]. In this method, the last crack profile from a previous step was used as the user defined crack shape for the next growth step. Specification of the elements used for each crack growth step is shown in Table 8. The surface-based tying interaction was used between the outer surface pins and the inner surface holes into which the pins were inserted. Figs. 14 and 15 show the modeling and installation of pins along a crack at the edge of an eccentric pin hole. The results of the calculations for mode I maximum stress intensity factor in the gas turbine casing are shown in Table 9.

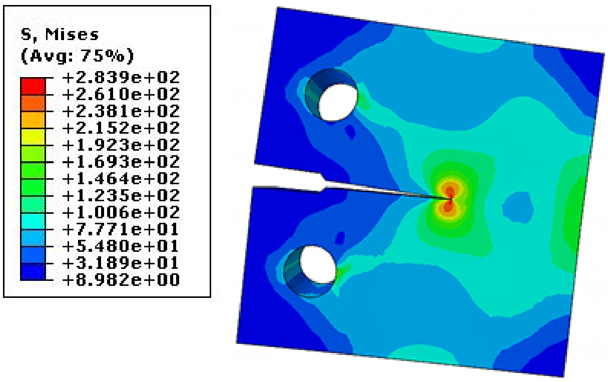
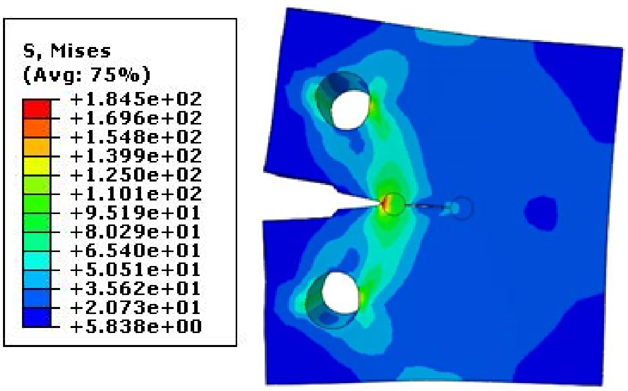
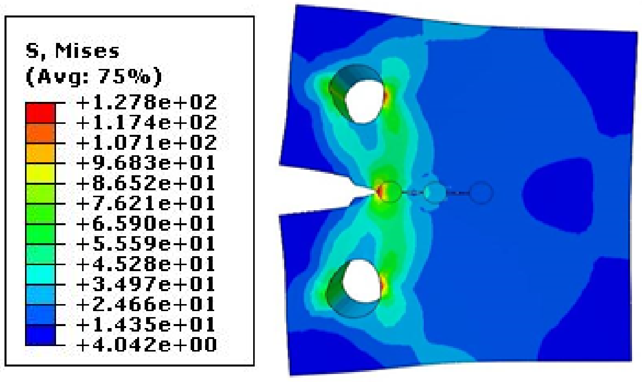


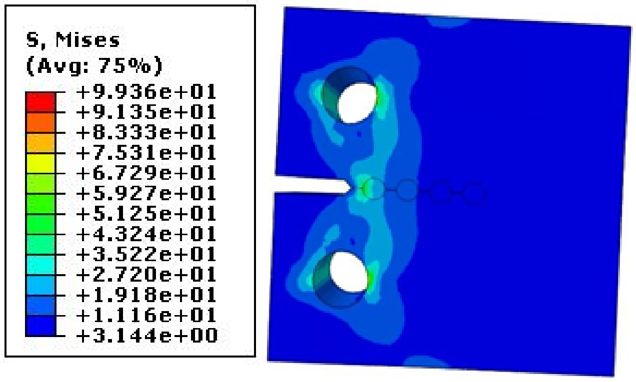
Fig. 9. CT specimen without repair (MPa)



(a)



(b)



(c)

Fig. 10. CT specimen with 2, 3, and 4 pins (MPa)

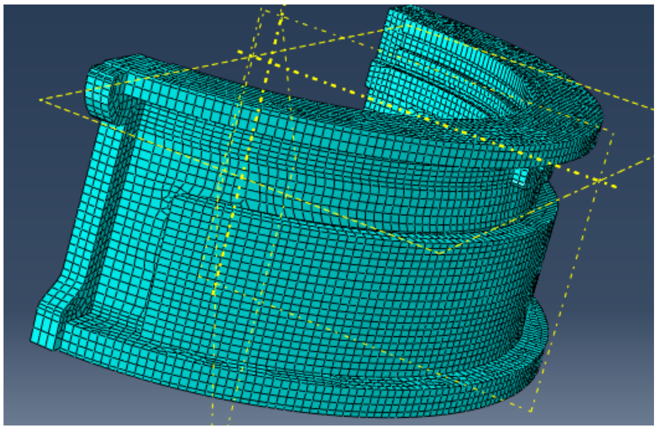


Fig. 11. The meshed model of casing

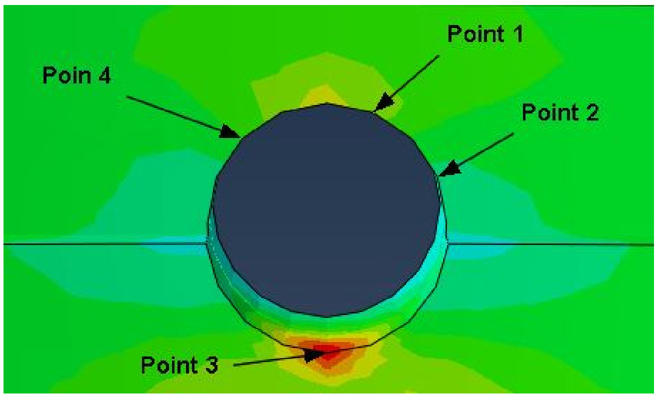


Fig. 12. Stress in selected points

Table 5. Mechanical properties of the Duplex steel 2507

Elongation	Density (kg/m^3)	Tensile strength, yield (MPa)	Modulus of elasticity (GPa)	Poisson's ratio
15	7800	800	210	0.3

Table 6. Mode I maximum stress intensity factor for CT specimens

Number of Pins	Without pin	Two pins	Three pins	Four pins
Mode I maximum stress intensity factor (MPa.mm$^{0.5}$)	1054.625	671.456	466.37	362.586
Threshold value (MPa.mm$^{0.5}$)	379.473	379.473	379.473	379.473

Table 7. Stress values for different mesh sizes

Stress (MPa) Mesh size (m)	0.02	0.018	0.0165	0.0155	0.014	0.0136	0.0132
Point 1	127.48	122.04	120.06	118.12	116.19	116.2	116.18
Point 2	107.32	104.46	102.5	101.5	101.1	101.14	101.1
Point 3	235.01	217.4	211.46	207.91	203.25	203.01	203.04
Point 4	122.1	117.13	114.7	113.8	111.5	111.25	111.35

Table 8. Specification of elements used for each crack growth step

Crack growth step	Element name	Type	Total elements
First	l04_q112x4	Quarter circular crack block (large method)	3897
Second	l04_t28x1	Through crack block (large method)	3897

Table 9. Mode I maximum stress intensity factor for gas turbine casing

Number of Pins	Without pin	Two pins	Three pins
Mode I maximum stress intensity factor (MPa.mm$^{0.5}$)	878.375	593.63	298.274
Threshold value (MPa.mm$^{0.5}$)	379.473	379.473	379.473

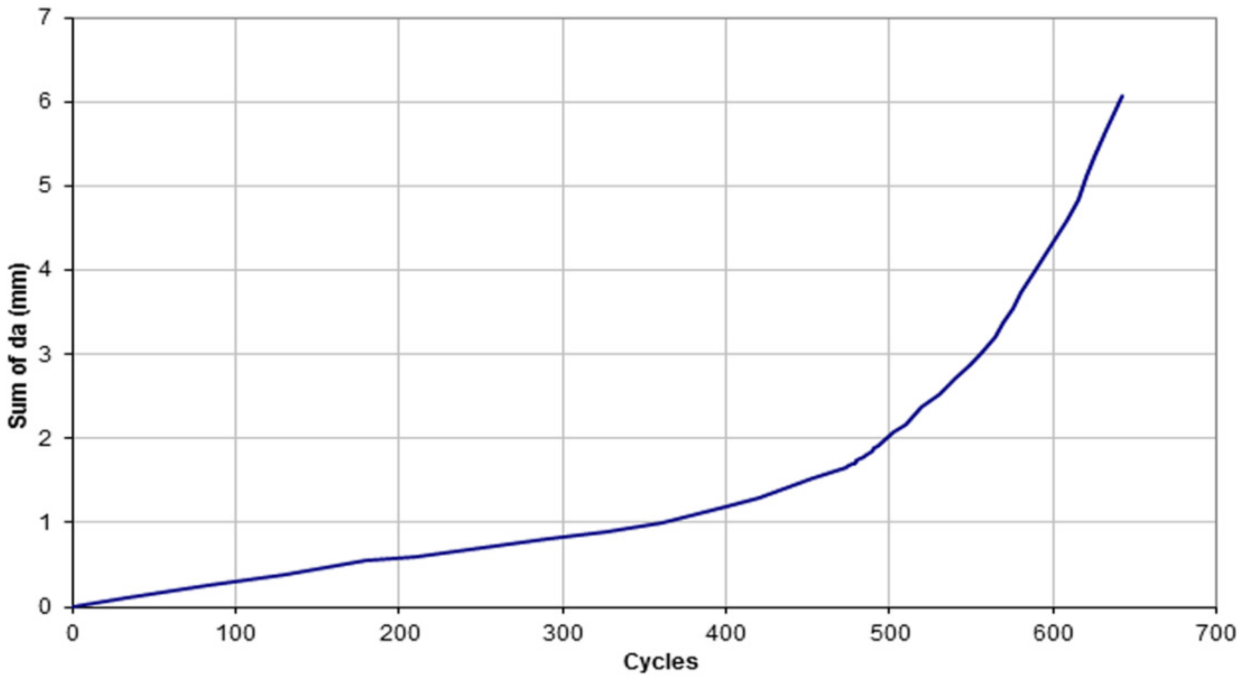


Fig. 13. The fatigue life curve for crack growth to state elastic-perfectly plastic [14]

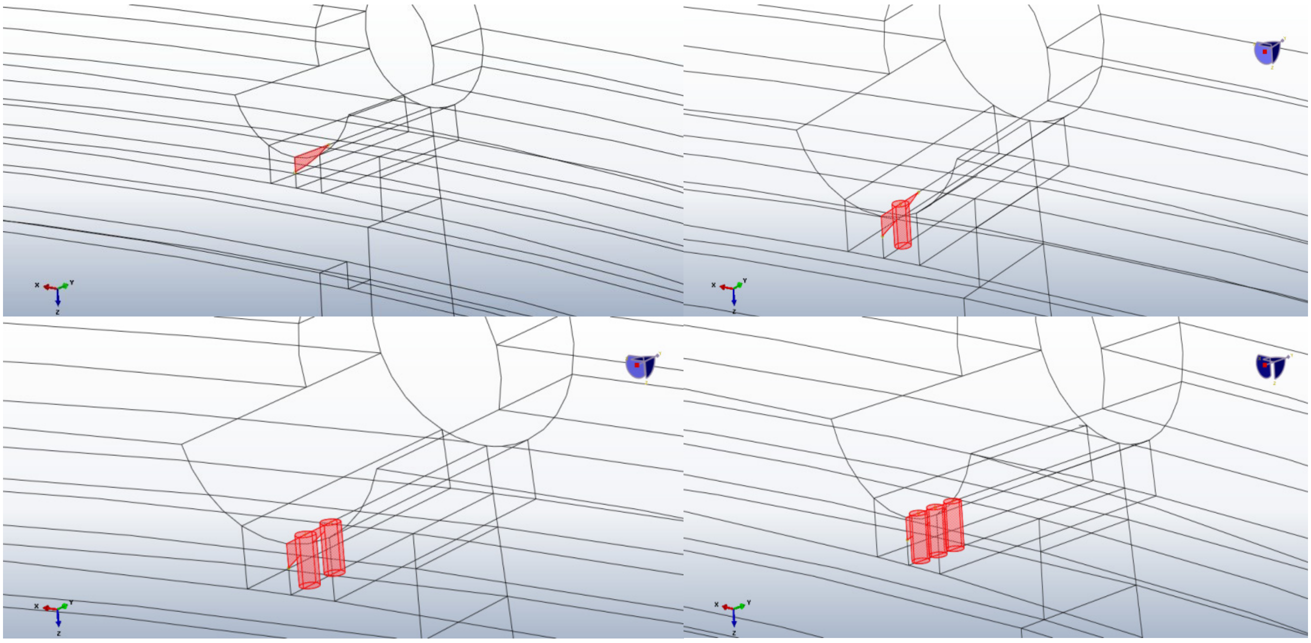


Fig. 14. Modeling of pins in the gas turbine casing

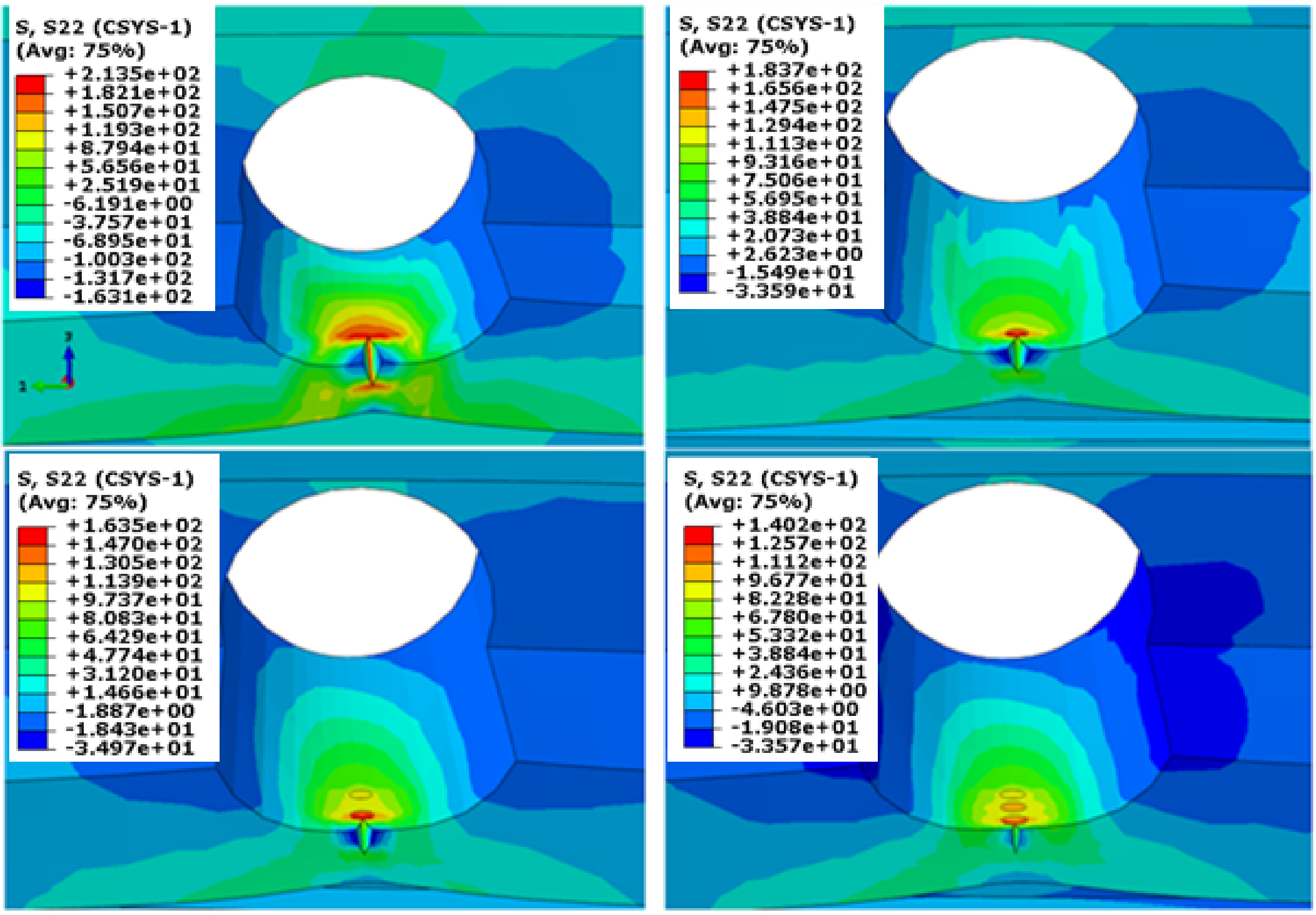


Fig. 15. Steps for installation of pins along crack at the edge of eccentric pin hole in elastic-perfectly plastic (MPa)

5- Conclusion

The present study presents a crack repair technology for gas turbines casings. The crack was repaired by tapping the pins into the place after drilling holes to draw the sides of the crack together. The relative effectiveness of the pins was identified for the various classes. The results demonstrate that cast master pins are the most effective stitching pins.

The efficiency of crack repair by the installation of pins was investigated along with the effect of the number of pins on crack repair efficiency. The mode I maximum stress intensity factor was calculated for cases without pins, and with 2, 3, and 4 pins. Generally, the higher number of fasteners significantly increased crack retardation.

Crack repair technology was used to increase the transient thermal fatigue life of a gas turbine casing. For this purpose, the pins along the crack at the edge of an eccentric pin hole in a metal gas turbine casing were replaced with duplex steel pins. The results of calculations for mode I maximum stress intensity factor in the gas turbine casing shows that as the number of pins increased along a crack at the edge of the eccentric pin hole, the mode I maximum stress intensity factor decreased until it reached a threshold value and cracking ceased.

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