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Effect of temperature on fatigue crack propagation under constant amplitude loading

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ABSTRACT

The present study relates to fracture mechanics and its aim is to find the effect of temperature on fatigue crack propagation under constant amplitude loading. The thermo-mechanical uniaxial and biaxial-planar fatigue behavior of the structural steel was investigated for constant amplitude loading at room temperature and between temperature range 673K and 923K. A fatigue analysis has been done for cruciform specimen using ANSYS 15.0 to find out the crack propagation and life of the material at different temperatures. A comparative study between the results obtained from ANSYS 15.0 and experimental results has been done to validate our analysis. A change from a mainly transgranular fracture at 673K to a mostly intergranular fracture at 923K was found under thermo-mechanical fatigue loading. Effect of temperature on crack propagation is presented which gives the best life prediction.

Keywords— *Effect of temperature, Fatigue crack propagation, Constant amplitude loading*

1. INTRODUCTION

1.1 General

By applying fracture mechanics, the failure through fatigue and fracture of many components such as machines, process plants, and household goods can be avoided. For more than 150 years, metal fatigue has been a subject of active research. The major design problem in the structures subjected to fatigue loading is the prevention of fatigue failure. Fatigue cracks mostly initiate at discontinuities such as holes, fillets, or a structure. The initiation of a significant number of fatigue failures in the aircraft structures has found at the pre-existing flaws e.g. Tool marks, manufacturers or welding defects. In a structure, a component may be susceptible to one, two or more kinds of failure.

1.2 Fatigue

"Fatigue" was introduced in 1854 by Braithwaite. The ASTM standard definition of fatigue is:
"The process of progressive localized permanent structural change occurring in a material subjected to conditions which produce fluctuating stresses and strains at some point or points and which may develop in a crack or complete failure after a sufficient number of fluctuations."

1) **Strain Localization:** Strain localization is a feature of elastoplastic materials undergoing non-homogeneous deformation. The phenomenon appears in the form of a shear band, a narrow zone of intense straining. In ductile materials, a narrow zone of intense shearing strain, usually of plastic nature, develops during severe deformation, which is known as strain localization or shear band.
2) **Crack Initiation:** A crack is usually observed to initiate at the tip of an existing crack or at some point of a free surface. Crack growth rate per unit cycle da/dN is an important parameter. Initially, a crack is extremely small, so da/dN is also small, which cannot be detected easily and therefore it is included in crack initiation.
3) **Crack Propagation:** As the crack becomes longer the rate of crack propagation per load cycle da/dN, also increases. Detectable crack is still sub-critical and needs to grow further under the fatigue load. The number of cycles required to grow the smallest detectable crack to critical size is known as crack propagation life Np.
4) **Fatigue Failure:** A component which fails through yielding at a high constant load, may fail under a substantially smaller fatigue load. Most of the fracture failures are initiated by fatigue loads. Initially crack length is subcritical and the crack is not dangerous. With subsequent load cycles, the crack grows to acquire length close to the critical length.

1.3 Modes of fracture failure

In fracture mechanics we are encountered with the three modes of loading depending upon the relative movement of the two crack surfaces:

1) Mode I
2) Mode II loading
3) Mode III loading

Mode I is crack opening mode. In this mode, fractured surfaces are displaced opposite to each other. Mode II is the shear mode, here the two fractured surfaces slide over each other in a direction perpendicular to the line of the crack tip. Mode III is the tearing mode, here the two surfaces slide over each other in a direction parallel to the line of crack front.

1.4 Thermo-mechanical fatigue

Thermo-mechanical fatigue is the application of a cyclical mechanical loading that leads to fatigue of a material, with a cyclical thermal loading. Thermo-mechanical fatigue is an important point that needs to be considered when constructing turbine engines or gas turbines.

There are three mechanisms acting in thermo-mechanical fatigue:

1) **Creep:** Creep is the flow of materials at high temperatures.
2) **Fatigue:** Fatigue is crack growth and propagation due to repeated loading.
3) **Oxidation:** Due to oxidation there is a change in the chemical composition of the material. The oxidized material is more brittle and prone to crack creation.

2. GEOMETRICAL MODELLING

2.1 General

The aim of our study is to find out the effect of temperature on fatigue crack propagation under constant amplitude loading. The first thing is to prepare the model of the cruciform specimen on ANSYS 15.0 and then doing its temperature analysis also on ANSYS 15.0 to find out crack growth rate and related variables at different temperatures.

2.2 Material

The investigated material is structural steel.

Table 1: Chemical Composition in wt% of the structural steel

C	Mn	P	S	Si
0.25-.029	0.60-1.20	0.04	0.05	0.15-0.40

Table 2: Mechanical Properties of the Structural Steel

Density	$7.85x10^{-6}$ kg mm^-3
Coefficient of Thermal Expansion	$1.2x10^{-5}$ C^-1
Specific Heat	$4.34x10^{5}$mJ kg^-1 C^-1
Thermal Conductivity	$6.05x10^{-2}$ W mm^-1 C^-1
Resistivity	$1.7x10^{-2}$ ohm mm
Yield Strength	250MPa
Tensile Strength	460MPa
Young's Modulus	$2x10^{5}$MPa
Poisson Ratio	0.3
Bulk Modulus	$1.67x10^{5}$MPa
Shear Modulus	76923MPa

2.3 Specimen

We are using cruciform specimen for biaxial planar testing. The shape and size of the specimen are given below:

Length on X-axis: 12mm
Length on Y-axis: 210mm
Length on Z-axis: 210mm

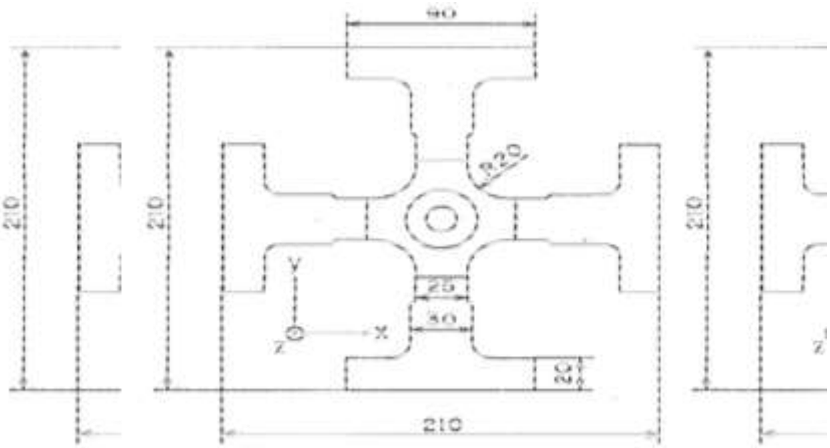

Fig. 1: Shape and Dimensions of the specimen in mm.

2.4 Geometrical modelling

For conducting a FEM analysis in ANSYS workbench first, we have to define the material properties in the engineering data cell of static structural analysis. After that, we need to draw the specimen. In ANSYS workbench, the part models and their sketches are defined in the Design Modeler window. We can define part models by creating the model in Design Modeler window of ANSYS workbench.

2.5 Steps involved in geometrical modelling

2.5.1 Creating a model

1) Start ANSYS workbench, double-click on static structural in the toolbox window. The static structural analysis system is added in the project schematic window.
2) In the static structural analysis system, double-click on the geometry cell, this display the Design Modeler window.
3) Set the unit to the millimeter. Create the model of the specimen of specified geometry in Design Modeler window.

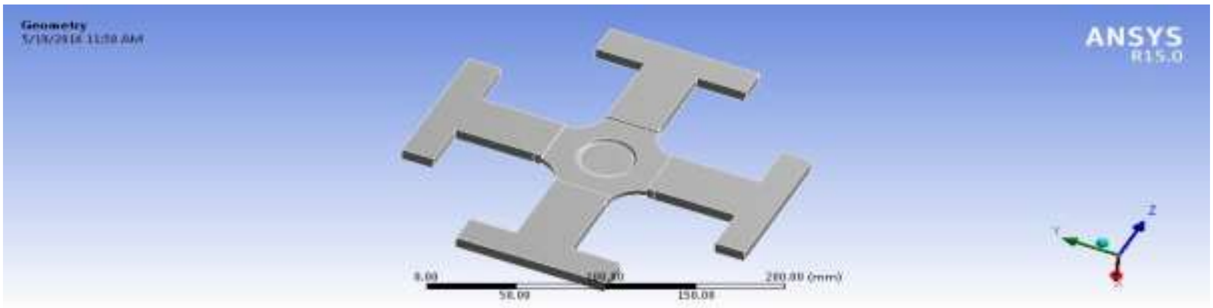

Fig. 2: Snapshot of model

2.5.2 Generating the mesh

1) After the model is created in the Design Modeler window, generate the mesh in the mechanical window.
2) In the project schematic window, select the model cell in the static structural analysis system, the mechanical window is displayed.
3) Select the mesh in the tree outline, so the details of the mesh window are displayed.

2.5.3 Details of mesh

Element used: Triangular element
Smoothing: Medium
Span angle center: Coarse
Minimum edge length: 2.50650mm
Elements: 8689
Nodes: 14775

2.5.4 Setting the boundary and loading conditions

1) After generating the mesh, we need to set the boundary and loading conditions under which the analysis will be performed.
2) For applying boundary conditions we have to perform the following operations:
   Select → static structural → environmental contextual → fixed support tool → face tool from the select toolbar.
3) Now select the face of the model.
4) Click on the apply button in the geometry selection box, so that it confirms the face for fixed support.
5) Step 2, 3 and 4 are repeated to fix the other three faces of the specimen.
6) The boundary is defined for the model. Now, we need to define the load for which the analysis is to be carried out.
7) For applying load on the specimen, we perform following operations:
   Select → static structural → environmental contextual → loads → force → face tool from the select toolbar.
8) Select the face of the model on which the force is applied.
9) Edit the magnitude and direction of the force to be: Magnitude: 125kN

2.6 Solving and post-processing the finite element model

1) After the boundary and loading conditions are specified for the analysis, we need to evaluate the results that are of importance for the analysis.
2) The various results that can be evaluated are stress intensity, fatigue i.e. crack propagation, damage, safety factor, biaxial indication and equivalent alternating stresses.
3) Now we select the solution node and then select the stress intensity and fatigue tool from solution contextual toolbar.
4) From fatigue, toolbar selects the crack propagation, damage, safety factor, biaxial indication and equivalent alternating stresses.
5) Next, we choose the solve tool from the solution toolbar to get the results of the analysis.

3. ANALYSIS

3.1 General

The FEM analysis over the cruciform specimen is carried out by using ANSYS 15.0 at different temperatures. Firstly we have done an analysis at room temperature and then at some elevated temperatures such as 673K, 823K, and 923K. The results obtained from the analysis of ANSYS 15.0 at different temperatures are given below:

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3.2 Fem analysis results at room temperature (293k)

At room temperature (293K)

Project First Saved	Saturday, February 27, 2016
Last Saved	Thursday, March 03, 2016
Product Version	15.0.7 Release
Save Project Before Solution	No
Save Project After Solution	No

Table 3: Units

Unit System Metric	(mm, kg, N, s, mV, mA) Degrees rad/s Kelvin
Angle	Degrees
Rotational Velocity	rad/s
Temperature	Kelvin

Model (A4): Geometry

TABLE 2: Model (A4) > Geometry

Object Name	*Geometry*
State	Fully Defined

	Definition
Source	C:\Users\Nirpesh\Desktop\model_files\dp0\SYS\DM\SYS.agdb
Type	DesignModeler
Length Unit	Millimeters
Element Control	Program Controlled
Display Style	Body Color
	Bounding Box
Length X	12. mm
Length Y	210. mm
Length Z	210. mm
	Properties
Volume	1.8383e+005 mm^3
Mass	1.4431 kg
Scale Factor Value	1.
	Statistics
Bodies	1
Active Bodies	1
Nodes	14775
Elements	8689
Mesh Metric	None
	Basic Geometry Options
Parameters	Yes
Parameter Key	DS
Attributes	Yes
Attribute Key	SDFEA; DDM
Named Selections	No
Material Properties	Yes
	Advanced Geometry Options
Use Associativity	Yes
Coordinate Systems	No
Reader Mode Saves Updated	No
File	No
Use Instances	Yes
Smart CAD Update	No
Compare Parts On Update	No
Attach File Via Temp File	Yes
Temporary Directory	C:\Users\Nirpesh\AppData\Local\Temp

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Analysis Type	3-D
Decompose Disjoint Geometry	Yes
Enclosure and Symmetry	Yes
Processing	Yes

Table 3: Model (A4) > Geometry > Parts

Object Name	Solid
State	Meshed

3.3 FEM analysis results at temperature 923k

At temperature 923k

First Saved	Saturday, February 27, 2016
Last Saved	Friday, March 04, 2016
Product Version	15.0.7 Release
Save Project Before Solution	No
Save Project After Solution	No

4. RESULTS AND DISCUSSIONS

4.1 Fatigue lives

The fatigue lives of the cruciform specimen of structural steel after applying a constant amplitude load from 100kN to220kN for FEM analysis and experimental analysis is shown in table 5.1. From table 5.1, it seems that at load 100kN the life of structural steel is 424.368 cycles for experimental analysis, while for FEM analysis the life is estimated at 353.64 cycles. It also shows that at the load 220kN, the fatigue lives for experimental analysis and FEM analysis are 53.6412 cycles and 44.701 cycles respectively (table 5.1). The fatigue life for the material reduces as the load increases for both the analysis. When comparing both the analysis, it shows that life obtained from FEM analysis is less than that of experimental analysis for the same amount of loading. The differences in the estimated lives are about 2%.

4.2 Alternating stresses

The alternating stresses for FEM analysis and experimental analysis of the cruciform specimen of structural steel are shown in table 5.1 while applying the load from 100kN to 220kN. The alternating stresses obtained at 100kN for FEM analysis and experimental analysis are 913.55MPa and 1096.26MPa respectively, as shown in table 5.1. Similarly, at 220kN load, the alternating stresses are 2009.8MPa and 2411.6MPa for FEM analysis and experimental analysis respectively (table 5.1). The alternating stresses increases as the load increases for both the analysis. Similar to fatigue lives alternating stresses for FEM analysis is less than the experimental analysis for the same amount of loads, and the difference obtained in alternating stresses is also about 2%.

4.3 S-N curve

A curve has been plotted in between fatigue lives and alternating stresses on the x-axis and y-axis respectively. The S-N plot for FEM analysis is shown by blue dots, while for experimental analysis is shown by red dots as shown in figure 3 it is clear that as the applied load increases the alternating stresses also increases while fatigue life decreases.

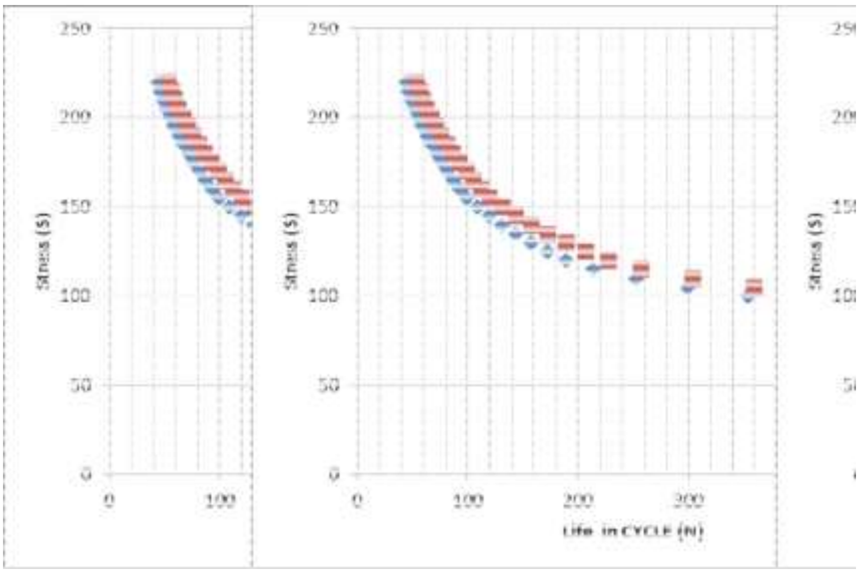

Fig. 3: SN curve of FEM analysis and Experimental analysis

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5. CONCLUSION

- In the present study, an appropriate biaxial-planar test rig for the investigation of the low cycle fatigue behavior at elevated temperature is presented. At the biaxial-planar testing systems, isothermal and thermomechanical fatigue tests at different stress states were successfully carried out.
- In general, the uniaxial life can be conservatively described by the fatigue lives of the low cycle fatigue tests at the upper temperature of 923K.
- Investigation of the microcracks under biaxial planar loading shows that crack initiation takes place within the grains along the slip systems with the highest loading or at the twin boundaries.
- For crack growth, a change of the mechanism from 673K with mostly transgranular propagation to 923K with the mainly intergranular crack growth occurred due to the increased oxidation of the grain boundaries at a higher temperature.
- Effect of temperature on crack propagation is presented which gives the best life prediction.

6. FUTURE WORK

The suggestions are based on limitations we felt. Some of the suggestions are as follows:

- Other types of loading like variable amplitude loading, block loadings are important to work.
- We can check the effect of temperature on other materials also.
- We can also check the effect of some other parameters on crack propagation
- We can formulate a generalized relationship between temperature and crack growth rate.
- We can do the analysis on the different type of specimens also.

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