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Fatigue Behaviour Of CNT Reinforced Material Matrix Composites

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Abstract - In this study we use strain based Smith-Watson –Topper fatigue approach to find the fatigue strength and life of a counter weight bar made of high strength steel under fluctuating loading and compare the results with FEA based software "COMSOL Multiphysics". Randomly oriented CNT's fibers are also developed by using live link between COMSOL Multiphysics & Matlab. Then the mechanical properties of CNT's are determined.Then the Effects of CNT reinforcement on the fatigue behavior of MMC of are predicted. Different plots are generated to compare the effects on the fatigue behavior when CNT is used as reinforcement in metal matrix. Results shows that effects of CNT reinforcement in metal matrix on the fatigue behavior are significant.

Keywords: CNT, Fatigue in MMC's, COMSOL Multiphysics.

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1. Introduction

METAL MATRIX COMPOSITES

Nowadays, Metal Matrix Composites (MMCs) are under serious consideration to replace conventional materials for a large number of structural applications such as those in the aeronautical/aerospace, sports industries because of their superior properties. The excellent mechanical properties and the comparatively low cost make them as an attractive option. They have favorable combination of low density and improved mechanical properties. The increasing applications of the MMCs in the different fields require an efficient method to predict their mechanical behaviors from the known properties of the constituents. Thus, one can design and optimize the microstructure of MMCs according to the requirement based on the knowledge of the correlation between microstructure, deformation, damage initiation and damage development in MMCs

CNT REINFORCED MMC's

With a continuous improvement of the production techniques for carbon nanofibers and carbon nanotubes along with an improvement of the available qualities of the materials, these reinforcements have been introduced into polymers, ceramics and metals. Carbon nanotubes with their high properties are of special interest to be introduced in metallic matrix materials. The mechanical properties of CNTs are usually reported to have an average modulus of elasticity of about 1–2 TPa. CNTs have higher mechanical properties where the stiffness, strength and resilience. They have high strength, high aspect ratio and high fracture strain and superior flexibility. Inhomogeneities structural in the metal matrix composite result in the degradation of the mechanical properties of the CNT composite materials. Also the poor interfacial bond strength between reinforcement (CNTs) and the matrix materials leads to a limited stress transfer capability from the matrix to the CNTs. The bond strength of reinforcement with the matrix, and uniform distribution within the matrix are essential structural requirements for the stronger metal matrix composite.

FATIGUE BEHAVIOR OF MMC's

Metal matrix composites (MMC) have a high specific mechanical strength and a high stiffness, compared to the corresponding unreinforced alloys. A detailed understanding of the low-cycle fatigue (LCF) behavior of these materials is required for an extension of its applications in industry, in particular when large deformations are unavoidable. Metal matrix composites (mmcs) helps in reducing the weight of the component with improved fatigue and impact performance.

Sharma [16] investigated the fatigue behavior of Al/SiC mmc and found superior performance compared to unreinforced 7075-T6 alloys. Chawla [17] reported that aluminum based mmc exhibited superior fatigue life and endurance stress compared to their unreinforced alloy under high cycle fatigue mode. Kaynak [18] reported that SiC particulates improved the fatigue resistance of the specimen over unreinforced specimens and also presented SN data.

2. LITERATURE REVIEW

Nano Composite (Carbon Nano Tubes)

After being discovered in 1991 [7], Carbon Nano tubes have received much attention in areas of science and engineering. According to Daniel & Justin [8] CNT has unique mechanical, thermal and electrical properties. Carbon fibers have high value of tensile strength, high young's modulus than common metal and alloys so they are used in structural components which are subjected to static and cyclic loading. The matrix of the composite provides bulk and load is taken by fibers. The percentage of CNT reinforced does not increase the weight, volume, cross-section of component so they are preferred in the design of aerodynamic structures.

CNT shows little degradation with cyclic loading because of the higher modulus of carbon fibers, which results in low level of cyclic strain imposed on the matrix. The mechanical properties of CNT reinforced composites increases with CNT content. In his study Jen & Wang [9] shows that there also exists a critical CNT content after which the strength of CNT reinforced composites decreases. Dispersion of CNTs also affects the mechanical properties of polymer composites by increasing the bonding strength and avoids stress concentration.

Toughness of reinforced composite is limited by early damage initiation. The transverse crack developed decreases the fatigue strength of composites. Jen & Yang [10] showed that using CNT as reinforcement hinders the development of cracks and improves fatigue life. The addition of CNT decreases the scale of damage which results in increase in the absorption of strain energy by creating Nano scale cracks this effect increases the damage growth under cyclic loading.

In the study of “Single-layer graphene oxide reinforced metal matrix composites by laser sintering” Lin, Richard Liu & Cheng [5] shows that the improvement in the fatigue life after laser sintering of GO-reinforced iron matrix nanocomposites. A model to calculate the tensile strength and Young’s modulus of GO–Fe nanocomposites has been developed Three-point bending fatigue life was also increased by integrating GO into iron matrix. Schijve [3] describes about the Fatigue life until failure consists of two periods: The crack initiation period and the crack growth period. Zhang & Chen [4] showed that Crack pinning by GO was observed, which also helps to improve the fatigue life during the crack propagation period. With a continuous improvement of the production techniques for carbon nanofibers and carbon nanotubes along with an improvement of the available qualities of the materials, these reinforcements have been introduced into polymers, ceramics and metals.

In their study Parka, Choa, Ikmin,& Park[12] “Fabrication and mechanical properties of magnesium matrix composite reinforced with Si coated carbon nanotubes” showed that the effective fabrication of CNT-reinforced metals depends on the homogenous dispersion of CNTs in the metal matrix and the interfacial adhesion between them. Fouret & Degallaix [13] in their study “Experimental and numerical study of the low-cycle fatigue behavior of a cast metal matrix composite Al–SiCp” describes about the low-cycle fatigue behavior of a cast metal matrix composite. The general conclusion of all the observations is that the fatigue damage mechanisms were not distributed but localized. One or several micro-cracks initiated on pre-existing defects and then propagated until a main crack is created, leading to the final fracture. IQBAL, ARAI & ARAKI [14] in their study “Fatigue crack growth mechanism in cast hybrid metal matrix composite reinforced with SiC particles and Al2O3 whiskers” shows that the high elastic modulus, crack deflection gives the cast hybrid MMC better fatigue crack growth resistance than the cast MMC with Al2O3 whisker and the cast Al alloy. Sung, Chung, Sohn & Lee [15] in their study “Improvement of flexure strength and fracture toughness in alumina matrix composites reinforced with carbon nanotubes Materials” the three-point bending test results indicated that the flexure strength increases with increasing volume fraction of CNTs

Mechanical analysis of composites

To find the average property of composite ply from the individual properties of its constituent. The properties include stiffness, strength, and thermal & moisture expansion coefficient. Develop the stress-strain r/l for unidirectional/ bidirectional lamina. This lamina is the single flat layer of unifacial fiber and woven fibers arranged in a matrix. Lamina is also called ply or layer. Laminate is a stack of plies of composites. Each layer can be laid in various orientations and can be made up of different material systems.

Macro mechanical analysis of lamina-A lamina is unlike an isotropic homogeneous material. It is made of fiber and matrix in which properties vary point to point. So mechanical modeling of lamina is complicated. For this reason macro mechanical analysis of lamina is based on average properties & considering the lamina to be homogeneous.

Anisotropic material have 21 independent elastic constant at a point .If material is non homogeneous these constant varies from point to point. So to find stress- strain r/l at a point these 21 constant must be known in case of anisotropic material .Monoclinic material has 13 independent elastic constant at a point. Monoclinic materials have a plane of symmetry. Orthotropic material have three plane of symmetry and have 9 independent elastic constant at a point. Transversely isotropic have 5 independent elastic constant at a point. Isotropic material in an orthotropic body are identical, it is an isotropic material. These materials have 2 independent elastic constant at a point.

FATIGUE LIFE MODEL

1. Nominal stress life model-This model uses stress and relates these to local fatigue strength for notched or unnotched components.
2. The local strain life model-It deals directly with local strain at notch and is related with smooth specimen strain controlled fatigue behavior.
3. Fatigue crack growth model-It requires the use of fracture mechanics and integration of fatigue crack growth rate equation to obtain number of cycles required to grow a crack from a given length to another length of fracture.
4. The Two stage model-It involves both strain life and fatigue crack growth model .The strain model gives life to formation of macro crack then followed by integration of fatigue growth rate. The two life are added together to get fatigue life.

FATIGUE IN COMPOSITE MATERIAL

The use of composite material in structural engineering components have continuously increased so it requires safe and reliable design rules particularly when they are subjected to varying loading. The problem in fatigue design is to predict the fatigue life of a structure under given loading conditions. Composite components are subjected to dynamic loading in their applications so fatigue analysis is important. Composites are heterogeneous material, they consists of laminates of different materials, lay-ups, and stacking sequences, so multi damage (fibers, matrix) mechanism is very complex, stress redistribution , crack growth and its propagation are very difficult to predict, so to establish a general fatigue failure criterion for composite is difficult. Fatigue causes extensive damage throughout the component volume, leading to failure. The different failure modes, complex stress field, anisotropic nature of composite material make its analysis very difficult.

Fatigue failure is defined as loss of adequate stiffness or loss of adequate strength. There are two approaches to determine fatigue life-

1. Constant stress cycling until loss of strength.
2. Constant amplitude cycling until loss of stiffness.

In general for much composite material failure criterion is stiffness reduction. Stiffness change is easily measured and easily indicates damage, which is related to microscopic degradation of composite material. In constant amplitude cycling, the degradation rate is related to the stress within the composite sample. Initially large load is required to deflect the sample, when fatiguing continues, load decreases hence lower stress exist in the sample. As the stress within the sample reduced the amount of deterioration in the sample decreases.

In unidirectional fiber composite, cracks may occur along the fiber axis which involves matrix cracking. Cracks may also develop in transverse direction to fiber which usually indicates fiber breakage and matrix failure. Salkind [6] found that when cracks are accumulated in transverse to fiber direction the load carrying capacity of composite decreases and leads to irregular failure under fatigue loading. One approach to determine fatigue life is to design, build and test prototype which gives highest reliability but consumes time, high cost, so not very practical. Some fatigue characteristic- e.g.-S-N curve and large scatter of experimental data have been well organized. The method for fatigue prediction for uniaxial loading has been developed up to some level but fatigue behavior under multiaxial loading is very less investigated. Unfortunately, there is neither an empirical nor a mechanical based general understanding of fatigue damage accumulation in composites has yet been established. Linear damage model accumulation proposed by MINER, show considerable deviations from experimental results for both metallic and composite material. Non-linear damage accumulation model are not applicable in general as they were derived and verified for special experimental conditions. The critical element concept of REIFSNIDER and STICHCOMB represents a non-linear damage fatigue life prediction methodology for layered composites, which accounts for fatigue damage initiation and growth as well as final failure.

3. PROBLEM STATEMENT

The fatigue properties of high strength steel are presented here. Computational analysis is performed using the local strain-life approach using COMSOL MULTIPHYSICS, where appropriate material properties for treated high strength steel are used. A counter weight bar made of high strength steel material is subjected to a fluctuating load whose magnitude is varies between the limits of 880kN to 88kN during its cycle.

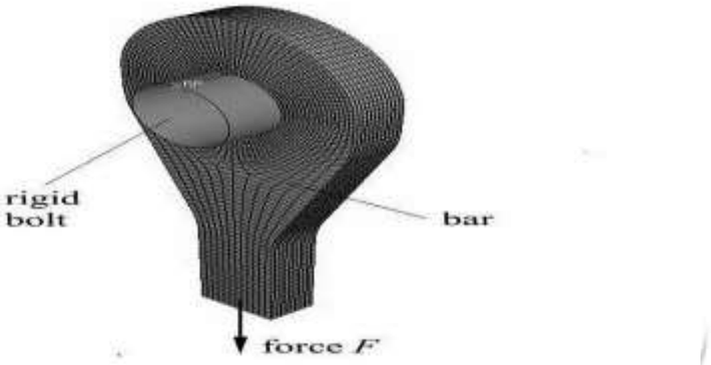

Figure-3.1 Counter weight bar of Steel

FATIGUE MODULE IN COMSOL

Strain based approach is used in the reference paper and the material parameters are derived experimentally which I have used in this model.

In COMSOL for strain based fatigue study Smith-Watson –Topper criterion is used which is, $\varepsilon_a = \frac{\varepsilon_e}{2} + \frac{\varepsilon_p}{2} = \frac{\sigma_f}{E} * (2 * N)^b + \varepsilon_f * (2 * N)^c$………………. 3.1

where $\mathcal{E}a$ is the amplitude of total strain , E is the modulus of elasticity, σ_f is the coefficient of fatigue strength, b is the exponent of fatigue strength, ε_f is the fatigue ductility coefficient and c is the fatigue ductility exponent.

The low-cycle fatigue variables for high strength steel model result in:

Coefficient of fatigue strength : σ_f = 2075 MPa

Exponent of fatigue strength: $b = -0.0995$

Fatigue coefficient of ductility: $\varepsilon_f = 9.91$

Fatigue ductility exponent: $c = -0.978$

These are all material parameters which are obtained from the plot of strain amplitude (ε) V/S number of cycles(N). Assign material properties to the COMSOL model. Young’s Modulus E= 200[GPa], Density of material =7800 kg/mm^3, Poission’s ratio=0.3, and then analyse.

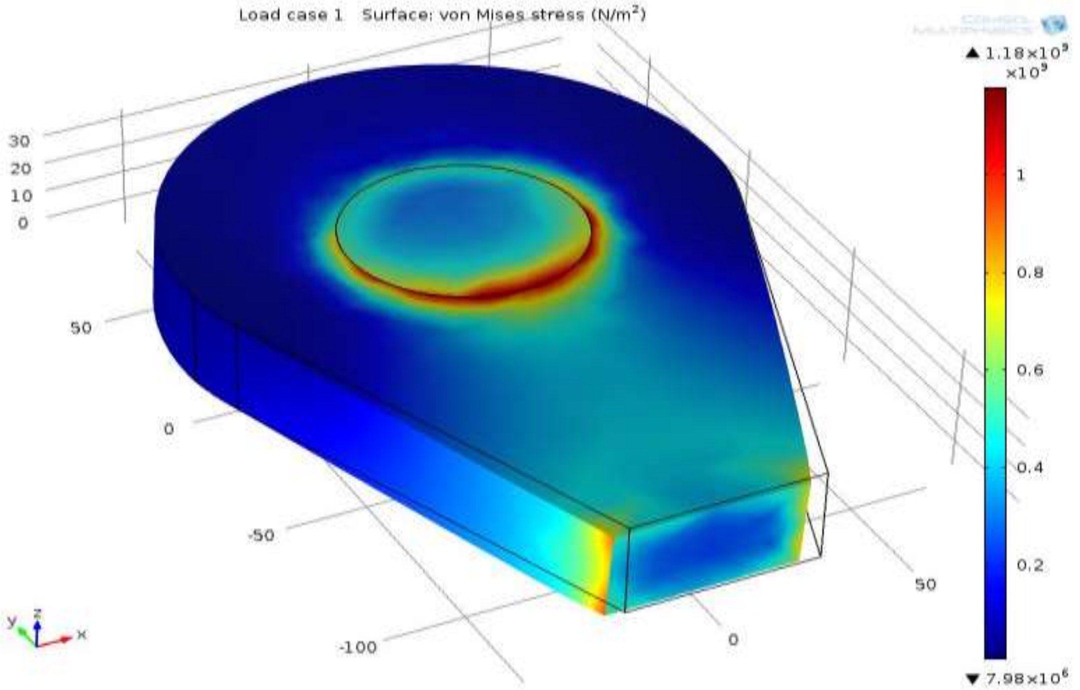

Fig.-3.2: Stress distribution in Steel model

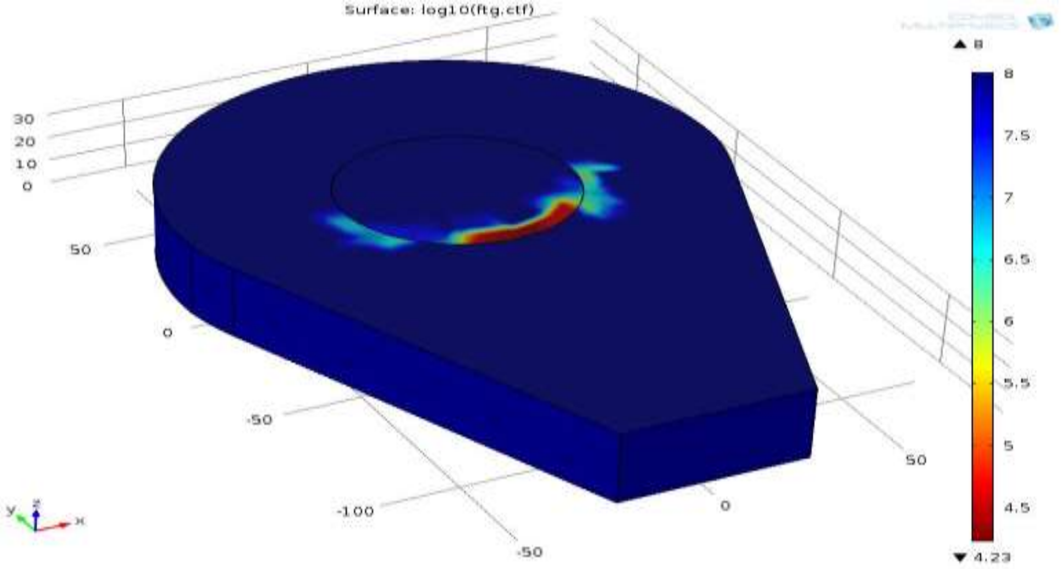

Fig.-3.3: No. of cycles to failure for Steel model

3.2 Present Study (Fatigue of CNT reinforced Steel model)

I have modeled randomly oriented CNTs in COMSOL and calculated value of it’s young’s modulas, shear modulas, poissions ratio.

Flow Chart for developing randomly oriented CNT-

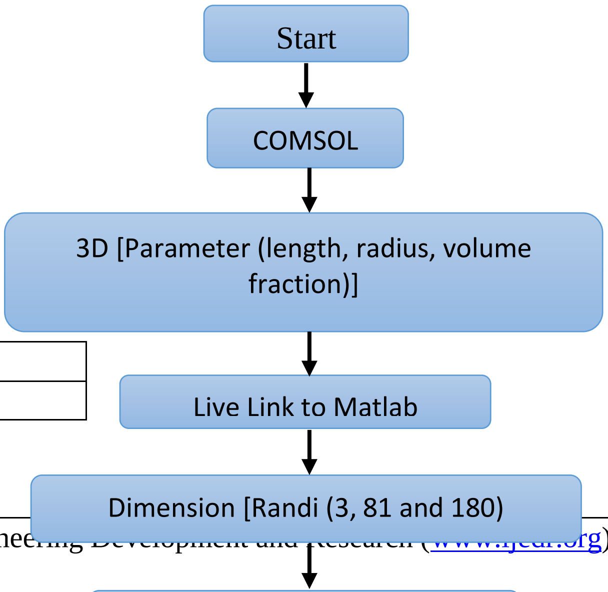

Table: Properties of CNT’s

Length	50nm
Radius	3.2nm

Poission Ratio	0.3
Density	700kg/m^3
Volume Fraction	0.01

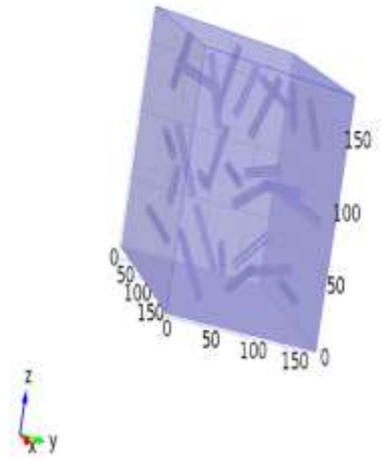

Fig.-3.4 Randomly oriented CNT's

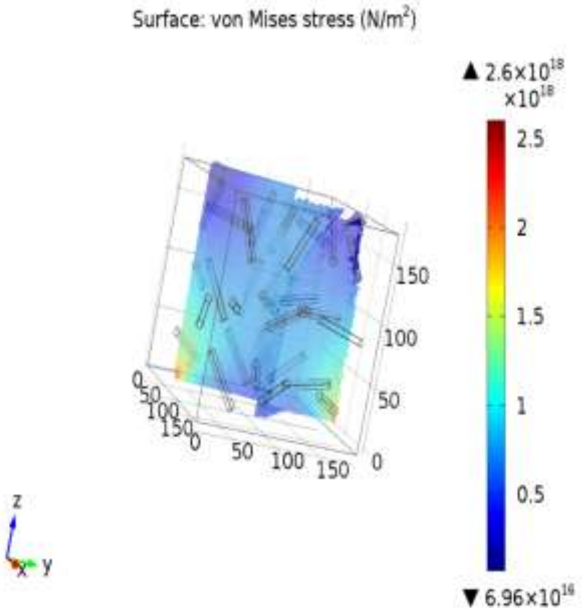

Fig.-3.5 Stress distribution in CNT model

Now fatigue behaviour of the CNT reinforced steel model is predicted using COMSOL.the steps followed are same as discussed above.

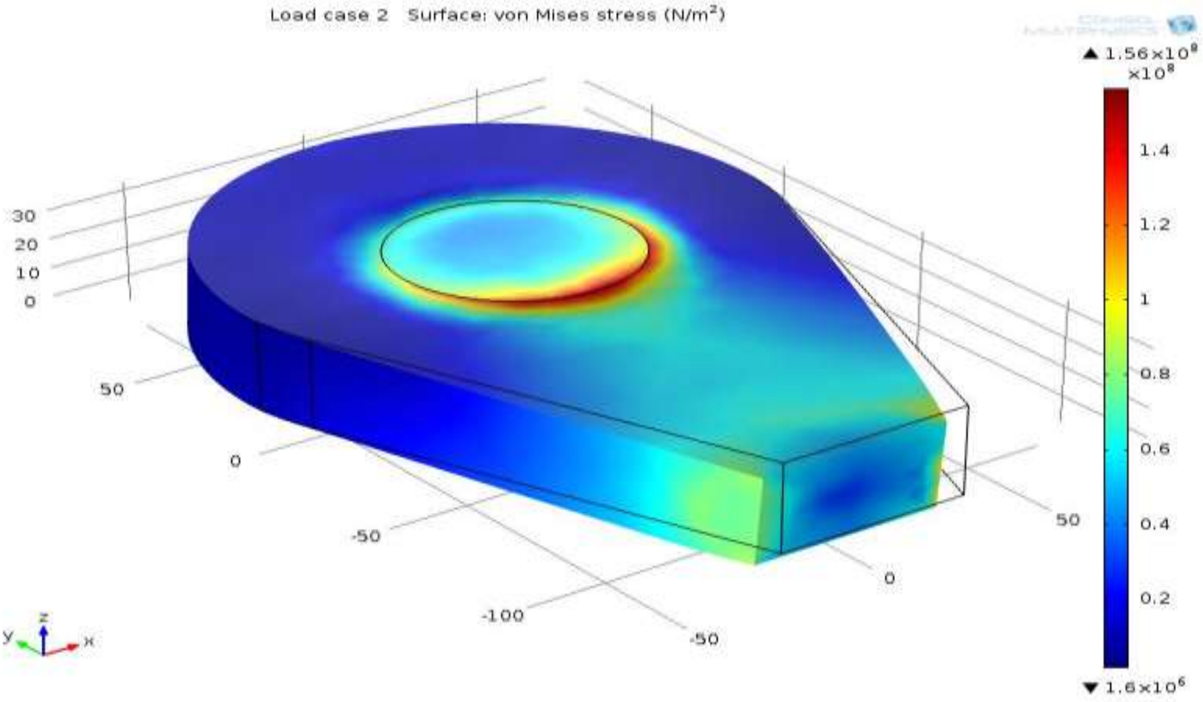

Fig.-3.6 Stress distribution in Steel reinforced CNT model

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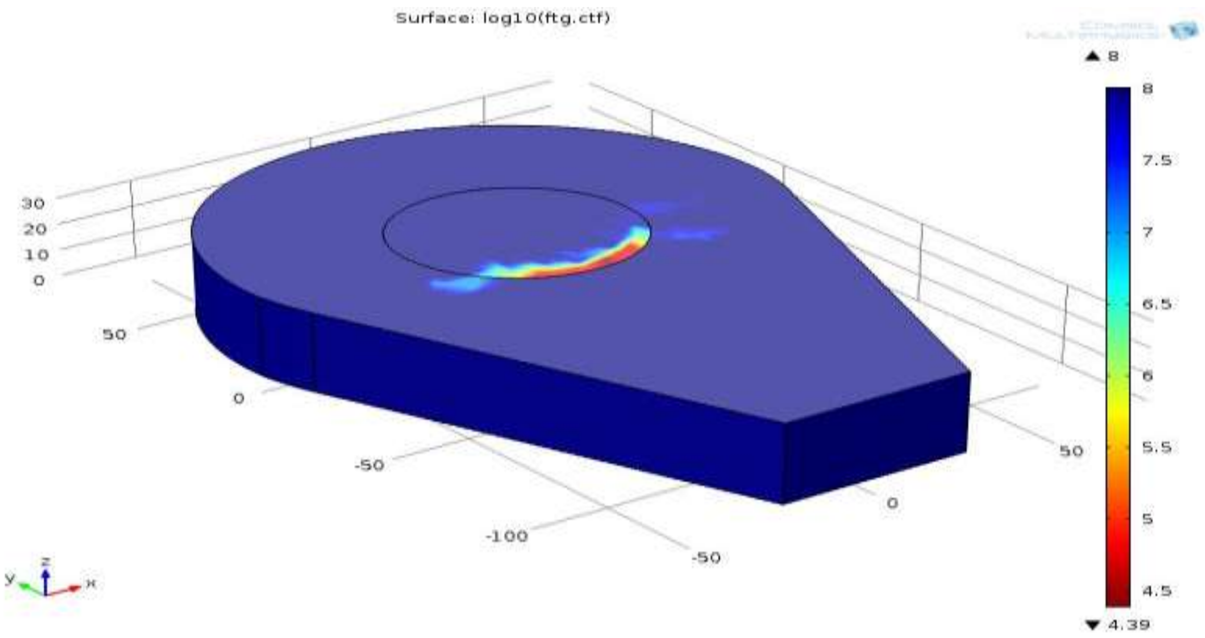

Fig.-3.7 Number of cycles to fatigue failure for Steel reinforced with composite model

4 Results & Discussion

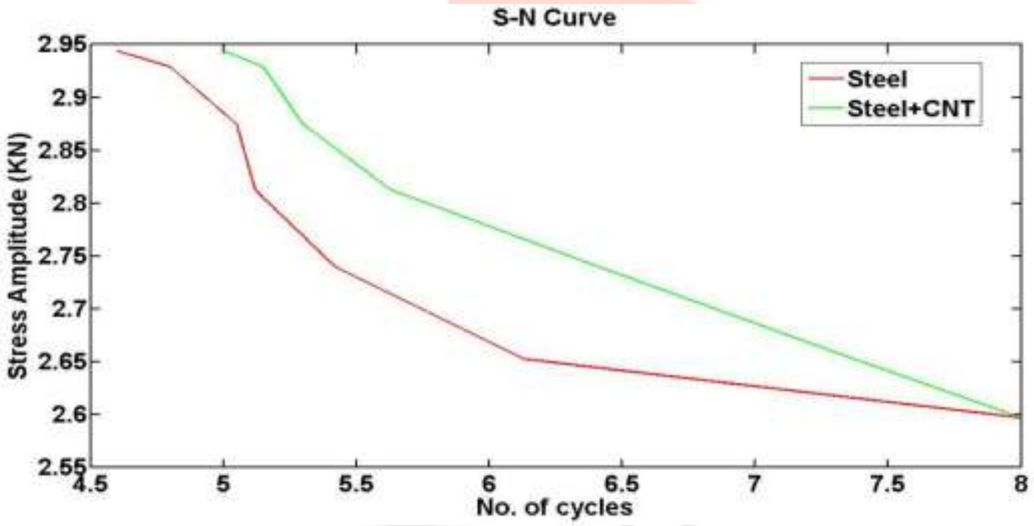

Fig:4.1 Comparison of S-N plot of (Steel) and (CNT reinforced steel) model

Fig.-3.2 shows stress distribution and Fig.3.3 shows the number of cycles to failure for a Steel model acted by the fluctuating loading . The number of cycles to failure obtained are 17082 cycles and Fig.-3.6 shows stress distribution & fig.-3.7 shows the number of cycles to failure of CNT reinforced steel model, which are obtained 24522 cycles from COMSOL analysis . So by reinforcement of CNT in the material the number of cycles to fatigue failure are increases.

CONCLUSION

In this study CNT is used as reinforcement in a high strength Steel model to evaluates its fatigue behaviour under fluctuating load.Since CNT's have very good mechanical properties so their reinforcement in metal matrix enhances the mechanical properties of pure steel model.Here same geometrical model for both high strength Steel and high strength Steel reinforced with CNT's are used under identical boundary condition and loading condition to predict their fatigue evaluations.It was observed from the analysis that the number of cycles for fatigue failure and fatigue strength in case of CNT's reinforced steel is increased in compare to the number of cycles for fatigue failure in high strength Steel model.

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