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Computation of Fatigue Life and Safety Factor of Elastomer

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Abstract —*Elastomers are widely used in academic as well as in industrial application. The present paper purpose is to understand the mechanical and cyclic properties of elastomers. Moreover how the fillers added in elastomers affect the mechanical properties and fracture behavior of the elastomers is discussed. Elastomers with two different grades of fillers are taken for research work. Experimental tensile test is performed to model the elastomers as hyperelastic material in software and to obtain the mechanical properties of elastomers. Constant amplitude fatigue test is performed on both the elastomers to obtain the cyclic properties and cycles to failure. This experimental data is taken for Stress Life Fatigue Analysis in FEA software to compute the Fatigue Life and Fatigue Safety Factor. Comparison of fatigue life and fatigue safety factor is tabulated to understand the fracture behavior and fatigue phenomenon in elastomers.*

Keywords*- Elastomers, Carbon black fillers, Uniaxial Tensile Test, Yeoh Hyperelastic Model, Constant Amplitude Fatigue Test, Stress Life Fatigue Analysis, FEA Software*

I. INTRODUCTION

Rubbers are wide group of materials with different chemical composition but similar molecular structure and mechanical properties. As all rubber materials are vastly elastic polymers thus a descriptive name “elastomer” is assign. The physical state and macroscopic properties of any material affects it failure mechanism. Material with glassy properties shows completely different crack propagation as soft material in melt state. Glasses show brittle fracture behavior while rubber with hyperelastic or viscoelastic property behavior with different loading condition shows different fracture mechanism. Rubbers are made up of long molecular chains known as monomers arranged in random motions having soft plastic consistency. In molecular state, the atoms are cross-linked with each other at each point in rubber material. The cross linking of each molecular chain is due to chemical process known as vulcanization invented by Charles Goodyear in year 1839.Thus a bond is developed between linking of each pair which is allowed to rotate freely. Thus because of this rubber possess unique physical and chemical properties. Mechanical properties of rubber are largely depended upon the cross-link density formed through vulcanization process. As cross-link density increases, modulus and hardness or rubber increases monotonically and rubber becomes more elastic and less hysteretic. It is important to study the rubber fracture behavior in different type of loading due to its unique mechanical properties such as high elasticity-its ability to sustain large straining without permanent deformation, low hardness, large volumetric stiffness, hysteresis property and stress softening behavior due to addition of filler. These characteristic of rubber eventually has great impact in commercial as well as in industrial application. Rubber are used as structural component, airspace jet fuel seals, automotive parts, barrier membrane, sporting goods, footwear application, etc.

ASTM defined fatigue as, “The process of progressive localized, permanent structural changes that occurs in materials when subjected to fluctuating stresses and strain that may result in development of cracks or fracture after sufficient number of cycles of fluctuation.” Several analysis procedures are available to study the fatigue phenomenon in any material and they are broadly classified as either ‘crack initiation’ or ‘crack propagation’ approaches. The fatigue phenomenon is generally divided into 3 stages: Stage I (Crack initiation), Stage II (Crack propagation) and Stage III (Fracture). In Stage I fatigue cracks initiates due to release of shear strain energy which are of 1 micron to 10 microns size nearly invisible through naked eye. The crack initiates in this way until it reaches the grain boundary and this mechanism is gradually shifted to the adjacent grain. When the crack grows approximately 3 boundaries, it changes its direction of propagation. The physical mechanism of fatigue changes in stage II. The crack has grown large enough to cause the geometrical stress concentration. Now at this part, crack propagates in perpendicular direction to applied loading. When a crack grows of critical size which will not allow the structure to withstand the next cyclic load, Stage III occurs.

In this research paper, the fracture behavior of material is observed for the experimental uniaxial tensile test and constant amplitude fatigue testing for rubber material. Uniaxial tensile test is performed to define the hyperelastic behavior of rubber in software for the fatigue analysis. Constant amplitude fatigue experiment is carried out on rubber specimen to obtain the stress amplitude v/s number of life cycles (SN curve). This data is used for further analysis to compute the fatigue life and fatigue safety factor of rubber material.

II. MATERIAL CHARACTERIZATION

3.1. The Hyperelastic Constitutive Model of the Carbon Filled Natural Rubber

Natural Rubber filled with carbon black fillers was used for the research work. Sample 1 contain 15% of carbon content and is abbreviated as N15 material while Sample 2 contain 55% of carbon content and is abbreviated as N55 material. Rubber material is filled with carbon black filler; it is modeled as hyperelastic material rather than visco-elastic material. In hyperelastic material, the relationship between stress and strain is characterized by strain energy potentials which is essential to for the FEA of rubber components. In order to modeled the material as hyperelastic material, experimental test data are required to determine the material parameters in the strain energy potential functions.

Tensile test is performed on rubber specimen design into dog-boned shaped specimen or dumb-bell shaped specimen according to American Society for Testing and Materials (ASTM D638-14)-Standard Test Method for Tensile Properties of Plastics. The dog-bone shaped dimensions are shown in Figure 1. Also, the test condition was displacement controlled and at rate of 500mm/min and carried out till the rubber, fractures.

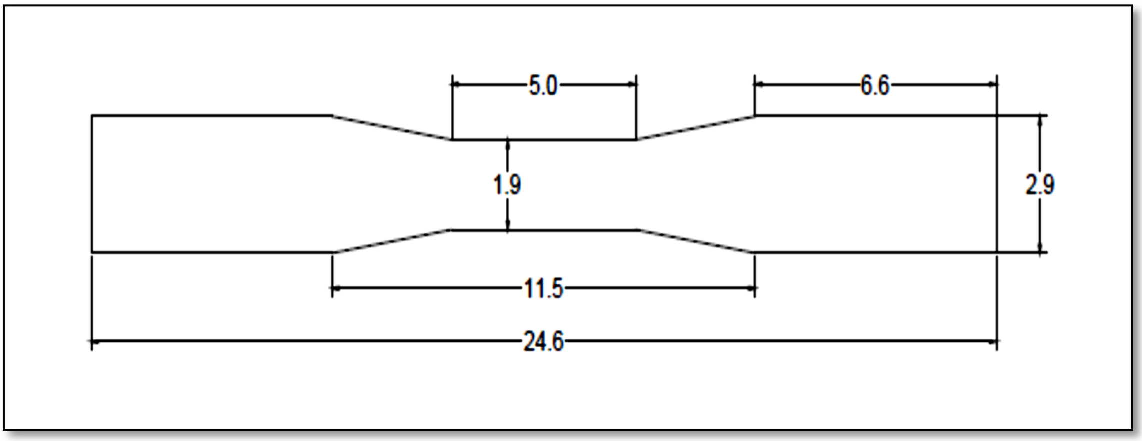

Figure 1 Dumbell Shaped Tensile Test Specimen

The Yeoh's 3rd order constitutive model is used to define the hyperelastic material behavior and the strain energy potential is expressed as:

$$W = C_{10}(I_1 - 3) + C_{20}(I_1 - 3)^2 + C_{30}(I_1 - 3)^3$$

Where,

C_{10}, C_{20} and C_{30} are material constants

I1 is the stress invariants

Yeoh model is used for the characterization of carbon-black filled rubber as it can capture upturn of stress-strain curve. It has good fit over a large strain range and can simulate various modes of deformation with limited data. This leads to reduced requirements for material testing. By data fit using the data acquired in uniaxial tensile test as shown in Figure 2 and Figure 3 for N15 and N55 rubber respectively, we determined the material constants for N15 and N55 rubber material shown in Table 1. Also the mechanical properties of both materials are obtained and are shown in Table 2.

Table 1 Yeoh's Material Constant for N15 and N55 rubber material

Yeoh's Material Constant	N15	N55
C10 (MPa)	1.393	0.81974
C20 (MPa)	0.55793	0.10423
C30 (MPa)	136.53	0.0073856

Table 2 Mechanical Properties for N15 and N55 rubber material

Property	Rubber N15	Rubber N55
Ultimate Tensile Strength (MPa)	0.62	3.02
Tensile Yield Strength (MPa)	0.37	0.5
Young's Modulus (MPa)	8.40	4.95
Poison's Ratio	0.40	0.45
Bulk Modulus (MPa)	14	16.5

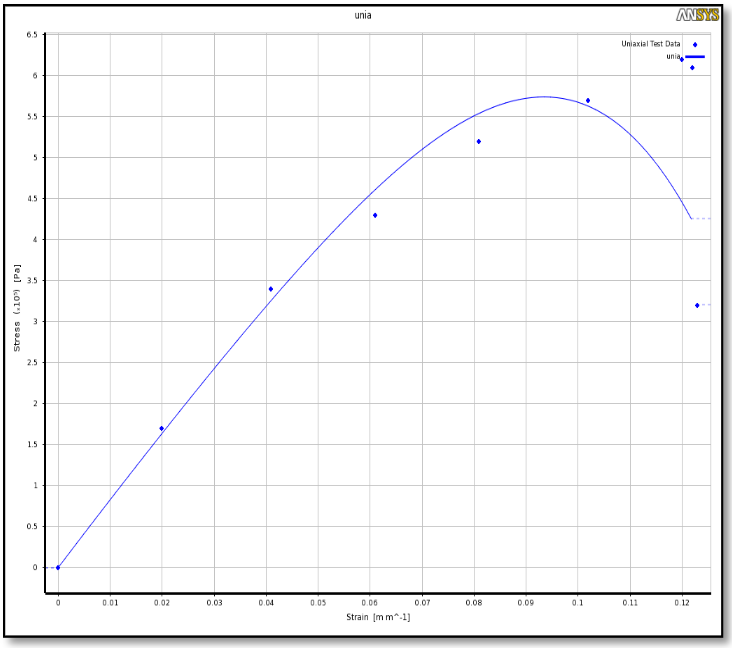

Figure 2 Curve Fitting of Uniaxial Tensile Test data for N15 rubber

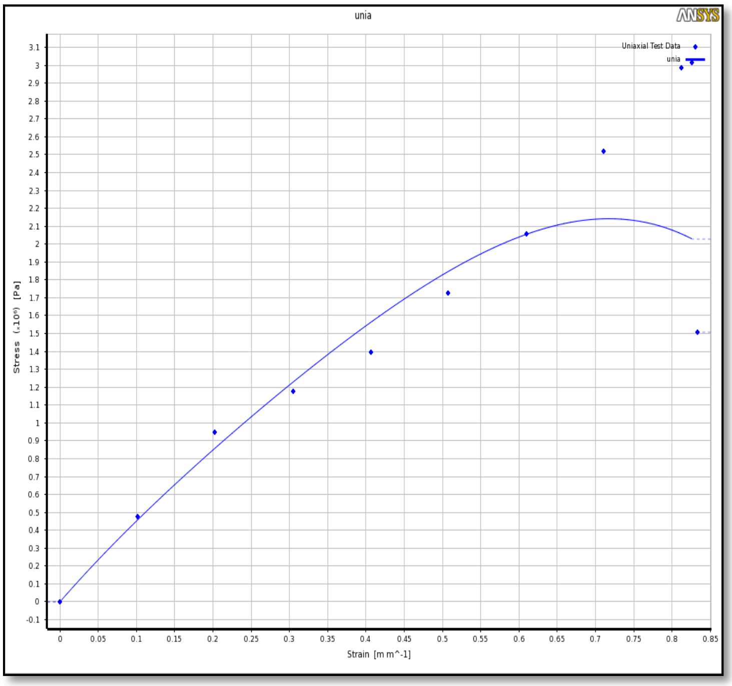

Figure 3 Curve Fitting of Uniaxial Tensile Test data for N55 rubber

3.2. Fatigue properties of the Carbon Filled Natural Rubber

There are two methods to define the fatigue properties of the material, one is the fatigue life equation and curve of stress amplitude vs. fatigue life (*S-N* equation and curve), and the other is the fatigue life equation and curve of strain amplitude vs. fatigue life (ε-N equation and curve) [1]. In order to evaluate the fatigue properties, dumbbell shaped specimen according to ASTM D412 standard was performed. A dumbbell shaped specimen dimension used for fatigue test is shown in Figure 4. The dumbbell specimen was subjected to cyclic loading with constant amplitude and non-zero mean stress at 3Hz frequency and stress ratio R=0. The stress amplitude v/s number of life cycles (SN curve) was obtained from the fatigue test with load controlled condition and data is shown in Figure and Figure for N15 and N55 rubber. The test was performed at ambient temperature of 27º C at Tii Chennai.

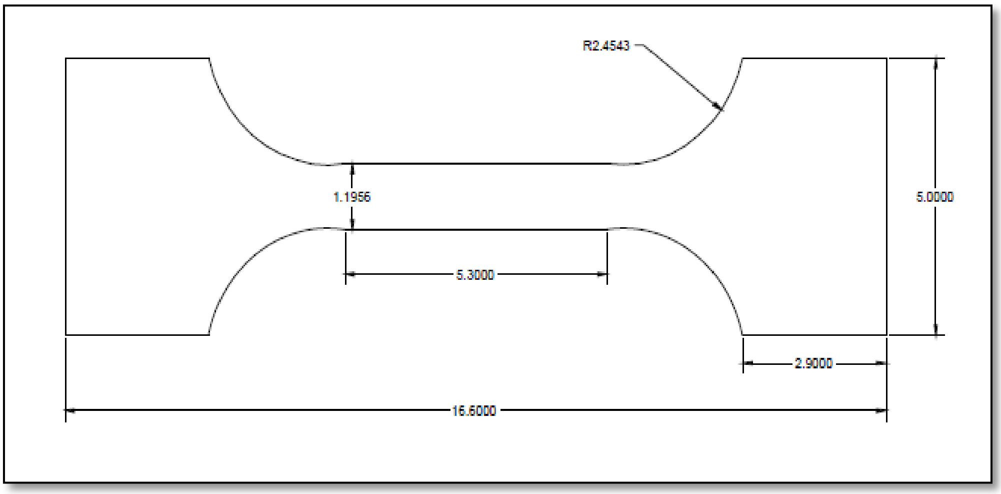

Figure 4 Dumbbell shaped specimen for Fatigue Testing

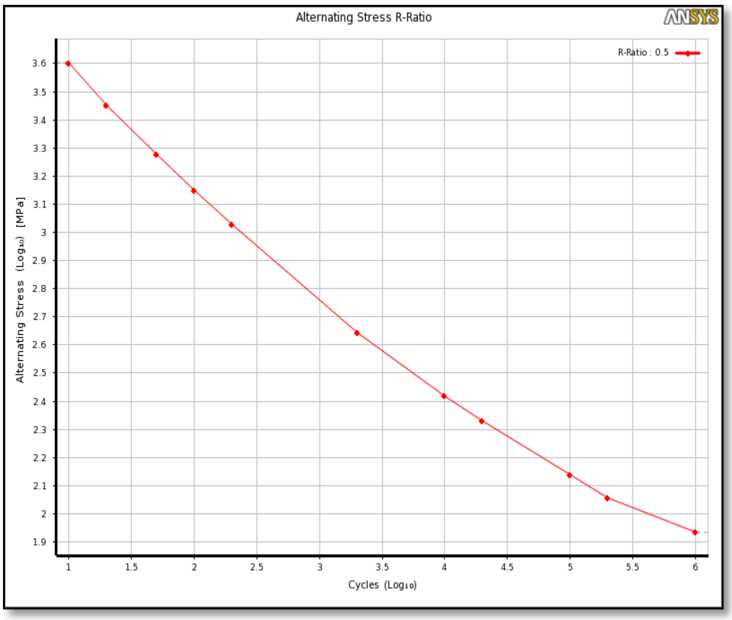

Figure 5 SN curve for N15 rubber material

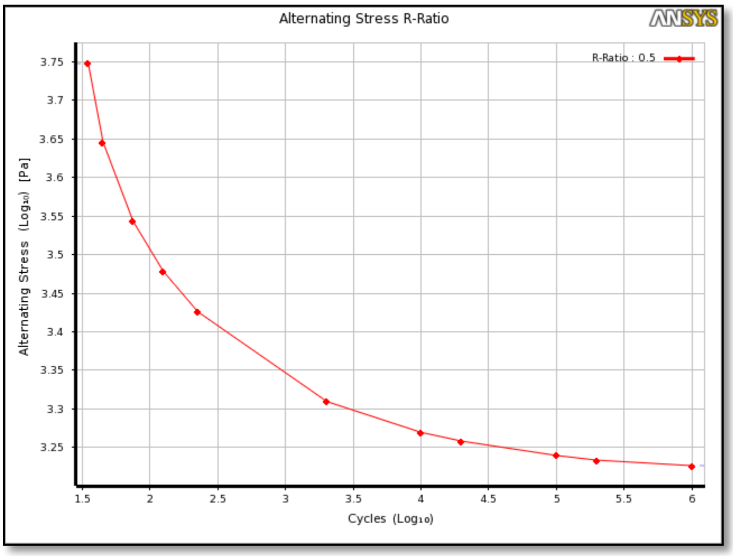

Figure 6 SN curve for N55 rubber material

III. FEA of an Elastomeric Sheet

The model of an elastomeric sheet is shown in Figure 7 which was analyzed by ANSYS software. Rubber layer is modeled as SOLID186 with the fixed boundary condition (i.e. $U_x=U_y=U_z=R_x=R_y=R_z=0$) and pressure of 3.45MPa is applied on the top surface layer. Yeoh's material coefficient is used to characterize the hyperelastic behavior. The dimension of geometry was 375mm long x 190mm wide x 12mm thick [1]. A finer mesh is assigned to the component for better result. Moreover fatigue properties are inputted in fatigue module such as Type of Stress Life, Stress Ratio, Mean Stress Correction Theory, etc. Output parameter is added in fatigue module such Fatigue Life and Fatigue Safety Factor.

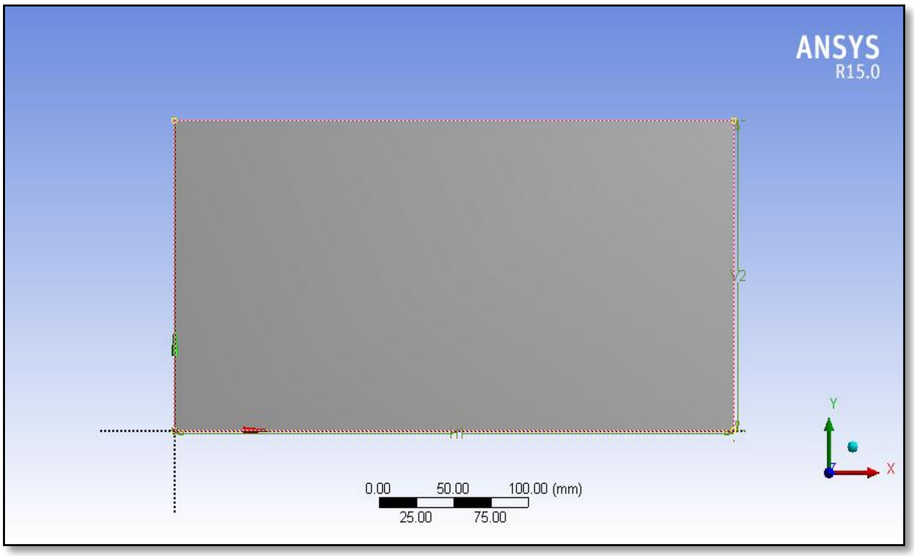

Figure 7 Elastomeric Sheet modeled in ANSYS

3.1. Fatigue Life Results

As Load controlled fatigue analysis was carried out on Rubber N15 and N55 we can predict the fatigue life's in term of cycles in Table 3. Also the contour plot of fatigue life obtained from the fatigue analysis in ANSYS Workbench is shown for N15 rubber in Figure 8 and for N55 rubber in Figure 9.

Table 3 Maximum Fatigue Life value for N15 and N55 rubber

Fatigue Life (cycles)	Rubber N15	Rubber N55
Analytical Maximum Life Value	10^6	1.47×10^6
Experimental Maximum Life Value	10^6	10^6

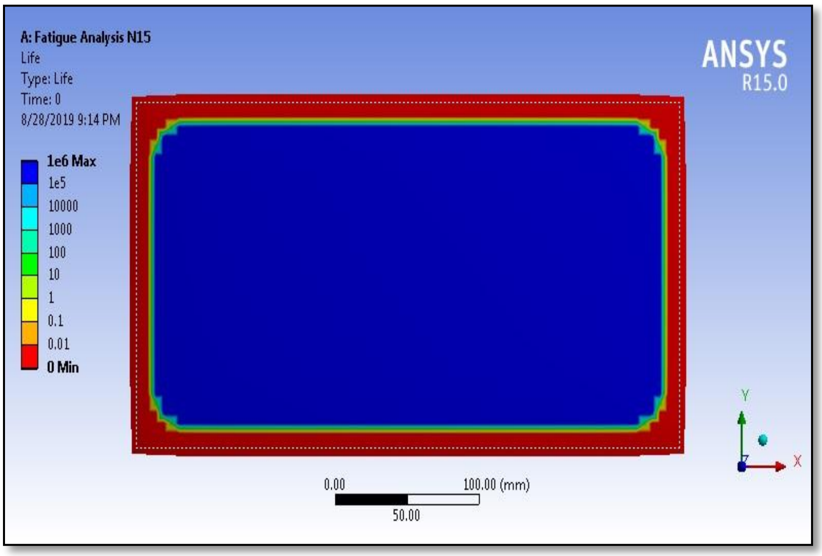

Figure 8 Fatigue Life Contour Plot for N15 rubber

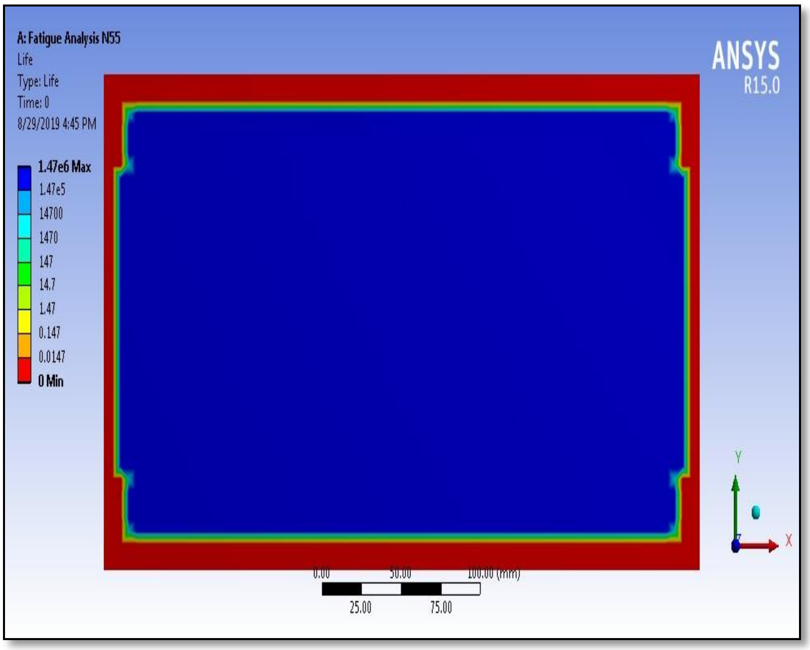

Figure 9 Fatigue Life Contour Plot for N55 rubber

3.2. Fatigue Safety Factor Results

Factor of safety for both Rubber N15 and N55 is calculated through analysis in software. Results are shown in Table 4 for both the material. Results in software are shown in Figure 10 and Figure 11 for material N15 and N55 respectively.

Table 4 Fatigue Factor Safety values for N15 and N55 rubber

Factor of Safety	N15	N55
Minimum	0.39469	0.00859
Maximum	2.1504	0.000779

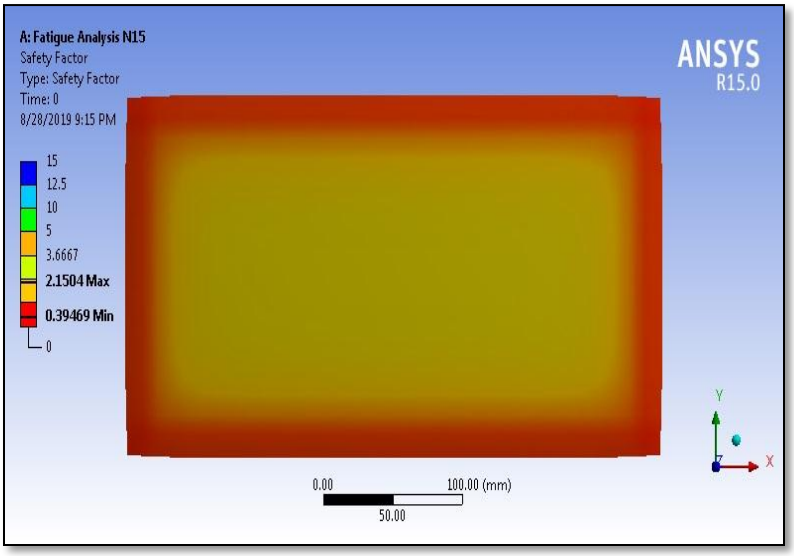

Figure 10 Fatigue Safety Factor contour plot for N15 Rubber

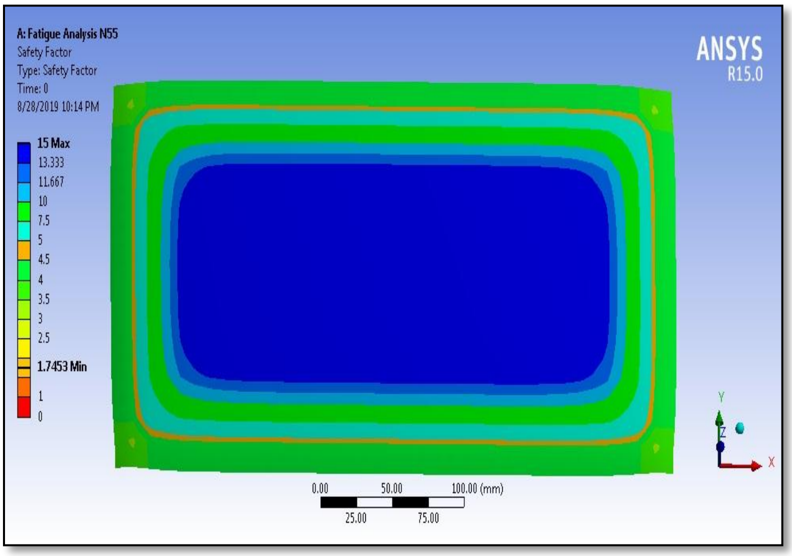

Figure 11 Fatigue Safety Factor contour plot for N55 Rubber

IV. CONCLUSION

From the experimental and analytical results obtained following conclusion can be made out:

- During the uniaxial tensile test, the fracture mechanism of rubber was observed to be ductile because necking of rubber material was seen.
- Contour plot of life shows that inner surfaces had maximum available life cycles than the outer edges.
- From Fatigue factor safety contour plot we get maximum value for N55 rubber i.e. 15 for the design life period which is 10,00,000 cycles and maximum fatigue safety factor is 2.1504 for N15 rubber.
- Also contour plot shows that maximum safety factor is obtained at inner surface because inner surface of component will deflect largely at downward side due to fixed boundary condition given for the following analysis.
- If we relate the fatigue life and factor safety results, we can say that for both the results we get maximum value at inner surface of the geometry which means that for a component to sustain at high life cycles, a high factor of safety has to be taken for the calculation.
- Generally the stress amplitude corresponding to 10,00,000 cycles is taken as endurance limit or endurance strength according to the theory for steel material, but for rubber material no theories had come out for following.
- While for fatigue testing, there was no necking observed and material failed suddenly which shows the brittle fracture mechanism.

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