Design and Construction of Device for Rubber Material Fatigue Test

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Abstract: Due to the wide use of rubber components in different engineering applications such as vibration isolators, engine mounts, car tires, and bridge bearing pads, etc., this rubber component is mostly subjected to repeated loads continuously. As a result, these loads will initiate cracks on the outside surface of a component and then, these cracks will grow over time, and then, the growth of the cracks increase leading to a failure of the rubber component. Many researchers have studied the behavior of fatigue under the action of many factors by utilizing many devices. These devices produce repeated loading on the sample made of rubber material, initiating cracks and, then crack growth, which leads to failure. Therefore, in this paper, a modern test device has been developed and constructed to perform laboratory rubber fatigue testing. This device has been proven to be accurate and with the ability of repeatability.

Keywords. Natural rubber, Fatigue life, Periodic load, Stress amplitude

1. Introduction
Rubber materials have long-chain molecules called elastomer polymer. Owing to its large reversible elastic deformation, good damping, and energy absorption specifications, rubber is widely used in many engineering applications. Rubber parts are related to almost every portion of everyday life. Typical uses of rubber components are vibration isolators, engine mounts, car tires, and bridge bearing pads, etc. Mechanical, electrical, environmental (such as oxygen, ozone, and ultraviolet radiation) and chemicals (for instance oil) are the principle sources of fatigue cracking in rubber. Other treads and ply separations are common failures in tires as well as failures that happen in motor mounts, bridge bearing pads, and suspension bushings, etc. Rubber components are almost subjected to dynamics forces resulting in a dynamic displacement [1,2]. Rubbers, in an identical form as other different materials, which include plastics and metals, fail at levels of stress far below their maximum stress, under repeated or longer-term stress [3]. Rubber material mechanical fatigue is shown by gradual degradation in physical characteristics at the application of dynamic loads or deformations that will produce slow crack growth. The fatigue life can be estimated by two methods. The first method is examining cycles to failure and the other is evaluating fatigue crack growth rate. The number of cycles needed to split a sample into two parts either at specific stress "for a stress-controlled" or at specific strain "for a strain-controlled" test defined as fatigue life. The experimental fatigue-life results are
mostly distributed. Normally, a large number of specimens are required in time-consuming experiments to attain an average value of rubber fatigue life. Test methods for estimating the life of fatigue can be classified into the following categories: cyclic loading between constant strain or stress values in compression or tension, reversed shear stresses (such as: achieved through torsional deformation) and in the end reversed bending stresses (such as : flexing of a sheet in one dimension) or two dimensions (such as : rotary deflections of cylindrical sample). Generally, the fatigue properties of rubbery materials can be calculated from (S-N) curve (S indicates to the dynamic stress applied for a stress-controlled test or, instead of that, S indicates to the dynamic strain applied for a strain-controlled test, and N indicates to the number of cycles to failure). Figure (1) shows the relationship between the dynamic stress (or strain) and the number of cycles to failure on a logarithmic scale. Depending on the aims of investigation, the fatigue crack nucleation and fatigue crack growth are two general methods for fatigue analysis. The first method (fatigue crack nucleation) concerns the life of a component until the crack is formed. The second method (fatigue crack growth) concerns the growth of cracks and defects found in the materials [4,5]. The basic sinusoidal oscillations were used for many studies about the behavior of fatigue for rubbery materials.

Several previous studies have examined the fatigue behavior of elastomers in the laboratory using various devices designed for this purpose. In several studies [6] used the universal testing device with various models, while some other works [7] used the servo hydraulic testing equipped. The instruments mentioned above were used experimentally to calculate the fatigue behavior characteristics of elastomer material, such as fatigue life with various parameters by producing repeated mechanical loading (Sine wave excitation). To measure the load and the displacement of cross-head data, Wang et al [8] utilized a system consisting of a data acquisition board, PC, and LabView software, called a data acquisition. Cam and Toussaint [9] compared two rubber compounds subjected to mechanical load under uni-axial displacement and a 50N by using Instron-5543 testing machine supply with a system of 12-bit dynamic sensiCam camera attached to the computer for acquisition of process image and data processing with septD program. Push-pull and torsion home-made electromechanical fatigue devices were used to conduct fatigue testing by Saintier et al. [10]. A unit transformer digital to analog transformer during a unit control PC control was supplied to the testing machine by a waveform. The PC control registered the force, displacement, and the number of cycles data through an analog-to-digital transformer. At room temperature and low frequency (1 Hz), all experiments were conducted. Push-pull and torsion experiments were performed at different loading ratios on Diabolo specimens. Noda et al. [11] used the device Fatiguron VFA-1kNA, A&D Orientec Co., Ltd, Sattama, Japan to examine fatigue behavior. A permanent observed of surface temperature and non-Linear dynamic viscoelasticity were performed through repeating loading. The applied load under constant amplitude was considered on the sample test and measured the surface...
temperature at the center of the sample test continually. Moreover, this instrument was designed to observe surface temperature under tension-tension load in the fatigue test but it cannot be utilized for fatigue testing under the compressive-compressive or combined load and variable stress amplitude. To examine the fatigue crack growth of elastomer utilizing a newly developed test equipment, Shinyoung Kaang et al.[12] used a developed test approach. The fatigue crack growth was examined under the influence of frequency and temperature. This instrument has been designed to research the growth of crack with pure shear. This instrument has been designed to research the growth of crack with pure shear. For diabolo sample test shape or varying amplitude, it cannot be utilized. The lives of fatigue for the rubber mount at various loads were studied by Li et al.[13], utilizing a fatigue test machine to evaluate and verify the reliability of the life of the fatigue calculation technique. The load conditions "Constant amplitude, sinusoidal cycling loads with a mean load of zero and a frequency of 10 Hz" was applied to the samples of the rubber mount. This test machine was used only for rubber mount samples, thus it not possible for the other sample shape and different stress amplitudes as well. A new testing machine was created by Long et al.[14], to evaluate lifetimes of fatigue and they studied bi-axial fatigue lifetimes of biomedical elastomers materials. Based on previous works, it is necessary to design a modern device that is easy to maintain and use and gives accurate results for fatigue testing. The device will be introduced to study the fatigue behavior of rubbery materials. The current project involved the construction of the instrument, characterization, applications, the adjustment mechanism and the arrangement of the tests conducted on the instrument being implemented.

2. Description of the device
The fatigue test device was developed and created to examine the rubber's fatigue behavior. The concept of a test rig for the fatigue behavior is to create a repeated movement, somewhat similar to a sine motion. This motion produces a fluctuating load such as tension or compression or combined of two loading conditions on the rubber diabolo sample test containing edge notch, until splitting the sample into two parts with stress-controlled. The device consists of base, electric motor, two plates gage 8 mm thickness (the main plate is movable and the upper plate is stationary), four vertical columns with threaded ends, two bearing brackets, four vertical shock absorbers empty of oil, rubber coupling, horizontal shift, two eccentric bushes (one bush is small and the other is large), ball bearing, spring system, load cell sensor, displacement sensor and variable frequency drive. The four shafts with ends threaded are connected to the base from the lower side and into the upper stationary plate from the other side by four nuts for each side. The four vertical shock absorbers are welded to the stationary upper plate and the shafts of shock absorbers are fastened to the main moving plate by four bolts. The purpose of shock absorbers is for easier movement of the main plate up or down or in the other directions used as instructed. Figures (2,3) show the front and side views in the case of tension and compression respectively. Figure (4) shows the real picture of fatigue test device. The load cell type used is ss300-500k with 500 kgf maximum capacity, tension, compression, and rated output is (2±0.005) mV/V. Figure (5) shows the calibration curve of the load cell. The load cell is attached from the lower side to the base by bolt and from the upper side to the sample test. The displacement sensor type used is the KTR-100mm linear position sensor which is fastened to one of the shock absorbers with a clamp. The sensor head is in contact with the moving main plate. The displacement sensor and the load cell are attached to the 5V power supply. The output voltage is estimated, controlled and registered through the arduino system which consists of computer, arduino, Lab-view to browse the stored data between the time and load as well as the time and displacement. The stopwatch is used to measure the time spent. The electric motor (3-phase, 220-380V, 50Hz, 2835 r.p.m, and 1.5Hp) is cooperated on-base utilizing four bolts and nuts [15 to 20]. The motor shaft is connected to the horizontal shaft by rubber coupling to obtain a stable rotation. The horizontal shaft enters through two bearing brackets fastened on the base by two bolts and nuts for each. The small eccentric bush is held by a key on the middle position of the horizontal shaft which is located between two bearing brackets and then the large eccentric bush is held by two screw bolts on the small eccentric bush and finally, the ball bearing is held on the large eccentric bush. So, this composition produces a change in an eccentricity ball bearing. This eccentricity of ball bearing displaces the movable plate up or down and control the stress amplitude by adjusting the eccentric large bush as shown in figure (6). The spring
system is fixed between the movable main plate and the stationary upper plate. Its purpose for this system is to apply force on the movable main plate to restore it to the original position. The adjusting bolt will change the force applied in magnitude. AC drive is used to adjust motor speed to a specified speed [21 to 24].

**Figure 2.** Front and side view of the rubber fatigue test device "Sample in tension". 1-Base, 2- Electric motor, 3-Rubber Coupling, 4-Bearing bracket, 5-Horizontal shaft, 6-Rubber sample, 7-Load cell, 8-Helical Spring system, 9-Ball bearing, 10-Vertical column, 11-Shock absorber, 12-Fixed plate, 13-Movable main plate and 14- Displacement Sensor.

**Figure 3.** Front and side view of the rubber fatigue test device "Sample in compression".
Figure 4. Real picture of fatigue test device.

Figure 5. Calibration curve of load cell.

Figure 6. Section and two 3D solid of adjustment Mechanism for stress amplitude.
3. Applications of fatigue test device

The design assumed for the fatigue test rig is very easy and appropriate for investigating rubber fatigue life through various factors such as frequency, mechanical loading, and stress amplitude. Additionally, investigations of crack growth for a sample with a single edge crack, the integrated test rig may be used for tensile, compressive, and tensile-compressive stress testing. The specifications (minimum stress $\sigma_{\text{min}}$, maximum stress $\sigma_{\text{max}}$, stress- ratio $R=(\sigma_{\text{min}}/\sigma_{\text{max}})$, number of cycles $N$ as well as sine wave profile) can be calculated from the Lab-View data. Furthermore, the time spent to split specimen into two parts can be registered by using the stopwatch and then, the number of cycles at the broken sample can be calculated as:

$$N_{\text{cycles}} = t_{\text{spent}} \times f$$

Where $N_{\text{cycles}}$ = Number of cycles, $t_{\text{spent}}$ = Spent time, and $f$ = Frequency.

4. Mechanical load history

Because of the alternating loads, mechanical fatigue includes nucleation and growth of cracks. The basic definition of "load" will be included in the discussions that follow to explain the strength of fatigue as determined by different factors, based on different methods of analysis such as stress, strain, energy release rate, strain energy density, etc. The following parameters in parentheses [minimum load ($S_{\text{min}}$), maximum load ($S_{\text{max}}$), alternating load ($S_a$), mean loading ($S_m$), and/or R-ratio ($R = (S_{\text{min}}/S_{\text{max}})$)] are depicted in figure (7) typically features of simple mechanical histories when subjected to laboratory samples [2].

$$S_a = \frac{S_{\text{max}} - S_{\text{min}}}{2}$$

$$S_m = \frac{S_{\text{max}} + S_{\text{min}}}{2}$$

![Diagram showing mechanical load history](image)

**Figure 7.** Relationship between time and stress amplitude [2].

The adopted test machine can be utilized to execute fatigue tests during various loading conditions (tension, compression, and combined) as shown in figures (2,3). To examine the behavior of fatigue under various stress and stress ratios the force is applied by a spring system. By adjusting the bolt, the value of force, it can be changing. From the eccentricity resulting in large and small bushes eccentricities that are connected above the horizontal shaft, the sine wave profile of load can be obtained. By rotating large eccentricity bush above the small bush to change the eccentricity [25 to 30], a measuring rig is made up for proper measurement of the stress applied. It is made up of a load cell, an Arduino board, and a computer. The value of applied stress is transformed into an electrical signal by the load cell. In addition, the electrical signal is transformed into stress values during the Arduino board and computer. The wave between stress and time can be reviewed by the lab-view program. The specifications: maximum stress, minimum stress, stress ratio, number of cycles and sine wave profile can be extracted from the wave resulting from lab-view.
5. Experimental work
The fatigue testing machine created can be used to conduct the fatigue test on diabolo samples under various load conditions such as tension, compression, and combination. The basic recipe formulation in this work is according to the standard specifications of Dunlop Company approved by the General Company for Rubber Industries / Babel branch, which consists of the following components as shown in Table (1). The recipe used vulcanized at a condition (175 °C, 32 MPa, and, 25 min.). The diameter of the sample utilized is 25 mm and it contains 5 mm edge crack in the middle of the specimen, as shown in figure (8). The repeated loading was applied at constant amplitude to the sample until it failed. The sample was split into two sections at failure. By observing the elapsed time from the beginning of the test up to failure that was reported by a stopwatch and using equation (1), the number of cycles was obtained. By utilizing equipment introduced at a constant strain amplitude that was applied to the sample at a frequency of 5 Hz and different maximum and minimum stress values, the fatigue behavior of rubber material was investigated. The influence of the strain amplitude on the behavior of fatigue was studied as well. All experiments were conducted at room temperature [31-40].

Table 1. Ingredients of the recipe used in the experimental test [41].

| Item | Material                  | Standard loading level (pphr) |
|------|---------------------------|------------------------------|
| 1    | Natural Rubber (NR)       | 100                          |
| 2    | Zno Oxide (Zno)           | 5.5                          |
| 3    | Streic Acid               | 1                            |
| 4    | TMQ                       | 1.5                          |
| 5    | Wax                       | 0.5                          |
| 6    | Oil                       | 5                            |
| 7    | Carbon black (N330)       | 48                           |
| 8    | CBS                       | 1.5                          |
| 9    | Sulfur                    | 2.3                          |
| 10   | CTP.100                   | 0.15                         |
|      | Total Ingredient          | 165.45                       |

* PPhr = Part per hundred.

Figure 8. Specimen shape and dimensions (All dimensions in mm).
6. Results and discussion

The fatigue test is done on the samples to generate the S-N curve and observe the influence of the strain amplitude on the fatigue behavior of the rubber material. The S-N curve illustrates in figure (9), where the experiment conducted at a specific magnitude of the frequency of 5 Hz and varying values of maximum and minimum stress. The resulting stress amplitude was evaluated to sketch the relation between the stress amplitude against the fatigue life (number of cycles) until failure occurs. It noticed that the presence of a crack in the middle region of the sample was grown and, increasing to failure occurred. The cracked sample was split into two portions up to failure, as shown in figure (10), and this is consistent with previous review research. Under combined load condition (tension/compression), tension only and different minimum strain amplitude with the same frequency, the fatigue tests were conducted. In these tests, at least three samples were used and then calculate the average value of cycles number at failure. Three samples test showed the same pattern at failure, as shown in figure (10). The sine wave profiles obtained from the results were acceptable, as shown in figure (11). As a consequence of the above results, it is obvious that the experimental setup developed has excellent repeatability.

![Figure 9. S-N curve of natural rubber (NR) with (48 pphr) of carbon black (CB).](image)

![Figure 10. Image of the three fractured specimens made of (100 pphr) natural rubber (NR) with (48 pphr) of carbon black (CB) in fatigue test under periodic loading to indicate the fractional regions.](image)
(a) minimum strain = -10.35%.

(b) minimum strain = -6.7%.

(c) minimum strain = 0%.

(d) minimum strain = 12.07%.

**Figure 11.** Sine wave profiles under constant maximum strain (20.7%) with the same frequency made of (100 pphr) natural rubber (NR) with (48 pphr) of carbon black (CB) in fatigue test under periodic loading.
7. **Conclusion**

The fatigue test of the rubber material instrument was introduced to offer the ability to examine the behavior of fatigue through various factors, for instance, stress amplitude, frequency, and mechanical load. In addition, the fatigue test can be conducted with constant strain amplitude under compression or tension or combination (tension/compression). Moreover, the presence of a crack in the diabolo specimen to investigate the crack propagation specifications. As a consequence of the observations above, the developed experimental setup has proved to be accurate with excellent repeatability of tests.

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