DESIGN OF RUBBER FATIGUE BEHAVIOUR TEST RIG

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ABSTRACT

Fatigue behaviour of rubber is a very important characteristic due to its extensive use in many engineering applications. In applications, rubber is commonly subjected to fluctuating loads, which often lead to fails due to the nucleation and growth of defects or cracks. Many factors are known to influence the mechanical fatigue life of rubber components. There were a lot of researches that investigated the fatigue of rubber and the factors that affect the fatigue behaviour, by using many different apparatuses and arrangements. Such apparatuses and arrangements generate cyclic loading on the rubber specimen, which leads to nucleation and crack propagation to failure. In present work a new test rig has been designed and manufactured to carry out laboratory rubber fatigue test. The introduced test rig has been tested and proved to be reliable and has good repeatability.

Keywords: Rubber, Fatigue life, Mechanical loading, Amplitude and Frequency.

1. Introduction

Rubber materials usually have long chain molecules known as polymers. Rubber, as an engineering material, has been used in many industrial branches such as automotive industries and in a wide range of applications such as engine mountings, tires, vibration isolators, medical devices and structural bearings. Such industrial components sustain large static and time-varying strains, which necessitate improvement of their durability and mechanical fatigue. Rubber is an ideal material for many applications because it can withstand very large strains over 500% with no permanent deformation or fracture. When it is subjected to fluctuating loads, it often fails due to nucleation and growth of defects or cracks. Fatigue characteristics of rubber remain empirical to a great extent. The main causes or factors affecting fatigue cracking in rubber are mechanical, thermal, environmental (oxygen, ozone, and ultraviolet radiation), and chemical parameters (e.g., oil and sour gasoline)[1,2].

Fatigue life is conventionally defined as the number of cycles to break a specimen into two pieces at a particular stress for stress-controlled, or at a particular strain for strain-controlled, tests. The experimental data of fatigue life are somewhat scattered. Usually, for obtaining an average value of rubber fatigue life a large number of samples are necessary in time-consuming experiments. Test methods in determining the fatigue life can be categorized as follows: periodic loading between fixed stress (or strain) limits in tension or compression, reversed shear stresses obtained by torsional deformation and finally, reversed bending stresses in one dimension (flexing of a sheet) or two dimensions (rotary deflection of a cylinder). Traditionally, the fatigue characteristics of materials, including

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rubbers, were determined by a "Wohler" curve, also known as S-N curve (S denotes the applied dynamic stress σ for a stress-controlled test or, alternatively, strain ε for a strain-controlled test, and N is the number of cycles to failure). Normally, the dynamic stress range (or strain range) is plotted against the number of cycles to failure on a logarithmic scale, as shown in FIGURE1. Two general approaches to fatigue analysis are available depending on the goals of the investigation, namely, fatigue crack nucleation and fatigue crack growth. The fatigue crack nucleation approach focuses on the life of a component until a crack forms. The fatigue crack growth approach focuses on the growth of existing cracks or flaws in the material[3,4]. Most studies of rubber fatigue behaviour, crack nucleation and propagation, have utilized simple sinusoidal excitations.
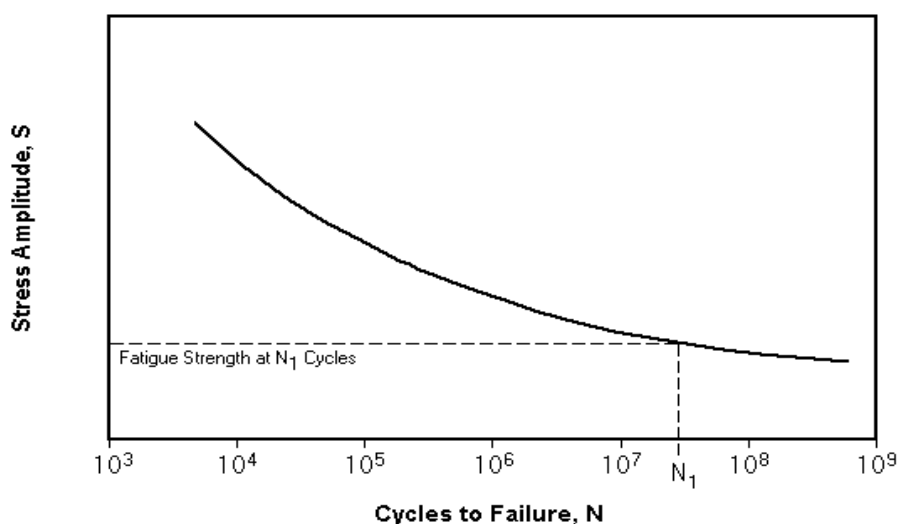
Fig. 1. S-N curve for rubber: S is the applied dynamic stress σ, of the cycle and N is the number of cycles.

Many apparatuses have been designed to conduct laboratory fatigue behaviour of rubber studies. *A servo-hydraulic* fatigue testing system was used in many studies [5–10], also *the universal testing machine* equipped with different models was used in many research works [8,11–18]. This apparatus was used to evaluate fatigue damage parameters and to determine the experimental fatigue life of rubber material, by generating cyclic loading sinusoidal wave excitation. The force was measured by a standard load cell; and the data were recorded by a computer. However, these test rigs are complex, expensive and need continuous maintenance specially the hydraulic unit. Noda et al. [19] studied the fatigue behaviour using the fatigue tester (Fatiguron VFA-1kNA, A&D Orientec Co., Ltd, Saitama, Japan), where continuous measurements of nonlinear dynamic viscoelasticity and surface temperature during cyclic fatigue were carried out. The sinusoidal stress with the constant amplitude was imposed on the specimen and the surface temperature at the

specimen center was continuously measured during cyclic fatigue. However, this apparatus was designed to measure the surface temperature in fatigue test under tensile load but cannot be used in fatigue test with compressive load and stress with variable amplitude. Shinyoung Kaang et al. [20] introduced an advanced test method in order to characterize the crack growth behaviour of rubbery materials using a newly designed test machine. The effects of temperature and frequency on the fatigue crack growth were investigated. However, this rig was designed to study the crack growth with pure shear. It cannot be used for diabolo specimen shape or variable amplitude. Wang et al. [12] used data acquisition system that consists of PC, data acquisition board and the Lab- View software, to record the load and cross-head displacement data. Cam and Toussaint [15] used Instron-5543 test machine equipped with optical setup. It consists of a cooled 12-bit dynamic sensicam camera connected to computer in order to process image acquisition and data treatment with the SeptD software. Li et al. [21] studied the fatigue lives of the rubber mount, using a fatigue test rig to measure and validate the accuracy of the fatigue life prediction method. The specimens of the rubber mount were subjected to constant amplitude, sinusoidal cycling loads with a mean load of zero, and frequency of 10 Hz. However, their rig was designed for rubber mount specimen, so cannot be used with another specimen shapes, and cannot be used for variable amplitude also. Baek and Khonsari [22] used a universal micro tribometer equipped with a computerized data acquisition system, for measurement of friction and wear. A crank mechanism, which produced the necessary oscillatory motion was designed, to accommodate changes in the displacement amplitude obtained from a variable-speed servomotor that provides sinusoidal reciprocating motion. Saintier et al. [18] investigated the performance of the fatigue testing using push–pull and torsion homemade electromechanical fatigue machines. Fatigue machines were supplied with waveforms generated by a digital-to-analogue converter under PC control. Number of cycles, force and displacement data were recorded by PC via an analogue-to-digital converter. All tests were carried out at room temperature and low frequency (1 Hz). Experimental results were obtained on diabolos specimens.

From the above literature review it is clear that introducing a new simple, efficient and accurate design of fatigue test apparatus is needed. The introduced apparatus will be used to study the fatigue behaviour of rubber. The present work includes apparatus design, description, state of the applications, the mechanism of adjustment and arrangement of the tests performed on the introduced apparatus.

2. Rubber fatigue behaviour test rig

2.1. Apparatus description

The introduced fatigue test apparatus was designed and manufactured for the purpose of testing the fatigue behaviour of rubber. The idea of the fatigue test apparatus is to generate a sinusoidal excitation (sine wave), which provides cyclic stress (tension or compression or combination of both of them) on the rubber specimen (diabolo, a single edge crack), up to its failure with stress control. It consists of: four vertical columns, three plates (upper, main

and lower plates), base, electric motor, motor base, ball bearing and spring system. Figures 2, 3 and 4 show a section elevation, a section side view and two photographs of the fatigue test apparatus, respectively. The diabolo specimen is glued with thin plates at each end and fastened by means of two bolts with two steel plates. One of them is connected to the spring while the other is connected to the load cell, which is connected to the movable plate through eccentric ball bearing. Such arrangement provides a constant clamping force during the deformation of the sample, which is clamped between the two ends. The load cell type is 546QDT-A5 with 220 kg full capacity, tension and compression, and 20 V input is used to detect the load magnitude continuously. Figure 5 shows the calibration curve for the load cell. The calibration curve was obtained at both loading and unloading at room temperature. The load cell is connected to 20 V power supply and the output volt is indicated, monitored and recorded using a data acquisition system that consists of PC, a data acquisition board, the Lab- View software and a stopwatch that is used to record the elapsed time. The driving motor (3-phase, 360 V, 3 hp, 1440 rpm) is fixed on slots on the frame by means of 4 bolts, to adjust the motor in the horizontal position. The motor is fixed on the base using 4 columns with threaded ends and a power screw at the center to adjust the motor in the vertical position. The power screw is rotated by a handle from one end while the other end is connected to a collar with a set screw. The power screw is used for lifting and lowering the electric motor. Thus, with the help of the stress amplitude mechanism shown in FIGURE7 it is possible to adjust the eccentricity of ball bearing shaft. This leads to the adjustment of the stress amplitude to the required predetermined value.
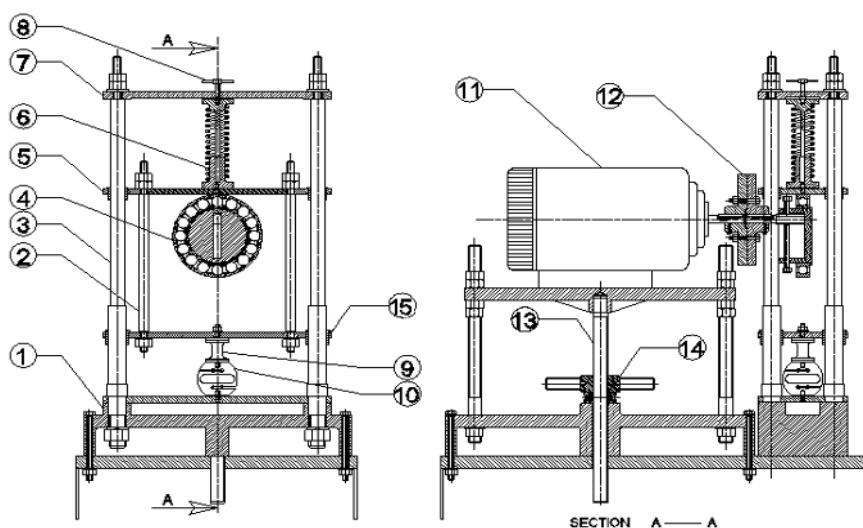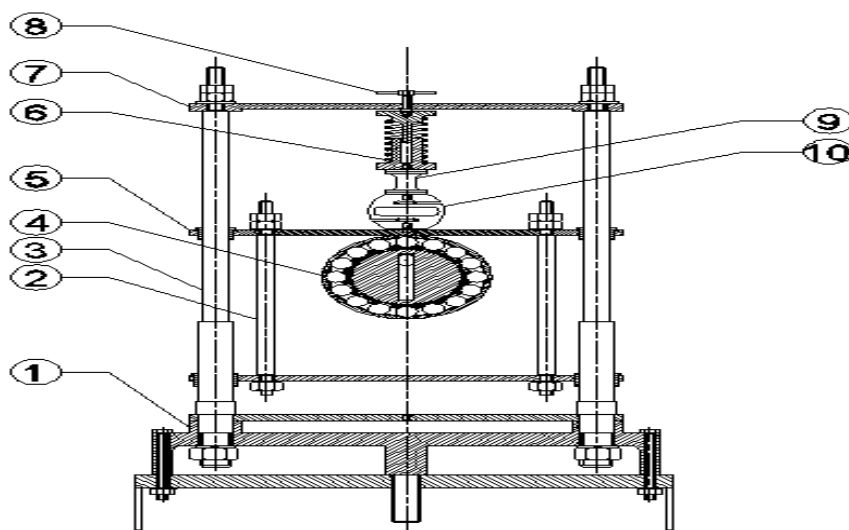

SECTION   A —— A

Fig. 2. Section elevation and section side view of rubber fatigue test apparatus (the specimen is in tension): 1-base, 2-column, 3-main column, 4-ball bearing, 5-main plate, 6-cylindrical helical compression spring, 7-upper plate, 8-adjusting bolt, 9-rubber specimen, 10-load cell, 11-electric motor, 12-flange coupling, 13-power screw, 14-bronze nut, 15- lower plate.

Fig. 3. Section elevation view of fatigue test apparatus (the specimen is in compression)

The motor shaft is connected to another shaft by a flange coupling. The latter enters in a vertical slot in the shaft of the ball bearing. Thus, its up and down movements in the vertical slot will result in change of the eccentricity of the ball bearing shaft. The flange coupling works as a flywheel too, to provide a stable rotation. A speed controller is used to change the motor speed to a predetermined speed (frequency). The applied force on the specimen is obtained by a helical compression spring. The magnitude of the applied force can be changed by the adjusting bolt.
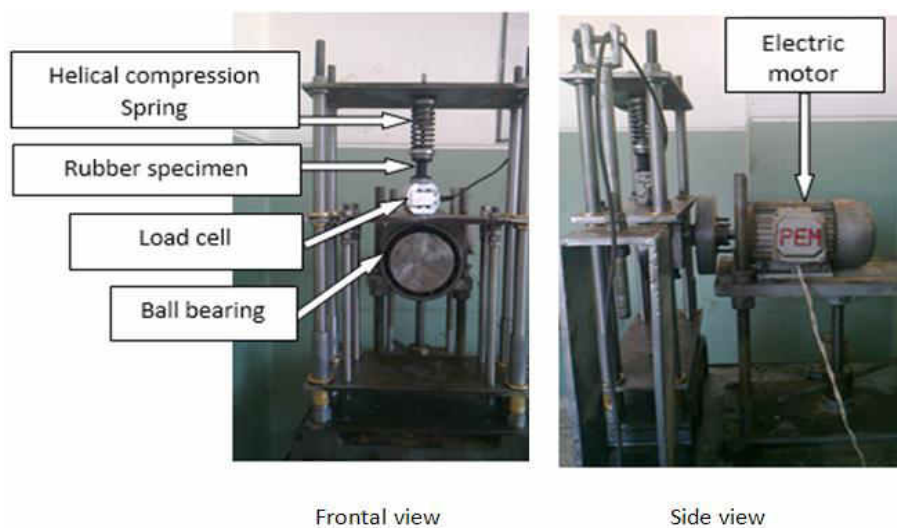
Fig 4. Photographs of fatigue test apparatus (the specimen is in the compression)
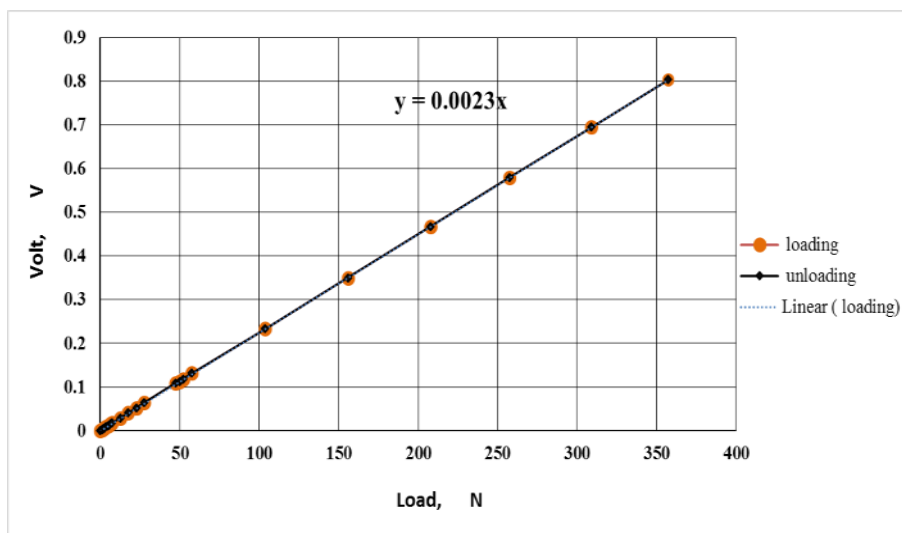
Fig. 5. Calibration curve of the load cell type 546QDT-A5.

2.2. Fatigue test apparatus applications

The adopted design of the fatigue test rig is simple and suitable to investigate the fatigue behaviour of rubber under different test conditions. The introduced test rig can be utilized in carrying out fatigue tests under tensile, compressive and tensile-compressive stress, in addition to crack growth investigations with a single edge crack specimens. Moreover, the different factors affecting the fatigue behaviour such as mechanical loading, amplitude and frequency can be investigated using the introduced test rig. From the lab-view software data the following parameters can be obtained: maximum stress, minimum stress, R- ratio, number of cycles and sine wave profile. Also, a stopwatch can be used to record the elapsed time to failure and, consequently, the number of cycles at failure can be determined as:

$$N = t. f \qquad \text{……………………………(1)}$$

Where N is the number of cycles.

 t is the elapsed time to failure in second.

   f is the frequency in Hz.

2.2.1 Mechanical loading

Simple mechanical histories applied to specimens are usually characterized by parameters such as maximum, alternating, minimum and mean loading, and/or the R-ratio. These parameters are illustrated in Fig. 6. where P_{max}, P_{min}, are the maximum and minimum load respectively, $R = P_{min}/P_{max}$, P_m is the mean load and P_a is the alternating load.

$$P_a = (P_{max} - P_{min})/2 \qquad \text{………………………..(2)}$$
$$P_m = (P_{max} + P_{min})/2 \qquad \text{…………………………. (3)}$$

The introduced test rig can be used to carry out fatigue tests under tension or compression as shown in Figs. 2 and 3, respectively. The load is applied by a helical compression spring. The magnitude of the load can be changed by means of the adjusting bolt. This enables investigating fatigue behaviour at different stresses and different stress ratios. The sinusoidal load pattern is obtained by the eccentricity in the ball bearing shaft. This eccentricity can be changed by raising or lowering the shaft connected to the shaft of the electric motor which is lifted or lower by the power screw and the bronze nut. For accurate measurement of the applied load a measuring setup is built up. It consists of a load cell, data acquisition board and PC computer. The load cell converts the magnitude of the applied load into a voltage signal. This signal is, in turn, converted into stress values through the data acquisition board and PC computer. A lab-view macro is built up to give the stress parameters, namely, maximum and minimum stresses, R- ratios, number of cycles and sine wave profile.
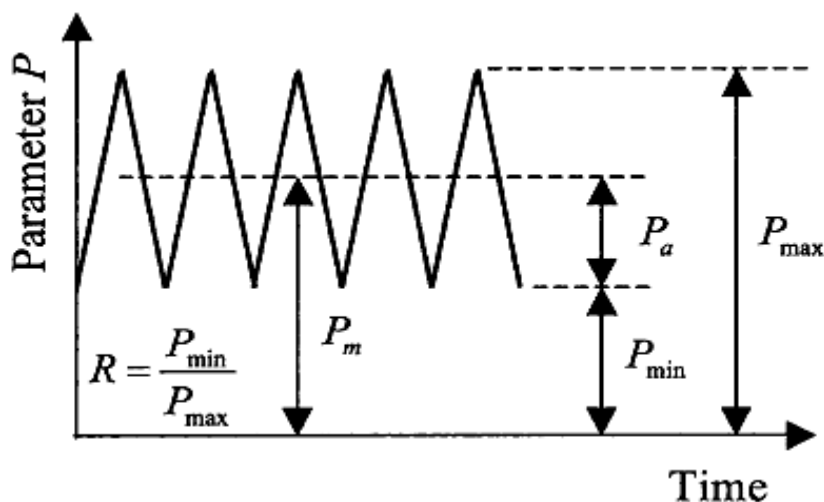
Fig. 6. Commonly used parameters for the description of constant-amplitude mechanical loading history

2.2.2. Stress amplitude

Figure 7 illustrates the mechanism used for the adjustment of the stress amplitude. Shaft (2) can be displaced up or down in the vertical slot, which cut in the ball bearing shaft. This displacement results in changing the magnitude of the eccentricity of the ball bearing shaft and, in turn, the stress amplitude. For accurate adjustment of the eccentricity two threaded bolts with fine threads are used as shown in Fig. 7.

2.2.3. Frequency

A variable speed controller is used to adjust the speed of the electric motor. Consequently, the loading frequency can be adjusted to any predetermined value.

3. Experimental procedure

The introduced fatigue test apparatus was used to perform fatigue test under tension/compression stress on diabolo specimen. Styrene-butadiene rubber (SBR-1502) material, with 20 phr (parts per hundred of rubber by weight) carbon black (CB) vulcanized for one hour at 160 ^{o}C, was used in the fatigue life test. Figure 8 shows the diabolo specimen with 25 mm diameter. The specimen was subjected to cyclic loading up to failure. At failure the specimen was broken into two parts. The number of cycles up to failure was obtained by knowing the elapsed time which was recorded by means of a stopwatch. Consequently, the S-N curve was obtained. By using this apparatus the fatigue behaviour of rubber was investigated at a constant amplitude cyclic load which was

applied on the specimen at different values of maximum and minimum stresses and at frequency 3.05 Hz. Also, the effect of the frequency on the fatigue behaviour at constant amplitude was investigated. The test was carried out at frequencies, 3.05, 3.5, 4 and 5 Hz. In each test, the minimum number of tested specimens was three and an average value of the number of cycles was recorded. Equation (1) was used to calculate the number of cycles. All tests were carried out at room temperature.
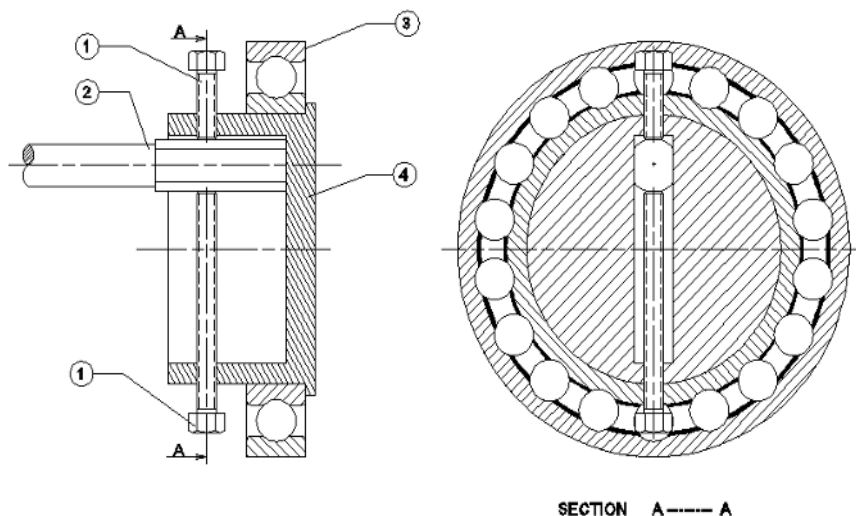
SECTION A------ A

Fig. 7. Section elevation of the stress amplitude adjustment mechanism:1- screw bolts, 2-shaft, 3-ball bearing, 4-ball bearing shaft

4. Results and discussion

Fatigue test was carried out on specimens to obtain the S-N curve and study the effect of the stress amplitude on the fatigue behaviour of rubber. Figure 9 shows the S-N curve where the tests were carried out at constant frequency of 3.05 Hz and at different values of σ_{max} and σ_{min}. The corresponding σ_a was calculated to draw the stress amplitude versus number of cycles up to failure. The crack was noticed to take place at the middle of the specimen or around its middle. The crack propagated and led to failure. At failure the specimen was broken into two parts. This is in agreement with that in literatures. Figure 10 shows the photograph of the broken specimen due to cyclic load at 3.05 Hz. Figure 11 illustrates the relationship between frequency and number of cycles. From this figure, it is clear that the fatigue lifetime decreases with the increase of frequency.
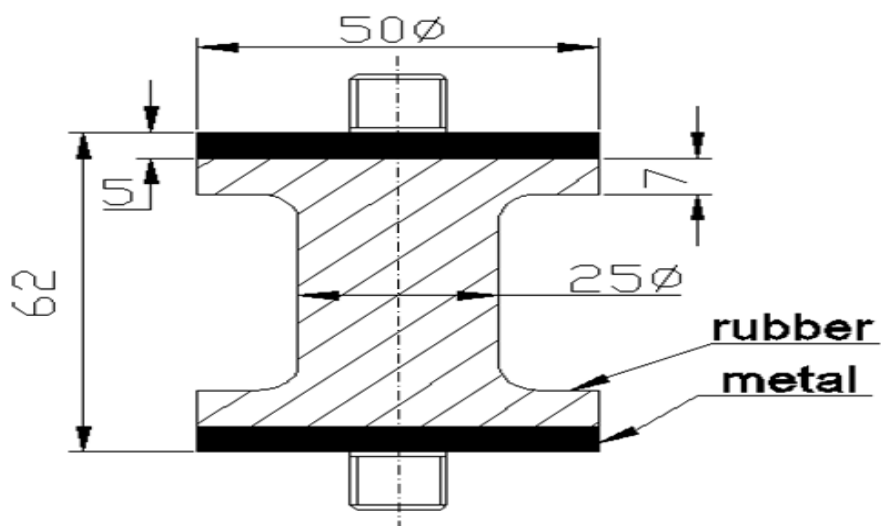
Fig. 8. Dimensions of diabolo specimen(Dims. in mm)

4.1. Repeatability of the apparatus

The fatigue test was carried out under tension/compression stresses. Using three specimens at least, the average value of the number of cycles up to failure was obtained. It was noticed that the specimens which were tested at the same stress amplitude and frequency showed the same pattern of failure as shown in FIGURE10. The built up measuring setup was tested at different amplitudes and at the same frequency, also at different frequencies and same amplitude. The results of these tests give the expected sine wave profiles as shown in fig. 12. As a result of the above findings it is clear that the introduced test rig has good repeatability.
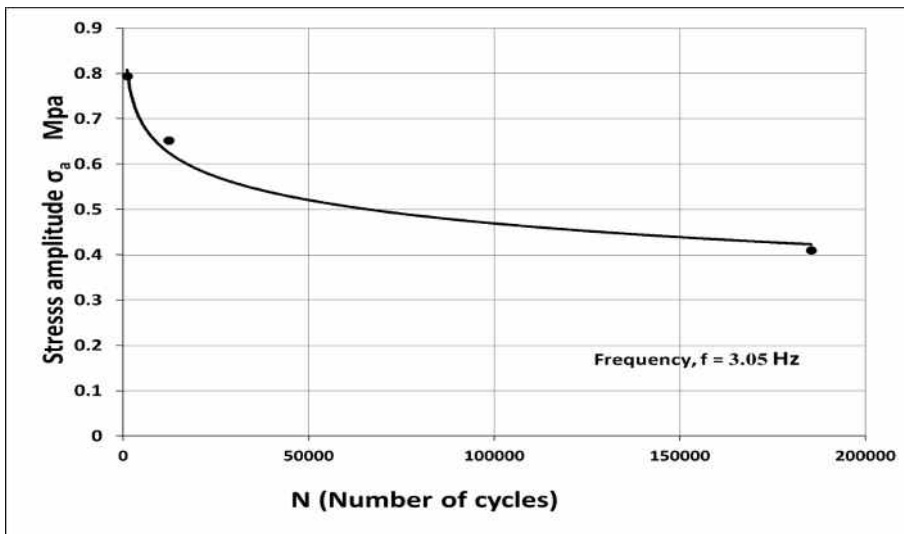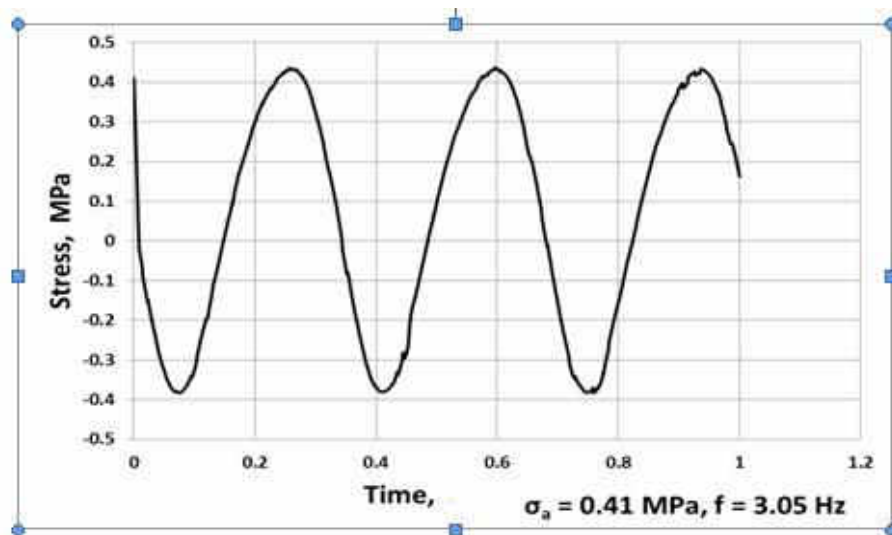
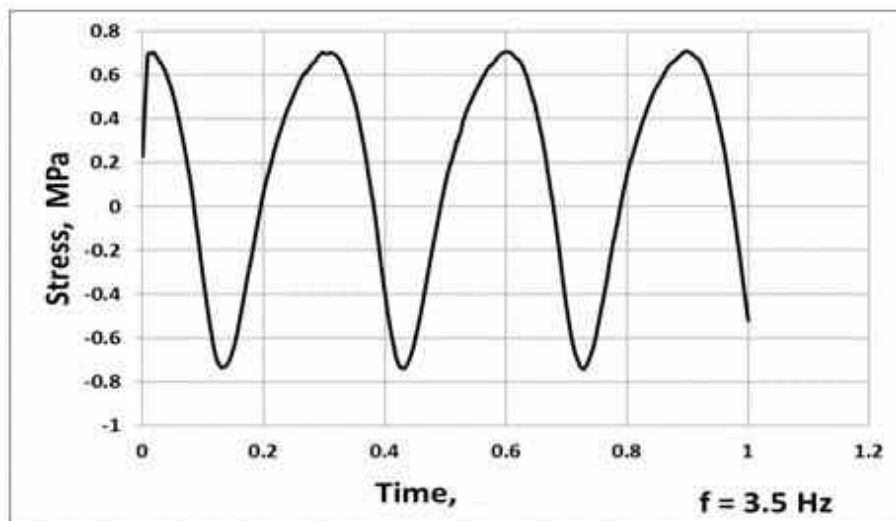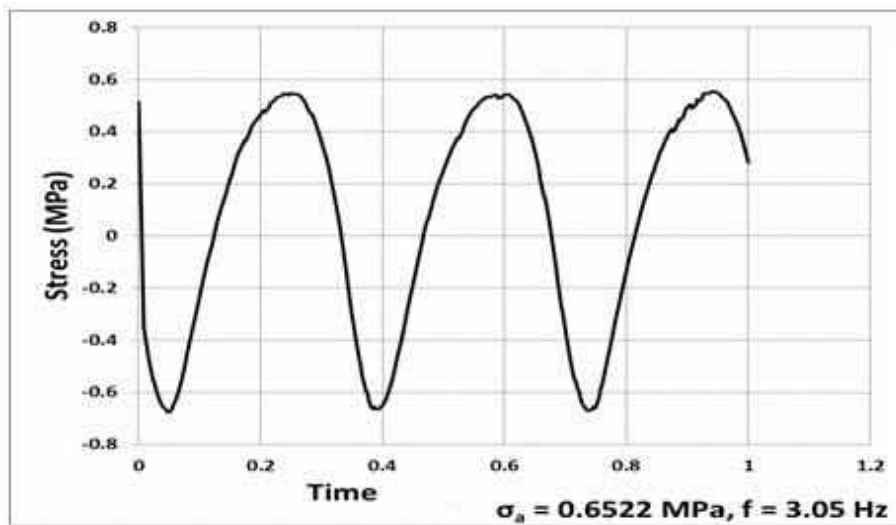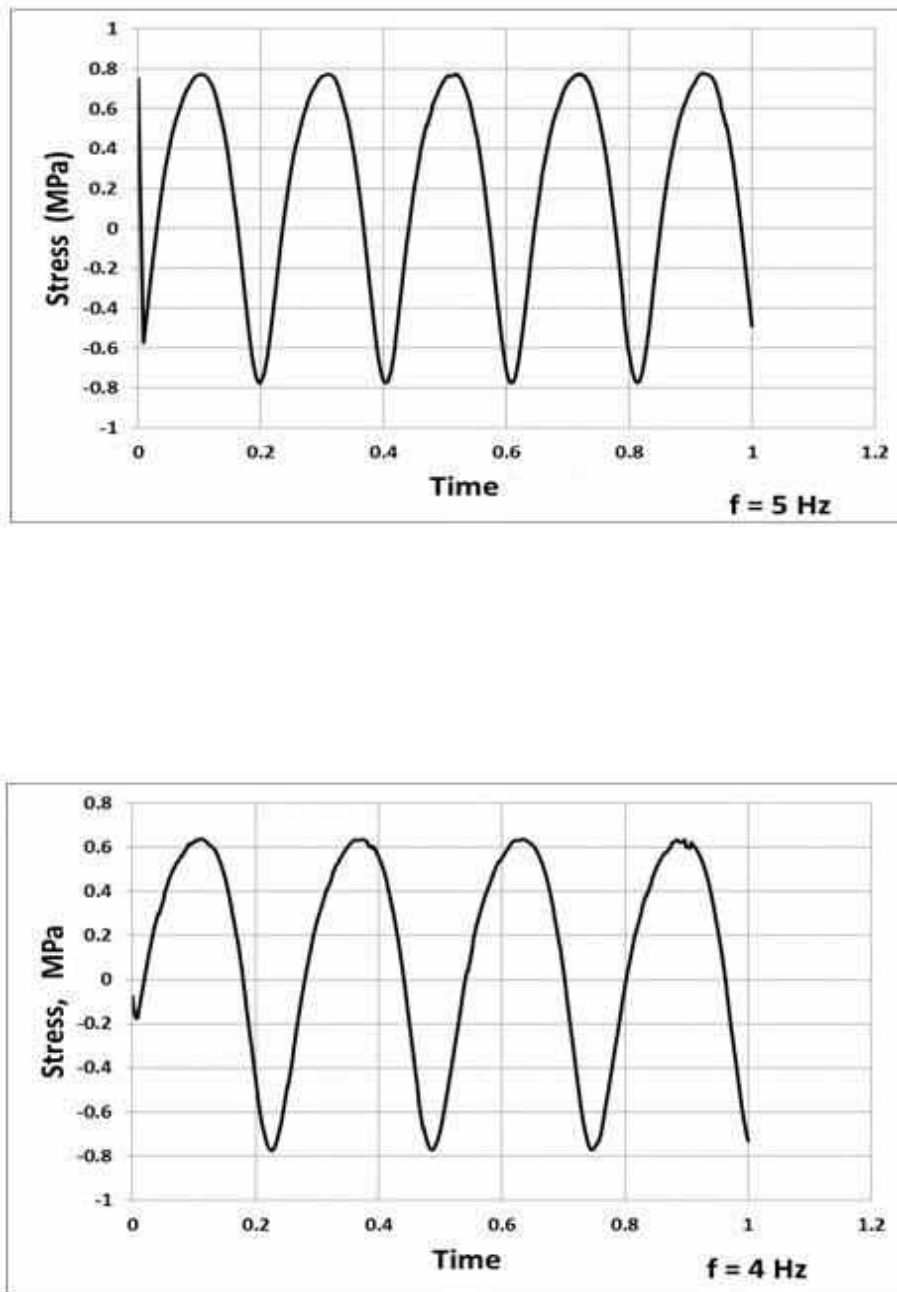**Fig. 9.** S-N curve of SBR with 20 phr of CB.

Fig.10. Photograph of the broken specimens of SBR with 20 phr of CB in fatigue test under cyclic loading
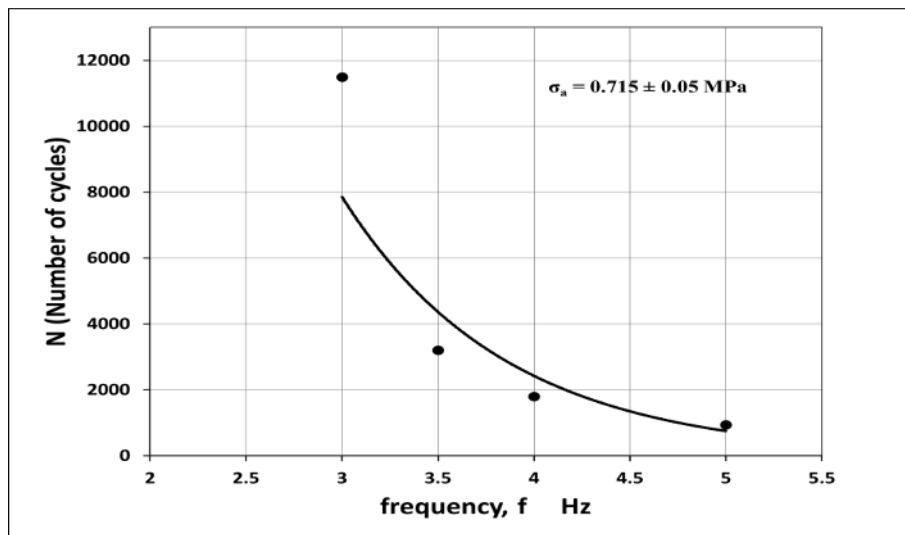
Fig. 11. Frequency versus the number of cycle to failure for SBR with 20 phr of CB

$\sigma_a = 0.6522$ MPa, f = 3.05 Hz

f = 3.5 Hz

Fig. 12. Sine wave profiles in tension /compression stress test for SBR with 20 phr of CB at different frequencies.

5. Conclusions

The introduced fatigue test apparatus is capable of investigating fatigue behaviour of rubber under different parameters such as; mechanical loading, amplitude and frequency. Fatigue tests can be carried out under tension or compression with constant amplitude. Diabolo specimens were adopted to be used with the introduced fatigue test apparatus in compression or tension-compression fatigue test. In addition, edge cut specimen can be used to investigate crack propagation characteristics of rubber using the introduced fatigue test apparatus. As a result of the above findings the introduced test rig proved to be reliable and has good repeatability of test results.

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تصميم جهاز لإختبار سلوك الكلال في المطاط

ملخص:

يعتبر سلوك الكلال في المطاط من الصفات والسمات الهامة نظراً للإستخدامات الواسعة له في التطبيقات الهندسية المختلفة حيث أن المطاط، في هذه التطبيقات، يتعرض لأحمال متكررة بشكل مستمر مما يؤدي إلى انهياره نتيجة لتكون وإنتشار الشروخ فيه و هناك العديد من الدراسات التي اهتمت بدراسة سلوك الكلال في المطاط باستخدام أجهزة إختبار كثيرة ومتنوعة. تم في هذا البحث تصميم وإنتاج جهاز جديد لدراسة سلوك الكلال في المطاط ودراسة العوامل المؤثرة فيه (الأحمال الميكانيكية، التردد)، مع إمكانية توليد وتسليط إجهادات ميكانيكية في حالة الشد أو الضغط أو كليهما معاً على عينة الاختبار. يشتمل هذا البحث على وصف للجهاز واستخداماته والأختبارات التي أجريت عليه ومناقشتها. أجريت تجارب مختلفة على عينة الإختبار بتحميل قيم مختلفة للأحمال في حالة شد/ضغط مع تثبيت قيمة التردد، وإختبارات أخرى بقيمة ثابتة للحمل وتغير قيمة التردد، حيث تم تسجيل عدد الدورات اللازمة لحدوث الإنهيار. ومن خلال النتائج المسجلة ثبت أن الجهاز يمكن الإعتماد عليه في دراسة سلوك الكلال في المطاط وأنه يمتلك خاصية التكرارية بصورة جيدة.