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Determination of reliable fatigue life predictors for magnetorheological elastomers under dynamic equi-biaxial loading

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Abstract

Fatigue life prediction is of great significance in ensuring magnetorheological elastomer (MRE) based rubber components exhibit reliability and do not compromise safety under complex loading and this necessitates the development of plausible fatigue life predictors for MREs. In this research, silicone rubber based MREs were fabricated by incorporating soft carbonyl iron magnetic particles. Equi-biaxial fatigue behaviour of the fabricated MREs was investigated by using the bubble inflation method. The relationship between fatigue life and maximum engineering stress, maximum strain and strain energy density were studied. The results showed that maximum engineering stress and stored energy density can be used as reliable fatigue life predictors for SR based MREs when they are subjected to dynamic equi-biaxial loading. General equations based on maximum engineering stress and strain energy density were developed for fatigue life prediction of MREs.

Introduction

Magnetorheological elastomers (MREs) consist of micron sized magnetically permeable particles suspended in a non-magnetic elastomeric matrix [1]. Upon application of a magnetic field, the rheological properties of these materials are rapidly and reversibly altered [2]. MREs can be fabricated either in the absence of, or in the presence of a magnetic field during the curing process, resulting in isotropic [3, 4] and anisotropic MREs [5, 6] respectively. Due to the field dependent rheological response of MREs, they are interesting candidates for adaptive tuned vibration absorbers, stiffness tuneable mounts, suspension components and variable impedance surfaces [7-10]. For engineering applications, understanding fatigue and designing to avoid fatigue failure are essential to MREs, especially in conditions of complex loading.

Widely used parameters for fatigue life prediction in elastomers include maximum principal stress [11, 12], maximum principal strain [13-16] and strain energy density [12, 16-18]. As most rubber fatigue experiments are conducted by cyclically applying a constant displacement to specimens, it is quite common to relate fatigue life to strain values. However, most of the service conditions of elastomeric products are under load control and testing under displacement control does not provide the precision required.

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Moreover, as the load experienced by the test piece consistently falls in a constant strain amplitude test, very little work is required to displace the specimen at high cycles. This is because due to the Mullins effect, filled elastomers present a loss of stiffness leading to cyclic stress softening and stress hysteresis occurring throughout the test or for the entire service life of a component [19]. In addition, when materials of different stiffness are compared under displacement control, the stiffer material will always be more harshly tested than the softer material and so should fail earlier, because a higher stiffness will lead to higher stresses and strain energy densities [20]. Considering this, by employing the dynamic bubble inflation testing system developed in the Centre for Elastomer Research in the Dublin Institute of Technology [21], equi-biaxial fatigue behaviour of MREs was investigated by using engineering stress as the control mode. Previous studies [22, 23] have shown that stored energy density can be used as a reliable fatigue life predictor for silicone based MREs. In this paper, commonly used fatigue life predictors for elastomers including maximum stress, maximum strain and strain energy density were investigated thoroughly with the aim of determining suitable fatigue life predictors for MREs and developing general equations for the fatigue life prediction of MREs.

Materials and Methods

Materials

Isotropic silicone rubber (SR) based MREs were fabricated by incorporating different volume fractions (15% ~ 35%) of soft carbonyl iron magnetic particles (d50 = 6.0 - 7.0 μm, CS grade, supplied by BASF) into a two component room temperature vulcanized (RTV) silicone rubber. Silicone rubber was mixed with a catalyst at a 10:1 ratio before carbonyl iron particles were incorporated into the mixture and mechanically stirred to distribute the particles evenly in the elastomer matrix. The whole mixture was degassed in a vacuum to remove entrapped air bubbles and then poured into an aluminium mould. After further degassing in the mould, the compound was kept at room temperature for 48 hours to allow solidification. Disc samples with a diameter of 50mm with a nominal thickness of *mm were prepared for fatigue testing.

Methods

Equi-biaxial fatigue testing of MREs with different CI contents was carried out by utilising the dynamic bubble inflation test system. The testing procedure used has been described in a previous paper [23]. Fatigue tests were conducted over a range of stress amplitudes with a minimum stress of zero under engineering stress control For the full range of volume fractions.

Results and Discussion

Maximum engineering stress

Figure 1 shows the dependence of fatigue life on maximum engineering stress for isotropic SR based MREs with different CI contents varying between 15% and 35%. For each particle content, it can be seen that the coefficient of each curve relating fatigue life to maximum engineering stress is very high for MREs. This suggests that maximum engineering stress can be used as a fatigue life predictor for isotropic SR based MREs.

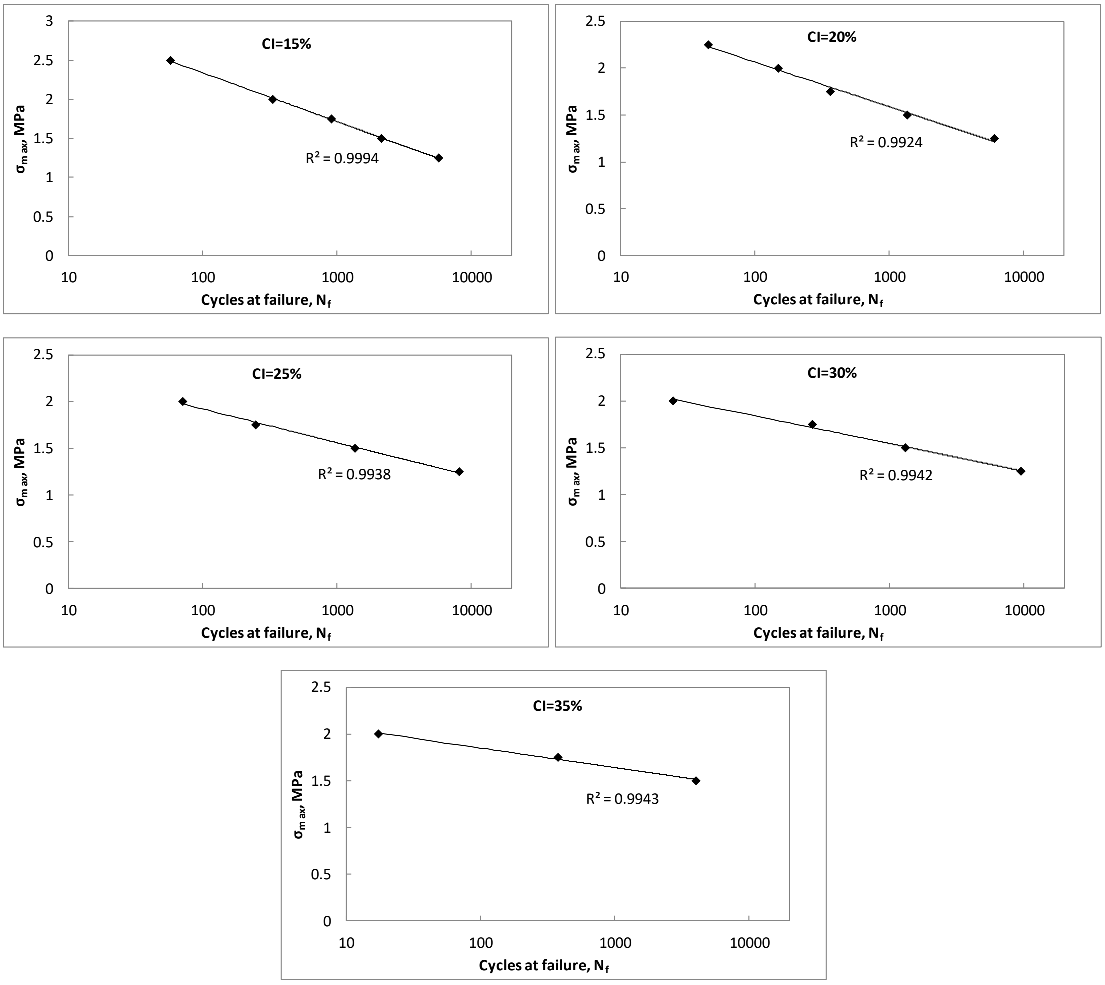


Figure 1 Dependence of fatigue life on maximum engineering stress for MREs with different CI contents

Equations for fatigue life prediction, relating life (N_f) to engineering stress amplitude (σ_a) for SR based MREs were derived as follows:

$$\sigma_{\max} = A_1 \ln\left(N_f\right) + A_2 \qquad \text{(Eqn. 1)}$$

$$\ln\left(N_f\right) = \frac{\sigma_{\max} - A_2}{A_1} \qquad \text{(Eqn. 2)}$$

where A_1 and A_2 are material specific constants dependent on magnetic particle content. The values of A_1 and A_2 for MREs with various CI contents are listed in Table 1.

Table 1 Values for A_1 and A_2 for a series of MREs with different CI contents

CI content	A_1 (N/mm^2)	A_2 (N/mm^2)
15%	-0.2716	3.5922
20%	-0.2062	3.0142
25%	-0.1558	2.6382
30%	-0.1276	2.4264
35%	-0.0912	2.2696

If A_1 is related to magnetic particle content (C_p) a second order polynomial relationship can be found between them:

$$A_1 = -2.2914\left(C_p\right)^2 + 2.0245\left(C_p\right) - 0.5219 \qquad (R^2 = 0.9963) \qquad \text{(Eqn. 3)}$$

And assuming $A_2 = \sigma_{FCon}$ (Eqn. 4)

where σ_{FCon} is the maximum engineering stress of the cycles after the material has been conditioned. The cycles to achieve conditioning will be different for different rubbers. However, as 10 conditioning cycles is a typical value applied in industry [24], the stress amplitude at 10 cycles was chosen as a reasonable value for σ_{FCon}. σ_{FCon} for MREs with various CI contents are shown in Table 2.

Table 2 σ_{FCon} for MREs with various CI contents

CI content	σ_{FCon} (MPa)
15%	2.9668
20%	2.5394
25%	2.2795
30%	2.1326
35%	2.0596

Consequently, the equation for fatigue life prediction based on the failure stress of a conditioned test piece and particle content (vol%) for SR and CI based MREs can be stated as:

$$\ln\left(N_f\right) = \frac{\sigma_{\max} - \sigma_{FCon}}{-2.2914\left(C_p\right)^2 + 2.0245\left(C_p\right) - 0.5219} \qquad \text{(Eqn. 5)}$$

where N_f is the cycles to failure; σ_a is the stress amplitude (MPa); σ_{FCon} is the stress amplitude for the sample to have a fatigue life of 10 cycles (MPa) and C_p is the volume fraction of the CI particles.

Hence it is suggested that Eqn. 5 can be used to determine the fatigue lives of a silicone based MRE component subjected to complex loading, provided the maximum alternating stress at the point of failure can be measured or determined. Further, it is suggested that Eqn. 5 can be used in its general form (Eqn. 6) for MREs based on other rubber compounds, where material constants D, E and F (units MPa) are determined from equi-biaxial fatigue testing.

$$\ln\left(N_f\right) = \frac{\sigma_{\max} - \sigma_{FCon}}{D\left(C_p\right)^2 + E\left(C_p\right) + F} \qquad \text{(Eqn. 6)}$$

Maximum strain

The maximum strain dependence of the fatigue life is shown in Figure 2 where the fatigue life of isotropic MREs for each CI content was plotted against the average maximum strain experienced by the material before failure. As can be seen from Figure 2, again there was a good correlation between fatigue life and maximum strain for MREs containing 15% and 20% CI particles. However, for MREs with higher CI contents (25%, 30% and 35%), the fatigue life did not correlate well with the maximum strain values. It was shown that the higher the particle content, the lower the coefficient. This indicates that maximum strain can not be used as a general fatigue life predictor for isotropic SR based MREs for a typical range of particle contents.

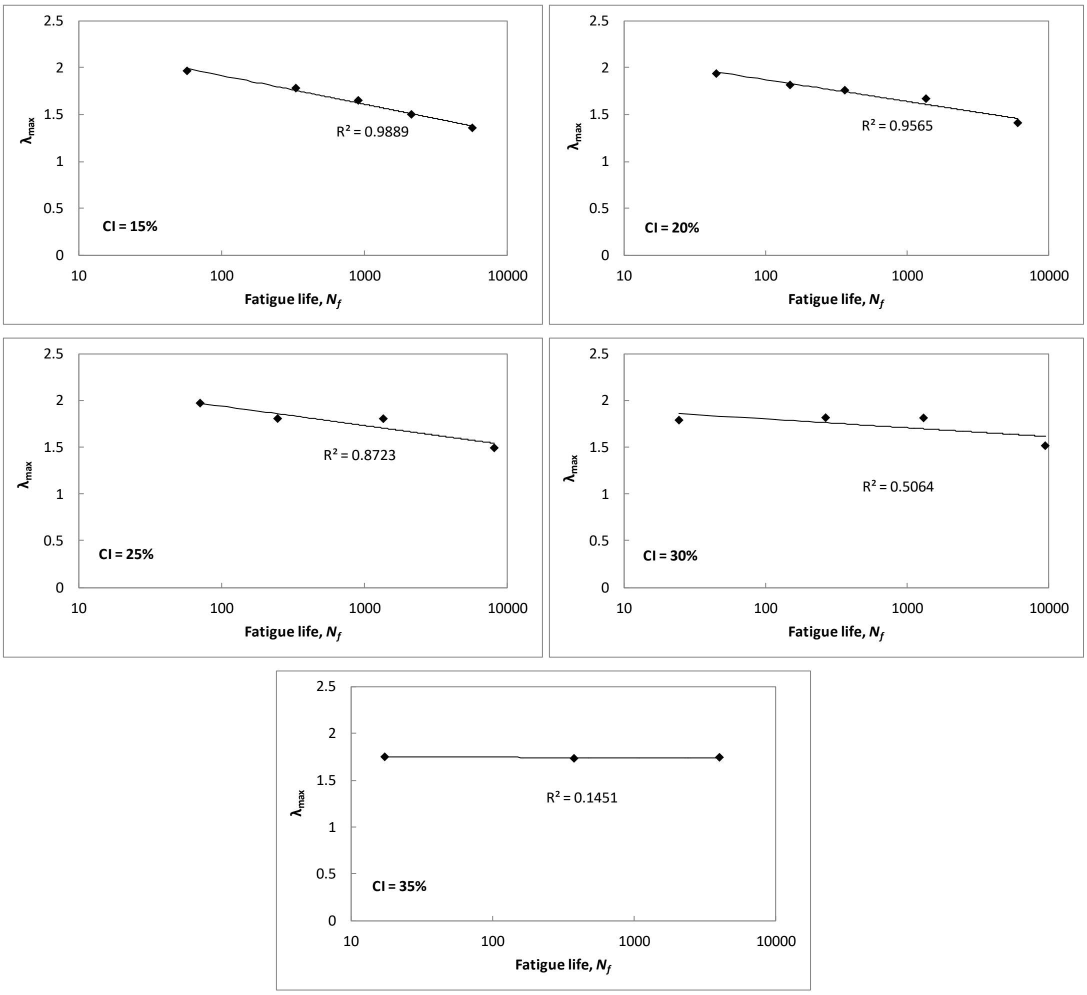


Figure 2 Plot showing dependence of fatigue life on maximum strain for isotropic MREs with different CI contents

Strain energy density

Particle reinforced elastomers exhibit a marked hysteretic response in the loading-unloading process in tension, compression and shear, as shown in Figure 3. Due to hysteresis, part of the total energy in deforming the material (the strain energy enclosed in the hysteresis loop) is dissipated as heat. The strain energy available in the unloading cycle represents the elastic stored energy in the rubber sample. Abraham [25] conducted systematical uni-axial fatigue analyses on filled and non-filled ethylene propylene diene monomer (EPDM) and styrene-butadiene rubber (SBR) The minimum stress in cyclic testing was either compressive or equal to zero. The results showed that for tests where the minimum stress was in compression or equal to zero the total or stored energy can be used to predict fatigue life irrespective of whether the rubber contained fillers or not. However, for a tensile minimum stress, total energy was an unreliable predictor, but dynamic stored energy remained a plausible predictor of fatigue life for filled systems.

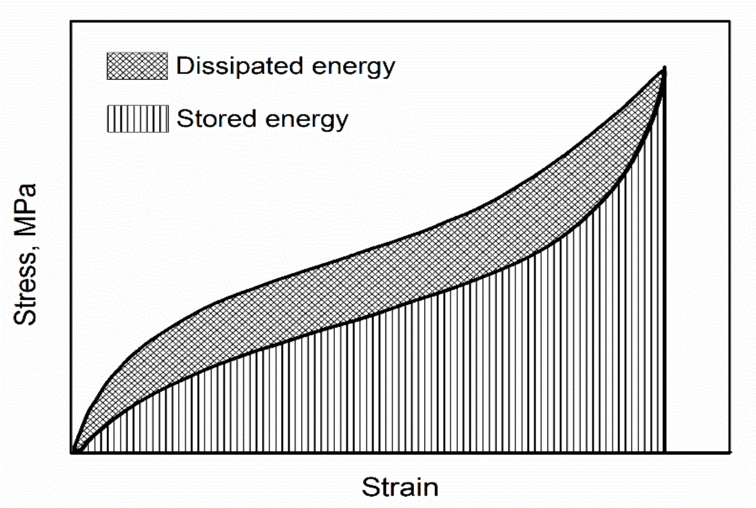


Figure 3 Diagrammatic representation of stored energy from a stress-strain curve

As reported in a previous paper [23], for isotropic MREs with a range of different particle content, stored energy density increased with the accumulation of cycles over a range of constant stress amplitudes. When plotted against cycles to failure, the stored energy density at failure for a range of stress amplitudes was found to decrease linearly, indicating stored energy can be used as a plausible fatigue life predictor for isotropic SR based MREs irrespective of the magnetic particle content and the stress amplitudes applied. A stored energy density based equation for fatigue life prediction was written by relating life (N_f) to stored energy density (W_s) as shown:

$$\ln\left(N_f\right) = \frac{W_S - B_2}{B_1} \qquad \text{(Eqn. 7)}$$

where B_1 and B_2 are material specific constants dependent on the magnetic particle content. Relating B_1 to magnetic particle content (C_p) and a second order polynomial relationship can be found between them:

$$B_1 = -0.6114\left(C_p\right)^2 + 0.8389\left(C_p\right) - 0.238 \qquad (R^2 = 0.9937) \qquad \text{(Eqn. 8)}$$

$$B_2 = W_{SCon} \qquad \text{(Eqn. 9)}$$

where W_{SCon} is the stored energy density of the cycle at which the test piece is considered to be conditioned (N/mm^2). As described earlier, 10 conditioning cycles was chosen and W_{scon} for MREs with various CI contents are shown in Table 3.

Table 3 Values for W_{scon} for MREs with various CI contents

CI content	W_{scon} (N/mm^2)
15%	1.1310
20%	0.9100
25%	0.7892
30%	0.6487
35%	0.5905

As W_s is a function of σ and λ

$$Ws = \int \sigma\lambda\partial\lambda \quad \text{(Eqn. 10)}$$

An equation for fatigue life predition based on stored energy density can be derived as:

$$\ln\left(N_f\right) = \frac{\int \sigma\lambda\partial\lambda - \left(\int \sigma\lambda\partial\lambda\right)_{Con}}{-0.6114\left(C_p\right)^2 + 0.8389C_p - 0.238} \quad \text{(Eqn. 11)}$$

where σ is the engineering stress; λ is the stretch ratio; $\left(\int \sigma\lambda\partial\lambda\right)_{Con}$ is the stored energy density of the cycles at failure after the material is conditioned and C_p is the volume fraction of the CI particles.

A general equation (Eqn. 5.13) relating fatigue life to stored energy density can be written for MREs based on other elastomer matrices provided the material constants L, M and N (units N/mm^2) are derived from equi-biaxial dynamic testing.

$$\ln\left(N_f\right) = \frac{\int \sigma\lambda\partial\lambda - \left(\int \sigma\lambda\partial\lambda\right)_{Con}}{L\left(C_p\right)^2 + M\left(C_p\right) + N} \quad \text{(Eqn. 12)}$$

Total energy density

Total energy density in deforming the material was determined for specific cycles from the stress-strain curves. The evolution of total energy density against cycles for MREs with different CI contents is depicted in Figure 4. It can be found from Figure 4 that changes in total energy density exhibited dependence on particle content and stress amplitude. For MREs with very high CI content (35%), total energy density increased as cycles accumulated irrepective of the stress amplitude applied. For MRE with particle content from 15% to 30%, total energy density decreased with cycles at high stress amplitudes but showed an overall increase with cycles at low stress amplitudes. For each stress amplitude, at least two tests were conducted and the plots of total energy density at failure against fatigue life for a range of MREs with different carbonyl iron contents are shown in Figure 5. It can be seen from Figue 5 that total energy density at failure decreased linearly when plotted against $\log_{10}$ cycles to failure, suggeting that total energy could also be used as a fatigue life predictor for MREs. But as there is no general trend for changes in total energy during the entire fatigue process at various stress amplitude, using total energy density as a fatigue life predicator should be treated with caution.

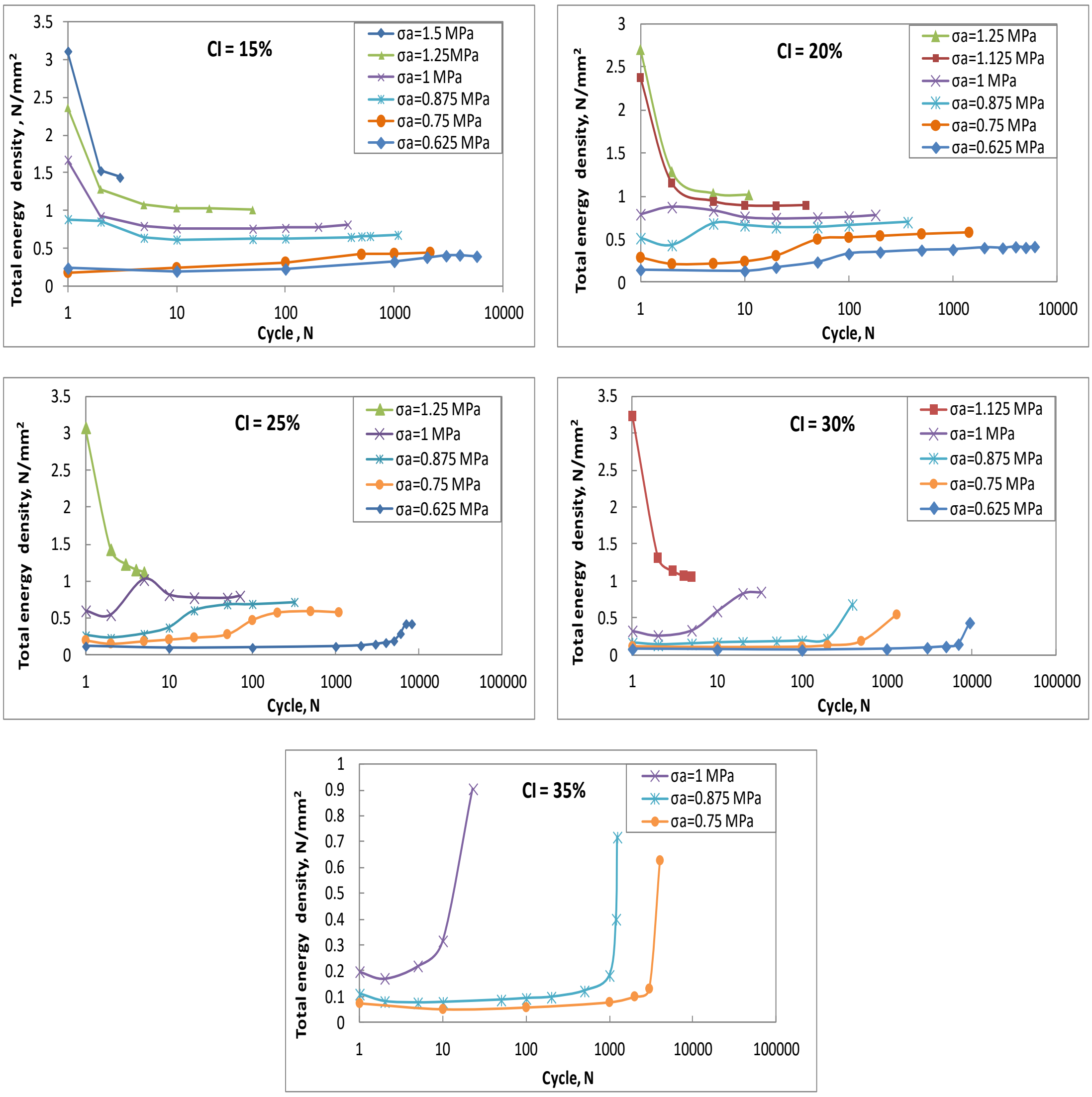
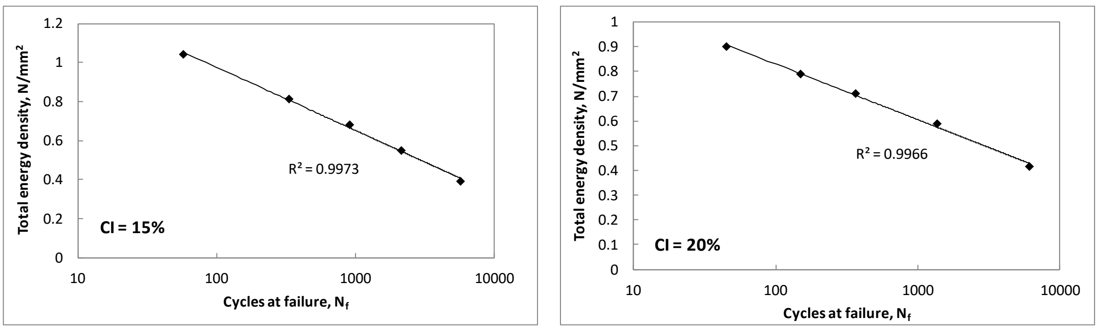


Figure 4 Evolution of total energy against cycles for MREs with different CI contents



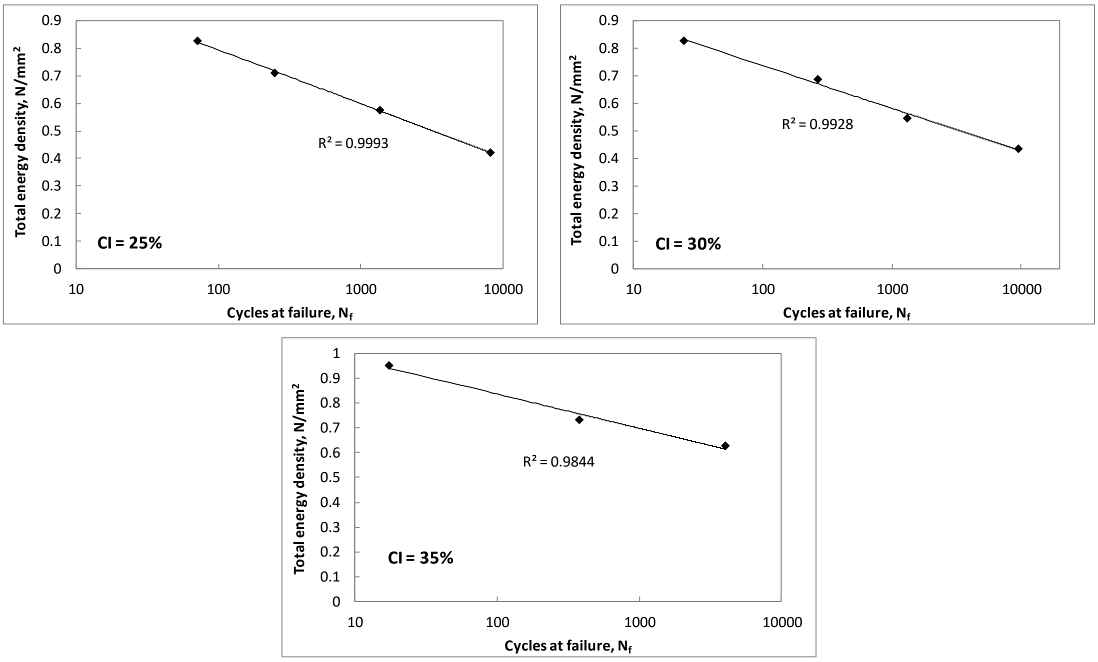
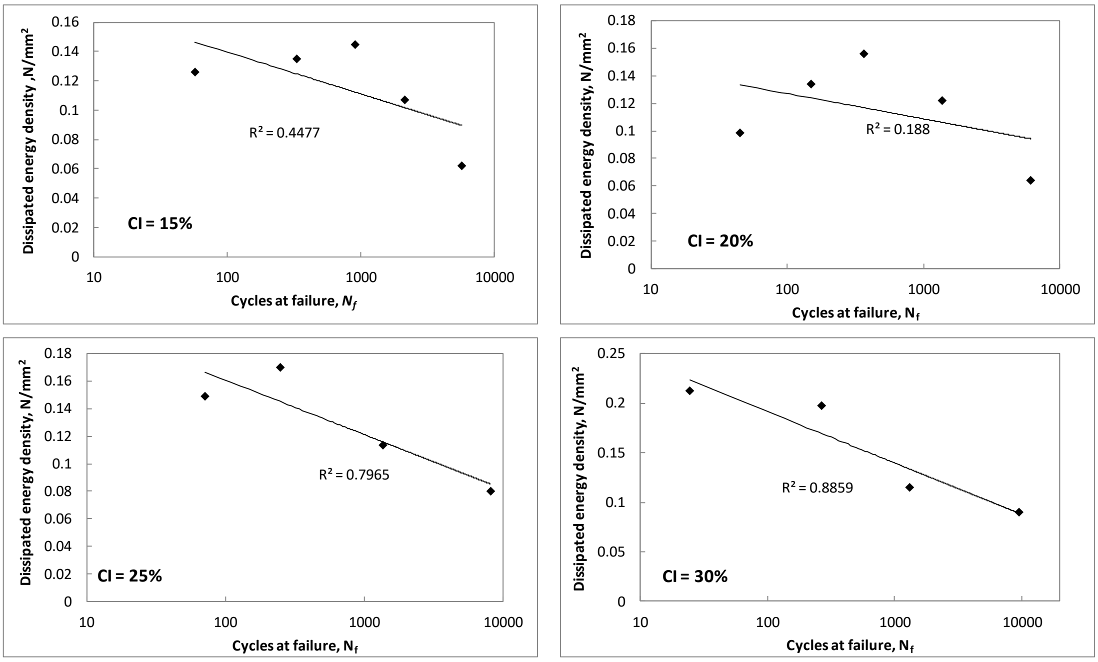


Figure 5 Plots of total energy density at failure versus log10 cycles at failure for isotropic SR based MREs with different CI content: (a) 15%; (b) 20%; (c) 25%; (d) 30%; (e) 35%

Dissipated energy density

The plots of dissipated energy dneisty at failure versus cycles at failure for MREs are shown in Figure 6. The low coefficients indicates that dissipated energy cannot be used as an appropriate fatigue life predictor for MREs.



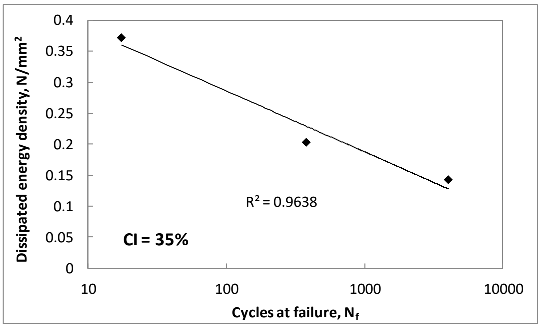


Figure 6 Dissipated energy at failure versus $\log_{10}$ cycles at failure for isotropic SR based MREs with different CI content

Conclusions

Equi-biaxial fatigue behaviour of isotropic silicone based MREs with a range of particle contents was investigated by using the bubble inflation system. Relations between fatigue life and stress, strain and strain energy density were studied. It was found that maximum engineering stress and stored energy density can be used as reliable fatigue life predictors for silicone based MREs subjected to equi-biaxial loading. By considering particle content and conditioning of rubber materials, general equations relating fatigue life to maximum engineering stress and stored energy density were developed. These equations can be used to calculate fatigue life in components produced from this compound. As dynamic stored energy has been shown to be a reliable parameter to employ in the determination of fatigue life for various filled rubbers, it is probable that this parameter could be used to determine fatigue life in other elastomers containing hard particles and this hypothesis could provide the basis for further research.

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