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NUMERICAL INVESTIGATIONS INTO DYNAMIC LOADING OF RUBBER COMPOUND (ACME 2015)

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ABSTRACT

The present paper analyses the heat generation build-up in silicone rubber samples when subjected to dynamic cyclic loading. Material properties of the rubber were determined through thermal and mechanical experimental testing. These properties are necessary to set up the computational model. The model includes a fully coupled transient nonlinear thermo-mechanical finite element analysis. In order to validate this approach, numerical results are compared with those gathered experimentally. The numerical model developed and validated could be used to simulate various industrial applications, involving rubber parts, for efficient and sustainable design.

Keywords: *rubber; heat build-up; cyclic load; dynamic; thermo-mechanical coupled model.*

1. Introduction

Elastomers or rubbers are polymers comprised of long polymeric chains. Upon application of loads these chains are extended upto 200-800% [1], and the elastomer will recover its original form when these loads are removed. Heating of rubber in the presence of sulphur (vulcanization) creates the cross links between polymeric chains making the chains harder to pull apart [2] and hence stronger and more durable rubber is made.
In a dynamically loaded rubber structure, heat generated by hysteresis losses during cycling deformations causes aging and degradation of its physical and chemical properties [3], consequently increasing stiffness and loss of damping characteristics.
This paper presents a novel numerical model to simulate temperature rise within the silicone rubber during dynamic cyclic loading. This involves a direct fully coupled transient nonlinear thermo-mechanical finite element analysis, implemented within Ansys software platform. The model incorporates predictions of energy loss responsible of heat build-up and a hyper-elastic material model. The numerical model is validated by mean of a comparison with the experimental data gathered during a dynamic cyclic test. The model could be used in simulating various industrial applications, such as roller coating, pneumatics, joints, etc…, to design rubber parts for efficiency and sustainability.

2. Dynamic Mechanical Analysis

Dynamic Mechanical Analysis (DMA) is a standard test to evaluate hysteresis and, hence heat generation rate, within a rubber. To achieve this, recall first that the hysteresis H is typically described by:

$$H = \frac{E_L}{E_T} = \frac{E_L}{E_S + E_L} \tag{1}$$

Notice that the total modulus E_T can be additively decomposed into the summation of a storage modulus E_S and a loss modulus E_L. Here, the storage modulus measures the stored energy representing the elastic portion. The loss modulus, on the other hand, measures the energy dissipation through heat representing the viscous portion. Therefore, it is possible to obtain the heat generation rate as:

$$Q = E_L \times f = H \times E_T \times f \tag{2}$$

where f represents the frequency of the loading. It is crucial to point out that the temperature build-up within a rubber is strongly dependent on the calculation of heat generation rate Q.

3. Ogden Hyper-elastic Constitutive Law

Rubber elastomers are characterized by a low elastic modulus and a high yield strain. They undergo large deformation when stretched and are able to recover their initial shape reversibly. They exhibit a nonlinear hyper-elastic behaviour that can be described through Ogden material model. This model uses the strain energy density function from which stress–strain relationship can be derived.
In this paper, the strain energy density per unit volume is expressed as a function of the three principal stretch ratio λ_j in the j^{th} direction, and material constants μ_i and α_i as:

$$W = \sum_{i=1}^{N} \frac{\mu_i}{\alpha_i}\left(\lambda_1^{\alpha_j} + \lambda_2^{\alpha_j} + \lambda_3^{\alpha_j} - 3\right); \forall\, \mathrm{j} = \{1, 2, 3\} \tag{3}$$

4. Curve Fitting 3rd Order Ogden Model

Under dynamic cyclic loading, rubber material will generate internal heat build-up due to energy loss that results in a temperature rise, and subsequently higher stresses. Here, stress-strain curves corresponding to a medium test speed of 50 mm/minute and five different temperatures in the range 25-125 ºC are used for curve fitting based on a 3rd order Ogden model. Material parameters (of Equation 3) derived after curve fitting are shown in the Table 1. With these values the constitutive equations were calibrated achieving good agreement with the experimental data.

Table 1 - Ogden material parameters (according to Equation 3) between 25 and 125 ºC at the crosshead speed of 50 mm/min

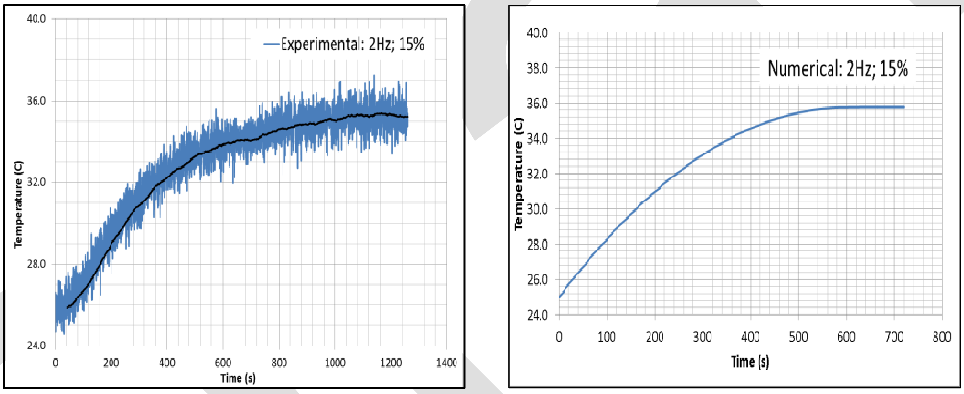
Temp ºC	Material parameters for Ogden model					
	μ_1	μ_2	μ_3	α_1	α_2	α_3
25	-41.037	46.134	231.382	0.645	0.626	0.003
50	-44.329	48.653	230.425	0.268	0.278	0.007
75	-52.614	40.305	230.968	0.610	0.671	0.035
100	-50.489	54.473	232.021	0.225	0.066	0.049
125	-72.853	71.120	204.775	0.253	0.081	0.079

5. Computational Model with Experimental Validation (2Hz, 15%)

Dynamic tests in compression mode were conducted to study the temperature build-up inside the cylindrical rubber of 25 mm diameter x 25 mm thickness. The tests were conducted on servo-hydraulic Phoenix universal testing machine at room temperature (25 ºC). A cyclic displacement of 3.75 mm (i.e. compressions of 15 %) is imposed on the top plate, whilst the bottom plate is fixed (see Figure 1). In this paper, a loading frequency of 2 Hz is assumed. The main objective of this testing is to illustrate the performance of the numerical approach in silicone rubber experiencing large deformation. For comparison purposes, a K-type thermocouple is inserted into the specimen centre, through a small drilled hole, so as to measure the exact temperature inside the rubber under loading.
A transient nonlinear direct coupled structural-thermal analysis in ANSYS Workbench is developed to perform the numerical calculations. An axisymmetric quadrilateral finite element (Plane 223 – selected using APDL command) is used, with the aim of avoiding volumetric locking [4] and pressure

instabilities [5]. The mechanical and thermal material data for the plates is assumed to be stainless steel, whilst the rubber material is fully characterised through the various experimental tests performed in the present work. Thermal and structural boundary conditions are assumed. The bottom-plate lower face is fully constraint where the temperature is also set to 25 °C. Free convection on external faces is considered respective to each material (with no radiation).
Bounded contact between rubber sample and plates is also considered. For each cycle (2Hz), four loading steps of 0.25s each are considered [2 x (loading/unloading)]. In our study, we allow the simulation to run for a minimum of 12min.

Figure 1: Test setup used for dynamic testing of silicone rubber



a) **b)**

Figure 2: Temperature evolution at the silicone rubber centre at 2 Hz and 15% displacement based upon: (a) Experiment; and (b) Numerical findings

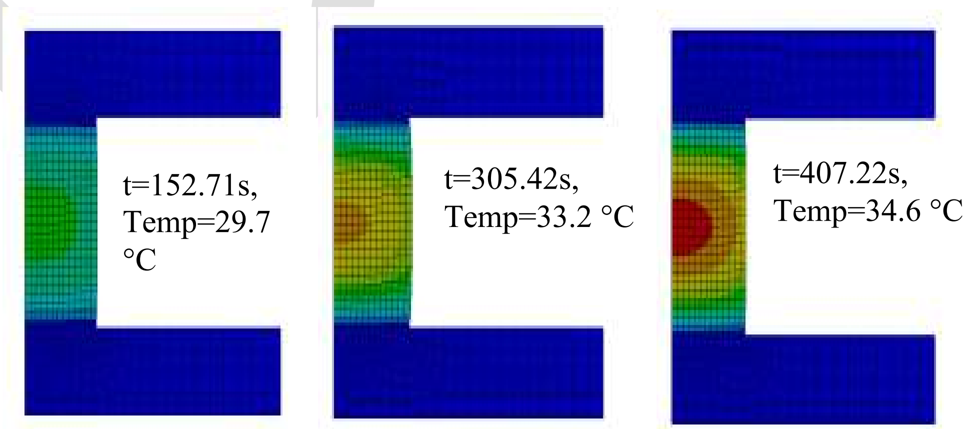
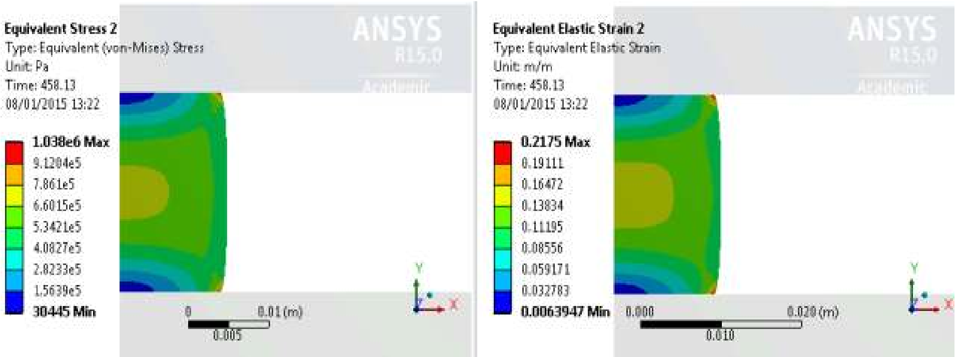


Figure 3: Simulation of temperature build-up within silicone rubber at various times; 2Hz & 15%



a) **b)**

Figure 4: Equivalent stress (a) and equivalent strain (b) contours at 458.13 sec; 2Hz & 15%

Experimental time-temperature variation is shown in Figure 2a. Oscillations in the data are mainly due to thermocouple being cyclically compressed and uncompressed within the rubber specimen. The '*black*' line represents an average of this data. The simulation results of this test are presented in Figure 2b and it shows a good agreement with the experimental data. After 10 minutes, a stabilised temperature of 37 ^{o}C is observed.

Temperature contours within the rubber at various time stations calculated numerically are shown in Figure 3. The maximum temperature is observed at the centre of rubber sample. The numerical model predicts the stress and strain evolution in the rubber. This is depicted in Figure 4. Apart from the discretisation issue at the contact region, stress and strain are higher at the specimen centre.

6. Conclusions

In this study, a silicone rubber compound has been characterised for evaluating important thermal and mechanical properties, to be used in a transient nonlinear direct coupled thermo-mechanical simulations. When compared against experimental trials, the proposed computational model was able to predict the temperature rise at the centre of the rubber as occurs in practice. This was made possible by considering a temperature dependent hyper-elastic material model and the computation of the hysteresis due to energy loss within the rubber under consideration. The numerical model presented could be used in designing rubber parts for efficiency and sustainability within complex industrial applications.

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