

## Viscoelastic Properties of Hybrid III Head Skin

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### ABSTRACT

The biofidelity of the Hybrid III headform in impact is largely dependent on local head geometry and viscoelastic mechanical properties of its polymer skin. Accordingly, for accurate simulation of the ATD headform in computational models, a quantitative understanding of the mechanical properties of skin material is required at a variety of strain rates and strain amplitudes. The objective of this study was to characterize the head skin material of the Hybrid III test dummy for finite deformations and at moderate strain rates for blunt impact simulation using finite element models

Head skin material from a single ATD was tested using uniaxial compression. A viscoelastic constitutive model with separable temporal and elastic responses was used to characterize the nonlinear and viscoelastic material behavior. Model parameters were determined using data from a series of relaxation tests up to 30% compressive strain (step displacement and hold for 60 s), and the model was validated using constant strain rate tests (up to 100% 1/s).

Rate dependence, hysteresis, and nonlinear elastic material behavior were seen during the testing. The results showed that the relaxation response of the material was strain independent up to 20% strain, with some strain-dependence seen at the 30% strain level. A two-term Ogden hyperelastic model was used for the instantaneous elastic function, and a

Maxwell viscoelastic model with five time constants was used for the reduced relaxation function. The temporal response of the material was fit with time constants of 0.01, 0.1, 1, 10, and 100 seconds. The 0.1 second and 0.01 second time constants were associated with relatively large relaxation coefficients, which was noteworthy given that many blunt head impacts occur over these time scales [1-2]. The model was validated up to 30% compressive strain using the constant strain rate tests.

### INTRODUCTION

The Hybrid III anthropomorphic testing device (ATD or dummy) has been widely used in automotive biomechanics testing as a robust human surrogate for assessing the potential for human injury [1]. The dummy has also been utilized for biomechanics research in sports injury [2] and military injury [3-4]. Finite element models of the Hybrid III have been developed to enable numerical simulation of motor vehicle accidents [5-6] and federal motor vehicle safety standards. Finite element dummy models are useful as they are generally less complex than human body models, and can be validated experimentally with repeated tests. To produce accurate Hybrid III simulation results over a range of input scenarios, the model must use appropriate material properties that have been characterized over the wide range of strain and strain rates that the dummy will experience during an impact or event. In this regard, the properties of skin materials play

an important role in the dummy response during a blunt impact scenario, as the bulk of the compliance in ATD heads is in the skin. Accordingly, simulation of this impact requires material properties derived from experimental data encompassing this regime of loading.

Viscoelastic material testing of rubbers may be performed using tension [7-8], compression [9-10] and shear [11] loading. Indentation testing coupled with finite element analysis has also been used to determine viscoelastic behavior [12]. To determine the viscoelastic behavior of the rubber skin material, compression loading was chosen. A common method for compression testing of rubber is testing a sample between two flat platens and using a prescribed compressive displacement while measuring the force generated by the compression [13-14]. In this setup, the end conditions of the sample have an effect on the stress distribution in the sample and on the measured response [13]. It has been shown in Hybrid III head test applications, such as head drop, that surface treatment with lubricants has significant influence of acceleration based injury metrics [1]. The mechanical effect of end conditions can also be controlled by lubrication of the sample contact surfaces [9, 13, 15]. Lubrication reduces the effective stiffness of the material by reducing the constraints applied to the ends of the sample, and thus gives a better measure of the material properties in pure compression.

Most rubbers have nonlinear viscoelastic properties [16]. There have been many approaches to modeling the behavior of time-dependent materials such as rubber and biological tissue [17]. Integral-type viscoelastic models are commonly used as they can be easy to implement for complex loading and nonlinear behavior materials [18-19]. Quasi-linear viscoelasticity (QLV) is a common viscoelastic theory used to characterize biological materials and polymers that have nonlinear elastic responses, as it reduces constitutive model complexity by separating the nonlinear elastic response from a linear temporal response [17, 20]. A fully nonlinear viscoelastic model, where the elastic and temporal responses cannot be considered independent, can be considerably more complex and require a large number of tests to fully characterize the model [16, 21].

The goal of this study was to characterize the viscoelastic material properties of the Hybrid III head skin. A nonlinear viscoelastic model with separable temporal and elastic responses (similar to QLV) was used to model the material. The viscoelastic model developed in this study will be used in finite element models of the Hybrid III to increase the accuracy of the response during blunt impact to the dummy head.

## MATERIALS AND METHODS

### EXPERIMENTAL SETUP

Cylindrical samples from a newly manufactured Hybrid III head skin (Denton ATD, Rochester Hills, MI) were cut from both lateral aspects of the head using a 0.5 inch diameter rubber punch mounted in a press. The samples were cut slowly with minimal force to minimize compression of the material [22]. Nine samples with a length/diameter ratio of one were chosen for testing, with four samples taken from the left side of the head and five taken from the right side. Viable area on the head skin from which consistent samples could be taken was limited by the surface curvature. Each sample was measured using digital calipers to determine the height and the diameter of the sample, with the diameter measured at a midlevel between the top and bottom surfaces. The average  $\pm$  standard deviation (SD) of the sample height ( $l_0$ ) and sample diameter ( $D_0$ ) were  $10.55 \text{ mm} \pm 0.62$  and  $9.97 \text{ mm} \pm 0.18$ , respectively. The left side samples were 1 mm shorter than the right side samples ( $p = 0.0035$ ), and 0.3 mm wider than the right side samples ( $p = 0.0012$ ).

Tests were performed by compressing each sample between two flat platens mounted to a servohydraulic testing system (MTS, Eden Prairie, MN). To minimize friction between the sample and the platens, petroleum jelly (Unilever, London, UK) was applied to both surfaces of the sample in contact with the platens during testing [9,13,15]. Minimal thickness of lubrication was used to avoid contribution to the overall height of the sample.

Samples were compressed using displacement control. Displacement inputs were based upon engineering strain as defined by the ratio of change in height ( $\Delta l$ ) to the initial height ( $l_0$ ) of the sample. Zero strain was defined by the height of the sample under a 1N initial load. This initial load was to ensure the proper contact of the bottom and top surfaces of the sample without substantial displacement from its initial unstressed height. Subsequent tests for each individual sample were separated by a period of at least 24 hours.

Each sample was subjected to separate step-hold tests to engineering strain levels of 10%, 20% and 30% compression. Each strain level was held for 60 s to study the relaxation behavior of the material. Displacement rates were set to the maximum velocity allowed by the system to study material response for the shortest available duration. The rise time for each step was approximately 40 ms. An additional series of step-hold tests were done on each sample four times at the same strain level to assess the repeatability of the testing, and to ensure that the material was not being damaged from testing. Each sample was then tested at constant engineering strain rate up to 30% engineering strain over four different

strain rates. The constant strain rates were 0.1%, 1%, 10%, and 100% 1/s.

Displacement and force data was recorded at 10 kHz using data acquisition software (LabVIEW, National Instruments). The resulting data was filtered and decimated using MATLAB (MathWorks) to perform model fitting and optimization done using Excel Solver (Microsoft).

## MODELING/ANALYSIS

The stress response,  $\sigma(\lambda, t)$ , was analyzed for each test using a convolution integral of the form:

$$\sigma(\lambda, t) = \int_0^t G_{\text{red}}(t - \tau) \frac{d\sigma^e}{d\lambda} \frac{d\lambda}{d\tau} d\tau \quad (1)$$

where  $G_{\text{red}}$  is the reduced relaxation function,  $\sigma^e$  is the instantaneous elastic function,  $\lambda$  is the stretch ( $\lambda = 1 + \Delta l/l_0$ ),  $t$  is the time,  $\tau$  is a dummy variable for integration, and  $\sigma$  is the material true stress ( $\sigma = F/A = \lambda[F/A_0]$ ).

The reduced relaxation function is based on a series of Maxwell elements, and expressed as the Prony series:

$$G_{\text{red}}(t) = G_{\infty} + \sum_{n=1}^5 G_n e^{-\frac{t}{\tau_n}} \quad (2)$$

$$\sum G_i = 1 \quad (3)$$

where  $G_{\infty}$  is the steady-state relaxation coefficient and  $\tau_n$  are the time constants corresponding to each of the relaxation coefficients,  $G_n$ . In this study, five terms in the Prony series were used, with time constants,  $\tau_n$ , constrained to decade values 100s, 10s, 1s, 100ms, and 10 ms [23]. The convolution integral, Eq. (1), was numerically integrated in terms of instantaneous elastic parameters, and relaxation coefficients [24]. This technique allowed for the evaluation of the convolution integral using an arbitrary displacement input based on displacement time-history of each test rather than an idealized step-hold displacement [24]. A generalized reduced gradient technique was used to find an optimal solution for instantaneous elastic parameters and the relaxation coefficients (Excel Solver, Microsoft).

Reduced relaxation coefficients and instantaneous elastic function parameters were simultaneously optimized by minimizing the sum of the squared errors for all 54 step-hold tests together. Multiple hyperelastic models were considered for the instantaneous elastic function, including Neo-Hookean, Mooney-Rivlin, 1-term Ogden, and 2-term Ogden models. The functional forms of each of the hyperelastic models in uniaxial compression are shown in Table 1 in order

of increasing complexity. Complete sets of relaxation and instantaneous elastic parameters were optimized for each of the elastic models. Quality of viscoelastic model fit was assessed using a sum of squared errors (SSE) metric.

**Table 1. Functional forms of hyperelastic models in Uniaxial Compression**

| Model          | Stress (True) – Stretch                                                                                                                                      |
|----------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Neo-Hookean    | $\sigma = \mu(\lambda^2 - \lambda^{-1})$                                                                                                                     |
| Mooney-Rivlin  | $\sigma = \mu_1(\lambda^2 - \lambda^{-1}) + \mu_2(\lambda^{-2} - \lambda^1)$                                                                                 |
| One-term Ogden | $\sigma = \mu(\lambda^{\alpha} - \lambda^{-\frac{\alpha}{2}})$                                                                                               |
| Two-term Ogden | $\sigma = \mu_1 \left( \lambda^{\alpha_1} - \lambda^{-\frac{\alpha_1}{2}} \right) + \mu_2 \left( \lambda^{\alpha_2} - \lambda^{-\frac{\alpha_2}{2}} \right)$ |

## RESULTS

Plots of representative material behavior during the step-hold relaxation testing and constant strain rate testing are shown in Figure 1. The relaxation tests (Figure 1A) showed typical viscoelastic behavior where the magnitude of compressive stress decreases with time during the duration of constant applied displacement. For the constant strain rate tests (Figure 1B), the material response was noticeably nonlinear and stiffening with increasing compressive strain. Additionally, there was a marked increase in material stiffness with increasing applied strain rate.

<figure 1 here>

Step-hold tests were repeated four times to ensure the repeatability of the stress response of the material. A representative series of four step-hold tests on a single sample is shown in Figure 2. The repeated testing up to 30% strain shows slight differences in long-term response, with normalized stress levels at 60 seconds varying by less than 10% of their mean. Importantly, the material shows no progressive decrease in stress-time response with number of tests, ensuring that no material damage occurred up to this strain level.