High Damping Rubber for Base Isolation Bearings: Mechanical Behaviour and Constitutive Modelling

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ABSTRACT

To obtain improved engineering properties, large amount of different fillers including about 31% carbon black are added during vulcanisation process to produce high damping rubber (HDR) for base isolation bearings. Experiments conducted on HDR under cyclic compression and shear deformations suggest the existence of Mullins' effect, residual strains, Fletcher-Gent effect, hysteresis, incompressibility and viscosity induced strain-rate effect. HDR displayed all these effects much more prominently than other common rubbers having much lower amount of fillers. To reproduce the general mechanical behaviour of HDR, a general constitutive model is now in the process of development. In this context, a new hyperelasticity model is developed to represent rate-independent elastic responses in compression and shear regimes. The model is incorporated in a rate-dependent finite deformation model structure. Development of a scheme to estimate the model parameters and implementation of the model in a general-purpose finite element code are addressed next. The proposed presentation highlights different aspects of this development.

1 INTRODUCTION

The discovery of the vulcanisation process and its subsequent improvement lay on the major engineering advancements of the last two centuries. During vulcanisation, carbon black, sulphur and some other materials are usually added as fillers. Such a process enhances the engineering properties of rubber to suite it for a specific end use. Vulcanised rubbers are widely used for making tires, shock absorbers, bridge seats, expansion joints, tunnel linings, wind shoes and dams for irrigation purposes. Recent use of rubber bearings for making base isolation devices to protect the structures from earthquakes has added a new dimension in its engineering applications. The bridges and buildings having rubber base isolation devices have so far displayed encouraging field level performances by sustaining severe shocks during Loma Prieta (1989), Northridge (1994) and Kobe (1995) earthquakes (Kelly 1997). Rubber bearings for base isolation devices are usually made of thin horizontal layers of rubbers bonded with alternately placed horizontal steel plates. In base isolation, steel plates impart large stiffness under vertical load, while rubber layers incorporate low horizontal stiffness, when the structure is subjected to lateral loads (e.g. earthquake, wind, etc.). The devices are thus usually subjected either to compression or combination of compression and shear. Figure 1 presents a schematic representation of deformed single rubber layers in these two modes.

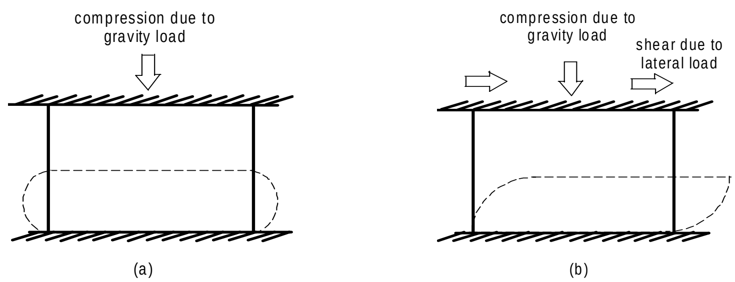

Figure 1. Schematic diagram for probable loading conditions in a single rubber layer of base isolation bearings (a) Compression (b) Compression and Shear. Solid and dotted lines show the undeformed and deformed conditions, respectively.

The devises thus requires large lateral flexibility together with high energy absorption property under large cyclic lateral load. This facilitates reduction of lateral displacement and extension of the natural periods of the structure. On the other hand, these devices need to be adequately stiff under low magnitude of lateral forces coming out of service loads, such as traffic loads. Hence for manufacturing special rubber for base isolation devices, most attention is paid for incorporating all the properties during vulcanization process. To meet such a need, rubber industries use large amount of fillers, e.g. carbon black, plasticizer, oils and some other materials with ordinary natural rubber in a special process to produce a special type of rubber referred as High Damping Rubber (HDR). Due to this special treatment, HDR shows a strongly nonlinear rate dependent response including Fletcher-Gent effect under monotonic load while a significant hysteresis property under cyclic loads. The other common properties of rubber like Mullins' effect and residual strains are also very pronounced.

To analyse and design HDR bearings using a numerical approach like finite element (FE) technique, it is required to develop an adequate constitutive model that can represent all these effects satisfactorily. If available, such a model can minimize the need of performing the expensive full scale tests on prototypes and to reduce the costs arising from designing and manufacturing the product and evaluating its performance. Yet, a thorough understanding on the mechanical behaviour of HDR in compression and shear deformation modes is of prime importance for developing a constitutive model. With this objective, a comprehensive work was undertaken to characterize the responses observed from cyclic experiments in uniaxial compression and simple shear. Identical tests on ordinary natural rubber (NR) specimens having low filler content were carried out for comparison. On the basis of experimental evidences, efforts were made to formulate the necessary constitutive relations, identify the model parameters and implement the models in available general-purpose FE codes. The paper reveals the major aspects of this research covering the challenges that are being faced and the difficulties that have so far been overcome.

2 CYCLIC BEHAVIOUR IN COMPRESSION AND SIMPLE SHEAR

Systematic experimental study in relevant deformation modes is required to obtain a comprehensive understanding on the mechanical behaviour of HDR. Such a study can offer a fundamental basis for reproducing its behaviour through a constitutive model. To this end, uniaxial compression and simple shear tests at different strain rates were carried out in a computer controlled servo-hydraulic testing machine, each time on new specimens. Figure 2 presents the schematic deformation of specimens in these two modes. Details of the experimental procedure have been extensively discussed in Amin (2001), Amin et al. (2002, 2003) and Wiraguna (2003).

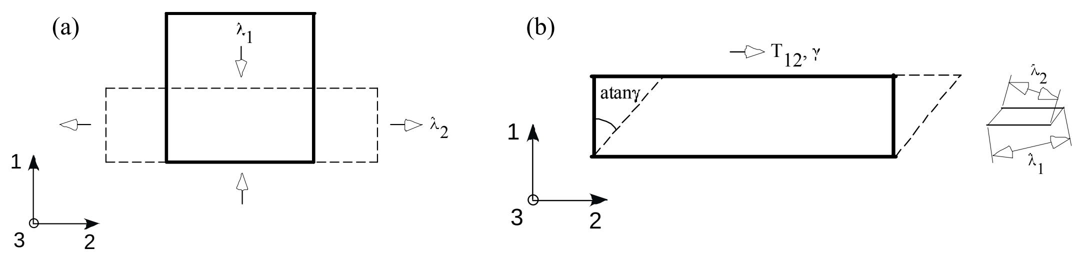

Figure 2. Fundamental description of deformation in large deformation tests
where λ=1+dL/L, L: undeformed length; (a) Homogeneous uniaxial compression (b) Simple shear

Figure 3 presents the responses obtained from HDR specimens in compression and shear. The existence of strongly nonlinear rate-dependent response at the loading path in HDR (Figure 3a and 3b) is distinctly visible. All the responses are particularly characterised by the presence of significantly high stiffness at low strain levels, presently referred to as the Fletcher-Gent effect (Amin et al. 2002, 2004). The effect shows direct dependence on the applied strain-rate. Furthermore, the unloading path differs from the loading path giving a substantial loss of energy in hysteresis process. The residual strain is also visible at the end of each loading cycle. A weak dependence of applied strain-rate in the unloading path can be noted. When compared with the corresponding responses obtained from NR under identical test condition the nonlinearity of the response at low strain level and its dependence on applied strain-rate at the loading path are found to be distinctly weaker than those of HDR (Amin 2001). Furthermore, hysteresis and residual strain effects as visible during cyclic loading are also found to be conspicuously weaker. The effects of fillers and the adopted vulcanization process are attributed to these facts.

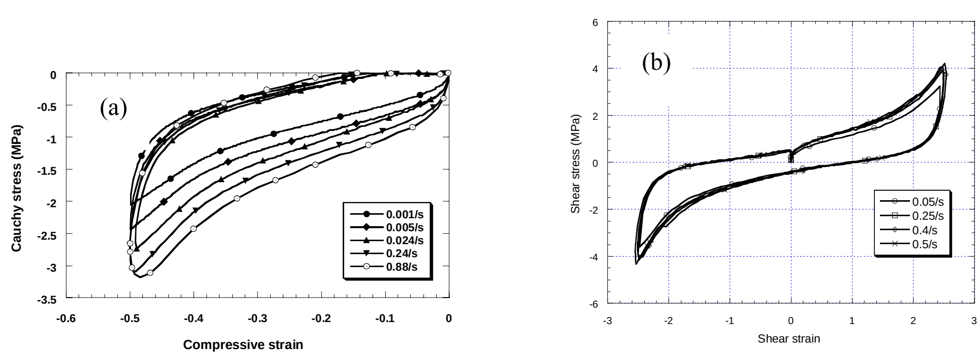

Figure 3. Response from HDR (a) Under cyclic compression, (b) Under cyclic simple shear

3 CONSTITUTIVE MODELING

3.1 On the way to a General Constitutive Model

The tests in compression and shear regimes revealed the significant presence of Fletcher-Gent effect, hysteresis and residual strain effects. Furthermore, the viscosity induced strain-rate effect is also distinctly visible. Usually, in literatures, hyperelasticity models have widely been used to model the nonlinear rate-independent responses. Such a model also forms the basis for more general model for simulation of visco-elastic or visco-elasto-plastic response in the most general case. In this context, current work aims towards developing an adequate hyperelasticity model capable of representing the nonlinear rate-independent monotonic response including Fletcher-Gent effect in compression and shear regimes.

3.2 Constitutive Description of Deformation

Uniaxial compression

When a body is subjected to homogeneous large uniaxial compression, the principal stretch (λ_1) in the loading direction becomes compression (Figure 2a). Considering isotropy and incompressibility, we have $\lambda_2^{\,2} = \lambda_3^{\,2} = \lambda_1^{-1}$. The deformation gradient tensor **F**, left-Cauchy Green deformation tensor **B** and the strain-invariants can be written as:

$$\mathbf{F} = \begin{bmatrix} \lambda_1 & 0 & 0 \\ 0 & \frac{1}{\sqrt{\lambda_1}} & 0 \\ 0 & 0 & \frac{1}{\sqrt{\lambda_1}} \end{bmatrix}; \quad \mathbf{B} = \begin{bmatrix} \lambda_1^{\,2} & 0 & 0 \\ 0 & \frac{1}{\lambda_1} & 0 \\ 0 & 0 & \frac{1}{\lambda_1} \end{bmatrix} \tag{1}$$

$$I_1 = tr\mathbf{B} = \frac{2}{\lambda_1} + \lambda_1^{\,2}, \quad I_2 = \tfrac{1}{2}\left\{(tr\mathbf{B})^2 - (tr\mathbf{B.B})\right\} = \frac{1}{\lambda_1^{\,2}} + 2\lambda_1, \quad I_3 = \det\mathbf{B} = 1$$

Simple shear

Figure 2b schematically presents the simple shear deformation. In contrast to uniaxial compression, the direction of applied displacement does not coincide with the directions of principal stretches; rather it involves a rotation of axes. Due to applied shear strain (γ, the deformation gradient tensor **F**, the left-Cauchy Green deformation tensor **B** and strain-invariants are described as:

$$\mathbf{F} = \begin{bmatrix} 1 & \gamma & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}; \quad \mathbf{B} = \begin{bmatrix} 1+\gamma^2 & \gamma & 0 \\ \gamma & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{2}$$

$$I_1 = I_2 = 3 + \gamma^2, \quad I_3 = 1$$

Stress expressions using a hyperelasticity model

Hyperelasticity models are usually expressed in terms of a strain energy density function, W used for representing the rate-independent responses. In a viscous solid, responses obtained at the equilibrium state and instantaneous states are considered as rate-independent responses and usually represented by a hyperelasticity model (Huber and Tsakmakis 2000). In these states, the stress is described by Cauchy stress tensor **T**:

$$\mathbf{T} = -p\mathbf{1} + 2\frac{\partial W}{\partial I_1}\mathbf{B} - 2\frac{\partial W}{\partial I_2}\mathbf{B}^{-1} \tag{3}$$

The hydrostatic pressure p is constitutively indeterminate, and hence it is obtained from the underlying equilibrium and boundary conditions of the particular problem. The expression for Cauchy stresses namely, T_{11} and T_{12} becomes as follows:

$$T_{11} = 2\left(\lambda_1^2 - \frac{1}{\lambda_1}\right)\left(\frac{\partial W}{\partial I_1} + \frac{1}{\lambda_1}\frac{\partial W}{\partial I_2}\right), \; T_{12} = 2\gamma\left(\frac{\partial W}{\partial I_1} + \frac{\partial W}{\partial I_2}\right) \tag{4}$$

3.3 New Hyperelasticity Model and Parameter Identification

Due to strong dependence of the stress response on the state of strain, experiments are required to identify an adequate form of W. Ideally, such a function should have the capability to predict responses at all possible deformation modes. However, Amin et al. (2002) reported the limitations of conventional hyperelasticity models in representing Fletcher-Gent effect in compression regime. An improved hyperelasticity model was proposed there. The model has been further improved here to represent the responses both in compression and simple shear deformation mode:

$$W(I_1, I_2) = C_5(I_1 - 3) + \frac{C_3}{N+1}(I_1 - 3)^{N+1} + \frac{C_4}{M+1}(I_1 - 3)^{M+1} + C_2(I_2 - 3) \tag{5}$$

where C_5, C_3, C_4, C_2, M, and N are material parameters. The corresponding expressions for Cauchy stress in compression and simple shear can be obtained as:

$$T_{11} = 2\left(\lambda_1^2 - \frac{1}{\lambda_1}\right)\left[C_5 + C_3(I_1 - 3)^N + C_4(I_1 - 3)^M + \frac{C_2}{\lambda_1}\right] \tag{6}$$

$$T_{12} = 2\gamma\left[C_5 + C_2 + C_4\gamma^{2M} + C_3\gamma^{2N}\right] \tag{7}$$

A parameter estimation scheme involving simultaneous minimization of least-square residuals of uniaxial compression and simple shear data has been developed. The difficulties of identifying a unique set of hyperelasticity parameters that holds for both compression and shear deformation modes are thus overcome (Amin et al. 2004). Table 1 presents the set of estimated parameters. The reproduction of the equilibrium state and instantaneous state responses in compression and shear deformation mode using the proposed hyperelasticity relation and estimated parameters are illustrated in Figure 4. The proposed model has been implemented in FEAP, a general-purpose finite element program to predict rate-independent responses for a boundary value problem. Figure 5 presents the predicted stress contours in a steel plate-laminated HDR bearing.

Table 1: Material Parameters for HDR

Responses	C_2 MPa	C_3 MPa	C_4 MPa	C_5 MPa	M	N
Equilibrium	0.145	1.182	-5.297	4.262	0.06	0.27
Instantaneous	0.166	2.477	-11.689	9.707		

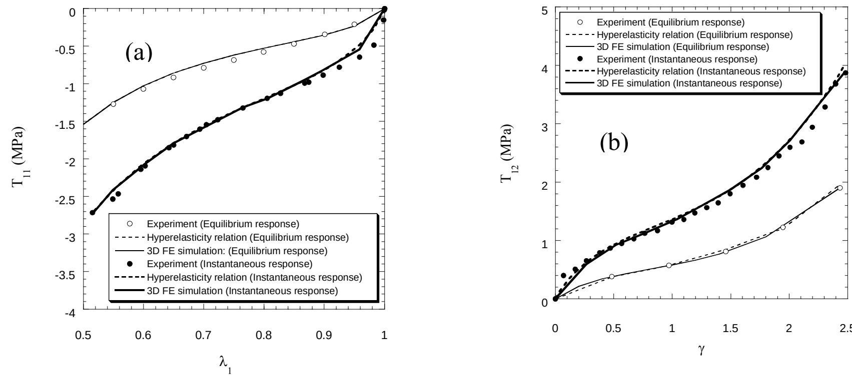

Figure 4. Representation of rate-independent monotonic responses of HDR using the proposed hyperelasticity model and identified parameters. Result obtained from 3D FE simulation is also presented for comparison. (a) Compression, (b) Simple shear.

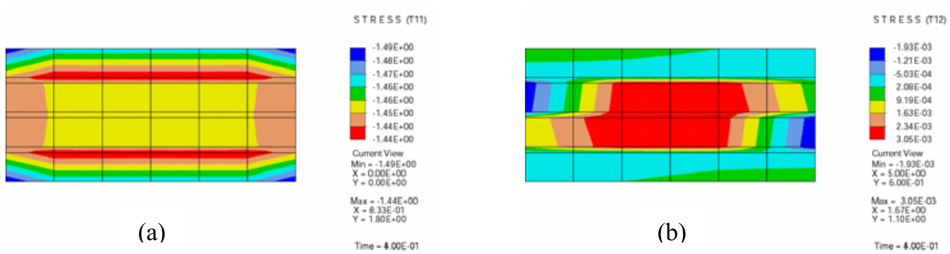

Figure 5. FE analysis of HDR bearings using new strain energy density functions. (a) T_{11} contours under uniaxial compression, (b) T_{12} contours under combined action of compression and shear

4 CONCLUSIONS AND FURTHER REMARKS

Cyclic compression and shear tests on HDR revealed the significant presence of Fletcher-Gent effect, strain-rate dependency and hysteresis. Due to the use of large fillers during vulcanisation process, HDR have shown these effects more prominently than NR. A new hyperelasticity model is proposed and implemented in a FE code to represent the rate-independent response including Fletcher-Gent effect. The identification of material parameters that hold for both compression and shear regime is also addressed. The proposed hyperelasticity model can readily be implemented in a finite-strain rate-dependent model (Huber and Tsakmakis 2000, Amin et al. 2002). Modelling of the rate-dependency effect and cyclic behaviour in shear and compression are of next interest of the authors.

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