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A generalized rate-dependent constitutive law for elastomeric bearings

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HIGHLIGHTS

- A generalized rate-dependent constitutive law for elastomeric bearings is proposed.
- The proposed model is developed from the viewpoint of elastomeric material.
- Material test and real-time hybrid simulation test were performed to verify the model.
- The experimental and numerical simulation results are in good agreement.

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ABSTRACT

Elastomeric bearings have been a mature and efficient technique to mitigate structural damage caused by earthquakes. This paper proposed a generalized mathematical model for accurately evaluating the rate-dependent stress–strain response of natural rubber bearing (NRB), high damping rubber bearing (HDRB) and super high damping rubber bearing (SHDRB). A novel strain energy function including an additional stiffness correction factor α is proposed to describe the Fletcher–Gent effect of elastomeric materials, which featured by high initial stiffness at small strain ranges. The proposed constitutive model is composed of two parts, the first part consisting of a hyperelastic spring represents the rate-independent equilibrium stress, while the second part consisting of a Maxwell element expresses the rate-dependent overstress. Parameter identification scheme is implemented based on the results of the multi-step relaxation tests and monotonic shear tests. Numerical simulations for monotonic shear tests were conducted to demonstrate the capacity of the proposed model in predicting the stress–strain relationship of elastomeric bearings at different strain rates. Finally, in order to investigate the accuracy and feasibility of the proposed model on the application to the seismic response assessment of isolated bridges, real-time hybrid simulation (RTHS) test was performed and favorable results were obtained.

1. Introduction

Elastomeric bearings have been widely used as seismic isolators to protect buildings and bridges from earthquakes for both new constructions and retrofit projects, and have proven to be effective and reliable. Among various types of elastomeric bearings, natural rubber bearing (NRB) and lead rubber bearing (LRB) have been well known and the application of them in civil structures has increased substantially during the last decades, especially in New Zealand, Japan and United States [1]. The NRB uses alternate layers of natural rubbers and steel plates, it has small damping and often be used to accommodate the shrinkage of the deck of isolated bridges. In recent years, two evolving types of elastomeric bearings were invented, named as high damping rubber bearing (HDRB) and super high damping rubber bearing (SHDRB). The rubber material of HDRB and SHDRB possesses high damping due to the add of specific chemical fillers like carbon black, plasticizer and oil during the vulcanization process. With these additives, HDRB and SHDRB provide structural systems additional damping to dissipate seismic energy and lengthen their fundamental period resulting in the decrease of the seismic response [2,3].

Since the acceptance of the performance-based design philosophy [4], nonlinear time history analysis is recommend by some design specifications [5,6] for the seismic response assessment of isolated bridges [7]. Hence, accurate modeling of the mechanical behavior of the elastomeric bearings is of great importance to a

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rational design of isolated bridges. In these specifications, the hysteretic behavior of NRB is approximated by equivalent linear method, and that of HDRB and SHDRB are represented by bilinear elasto-plastic model. However, the chemical fillers in rubber make the hysteretic behavior of the elastomeric bearings, in particular the HDRB and SHDRB, considerably complicated. Therefore, any existing linear models cannot reproduce their mechanical characteristics with satisfactory accuracy, especially the rate-dependent property as found by many researchers [8,9]. In the past studies, a few rate-dependent constitutive models for NRB and HDRB were proposed to ameliorate the aforementioned limitations [8–12], while the analytical models available to SHDRB are rare [3,13]. Moreover, most of these theoretical models are based on the experimental hysteretic loops of the elastomeric bearings, this indicates the necessity for the further study of elastomeric bearings in terms of rubber material. On the other hand, NRB, HDRB and SHDRB are often used together in engineering practices, nowadays the design and seismic analysis of isolated bridges with elastomeric bearings are extremely complex because different hysteretic models should be employed, in this regard, a major need exists for a simplified analytical and design approach. Development of a generalized constitutive law to describe the mechanical behaviors of these three types of elastomeric bearings is motivated by these reasons.

In this paper, a generalized rate-dependent constitutive law for three types of elastomeric bearings (i.e., NRB, HDRB and SHDRB) under the horizontal shear deformation is presented from the viewpoint of rubber material. A modified version of classical Zener model is established to express the stress–strain function of rubber material and the total stress is decomposed to rate-independent equilibrium stress and rate-dependent overstress to describe the fundamental viscoelastic behavior of the rubber. A nonlinear viscous damping coefficient is introduced into the mathematical formulation to characterize the rate-dependent effect. Furthermore, multi-step relaxation tests and monotonic shear tests are performed to identify the material parameters. The numerical and experimental results are compared to verify the accuracy of the proposed model. Finally, in order to investigate the accuracy and feasibility of the proposed model on the application to the seismic response assessment, real-time hybrid simulation (RTHS) test was performed and favorable results were obtained.

2. Strain energy function

According to the phenomenological theory, rubber is a hyperelastic material and the mechanical properties of rubber can be characterized by its strain energy function W [14], which can be represented in terms of deformation tensor invariants $(I_1,\ I_2,\ I_3)$,

$$W = W(I_1, I_2, I_3) \tag{1}$$

where

$$\begin{cases} I_1 = \mathrm{tr}\mathbf{B} = \lambda_1^2 + \lambda_2^2 + \lambda_3^2 \\ I_2 = \frac{1}{2}[(\mathrm{tr}\mathbf{B})^2 - (\mathrm{tr}\mathbf{B}^2)] = \lambda_1^2\lambda_2^2 + \lambda_2^2\lambda_3^2 + \lambda_3^2\lambda_3^2 \\ I_3 = \det\mathbf{B} = \lambda_1^2\lambda_2^2\lambda_3^2 \end{cases} \tag{2}$$

tr and det represent trace and determinant of left Cauchy–Green deformation tensor $\mathbf{B}$, λ_i ($i = 1,2,3$) denotes principal stretches. Moreover, considering that rubber is incompressible, the third invariant $I_3 = 1$, thus W is expressed as a function of I_1 and I_2 only, i.e., $W = W(I_1, I_2)$.

Since an adequate strain energy function is of great importance in establishing a reliable constitutive model, there are many strain energy function expressions in the literature [15], the most general one is proposed by Rivlin [16] as follows:

$$W_{Rivlin} = \sum_{i=0,j=0}^{\infty} C_{ij}(I_1 - 3)^i (I_2 - 3)^j \tag{3}$$

where C_{ij} is the material parameter.

The Mooney–Rivlin model [17] is a first-order polynomial form of the Rivlin's expression and has been widely used for its simple form and sufficient accuracy to predict the response of rubber material from small to moderate strain amplitudes.

$$W_{Mooney-Rivlin} = C_{10}(I_1 - 3) + C_{01}(I_2 - 3) \tag{4}$$

where C_{01} and C_{10} are the material parameters.

However, strain energy functions available in published researches are mainly focusing on rubber-like materials, the investigations on the behavior of innovative rubber materials aforementioned are found only in a few works [12]. Furthermore, previous researches mainly deals with the uni-axial stress–strain relationship of rubber material, hence, these studies fail to investigate the shear regime, which is essential for elastomeric bearings under the earthquake exaction. Therefore, development of an adequate strain energy function applicable to shear deformation for seismic application is aroused by these reasons.

Past investigations on the performances of existing strain energy functions showed their incapability to represent the complex mechanical behaviors of hyperelastic materials, especially the high stiffness at small strains [12]. This feature is referred to as the Fletcher–Gent effect on the effect of fillers in NRB [18], it should be noted that this effect seems more significant in HDRB and SHDRB due to the higher fillers contents. In this study, in order to not only reproduce the rubber response accurately but also minimize the material parameters and ensure the simplicity of mathematical formulation, a strain energy function of I_1 and I_2 with an additional stiffness correction factor α is proposed as follows:

$$W(I_1, I_2) = C_1(I_1 - 3) + \frac{2}{3}C_2(I_1 - 3)^{\frac{3}{2}} + \frac{1}{2}C_3(I_1 - 3)^2 + \frac{2}{5}C_4(I_1 - 3)^{\frac{5}{2}} + \frac{C_5}{\alpha + 1}(I_2 - 3)^{\alpha + 1} \tag{5}$$

where C_i ($i = 1$–5) and α are the material parameters.

3. Constitutive equation for rate-dependent property

To model the rate-dependent phenomenon of elastomeric bearings, a phenomenological Zener model shown in Fig. 1 is considered. The hyperelastic spring A represents the rate-independent equilibrium stress, while the Maxwell element consisting of a hyperelastic spring B and a nonlinear dashpot C expresses the rate-dependent overstress.

The total stress $\mathbf{S}$ is given by

$$\mathbf{S} = \mathbf{S}_{eq} + \mathbf{S}_{ov} \tag{6}$$

where $\mathbf{S}$ symbolizes the Cauchy stress, the subscript eq and ov denote equilibrium stress and overstress, respectively. Furthermore, the Cauchy stress is expressed as

$$\mathbf{S} = 2\left(\mathbf{B}\frac{\partial W}{\partial I_1} - \mathbf{B}^{-1}\frac{\partial W}{\partial I_2}\right) - p\delta \tag{7}$$

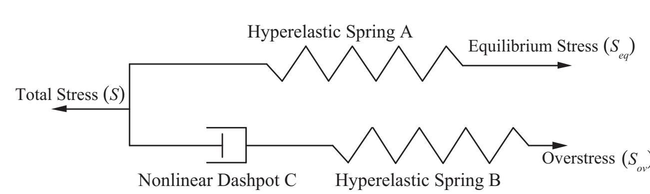

Fig. 1. Schematic of modified hyperelastic Zener model.