

An improved rheology model for the description of the rate-dependent cyclic behavior of high damping rubber bearings



D.A. Nguyen^{a,*}, J. Dang^a, Y. Okui^a, A.F.M.S. Amin^b, S. Okada^c, T. Imai^d

^a Department of Civil and Environmental Engineering, Saitama University, Saitama 338-8570, Japan

^b Department of Civil Engineering, Bangladesh University of Engineering and Technology, Dhaka 1000, Bangladesh

^c Civil Engineering Research Institute for Cold Region, PWRI, Sapporo 062-8602, Japan

^d Rubber Bearing Association, Tokyo 107-0051, Japan

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ABSTRACT

An improved rheology model, inspired from explicit experiments is conceived to represent rate-dependent cyclic shear behavior of high damping rubber bearings at subzero and room temperatures. Total stress has been decomposed into nonlinear rate independent elasto-plastic stress, nonlinear elastic stress and nonlinear visco-elasto-plastic overstress branches. To represent nonlinear viscosity behavior, 'overstress branch' has been generalized by putting linear elastic spring in parallel to nonlinear elasto-plastic model, placed in series with nonlinear dashpot. Constitutive relations for model elements have been designated for respective fundamental phenomenon observed in constant strain rate experiments. An optimum calculation approach is developed to determine a unique set of overstress parameters capable not only of representing constant strain rate cyclic tests but also sinusoidal tests with variable input strain rates. Essential abilities of the proposed model and adequacy of estimated parameters have been confirmed by comparing numerical simulation results with experiments conducted at $-30\text{ }^{\circ}\text{C}$, $-10\text{ }^{\circ}\text{C}$ and $23\text{ }^{\circ}\text{C}$.

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1. Introduction

Application of laminated rubber bearings as base isolation devices [1,2] got wider acceptance in Japan after promising field level performances in 1995 Kobe Earthquake. To introduce energy dissipation properties within the bearing device, lead rubber bearing (LRB) was developed in New Zealand [3,4] with lead plugs installed inside laminated natural rubber bearings (RB). High damping rubber (HDR) later emerged as a novel material for such bearing devices not only to eliminate the necessity of installing lead plugs inside RB but also to enhance energy dissipation properties compared to LRB. A more recent concern over the reduction of energy dissipation property per cycle in LRB due to self-heating of lead plug upon cyclic loading [5,6] is also questioning the capability of LRB in long duration earthquakes, for example 2011 Tohoku earthquake. The innovation of HDR led to a wide adoption of high damping rubber bearings (HDRBs) as visco-elasto-plastic dampers in next generation base isolated structures all over the world (Fig. 1). In contrast to LRB, where rate dependence effect is much less significant even for low temperature cases [3,7], however, even after years of practice, some of the

very important mechanical behaviors of HDR, such as the rate or temperature dependent behaviors are still difficult and less understood issues in engineering practice [8]. Yet, development of an advanced rheology model of HDRBs for designing base isolated structures in cold weather conditions and more general dynamic loading cases is much warranted. Nevertheless, any effort in this direction shall be founded on basic understanding of constitutive properties of HDRBs observed under low temperature test conditions.

Fundamental nonlinear elastic and nonlinear viscosity behaviors of HDR at room temperature are known from the observations reported in Amin et al. [9–11]. Contemporary experimental observations [12,13] on laminated rubber bearings also show that restoring force–displacement loops of HDRBs depend prominently on loading history and strain level. Hysteresis loops of HDRBs were further observed to strongly depend on loading rate, ambient temperature and even time interval between two loading tests. Bhuiyan et al. [14] reviewed well-known constitutive behaviors of HDR and their effects on the mechanical behavior of HDRBs. Past efforts on developing analytical representation of room temperature mechanical behaviors in rate dependent and rate independent rheology models were also summarized there. Subsequently, Bhuiyan et al. [14] extended the Maxwell model (Elements C and D, Fig. 2) by adding a nonlinear elastic spring (Element B) and an elasto-plastic model (spring-slider, Element A and S) in parallel to

* Corresponding author. Tel.: +81 48 858 3558; fax: +81 48 858 3558.

E-mail address: dungsaitama@gmail.com (D.A. Nguyen).

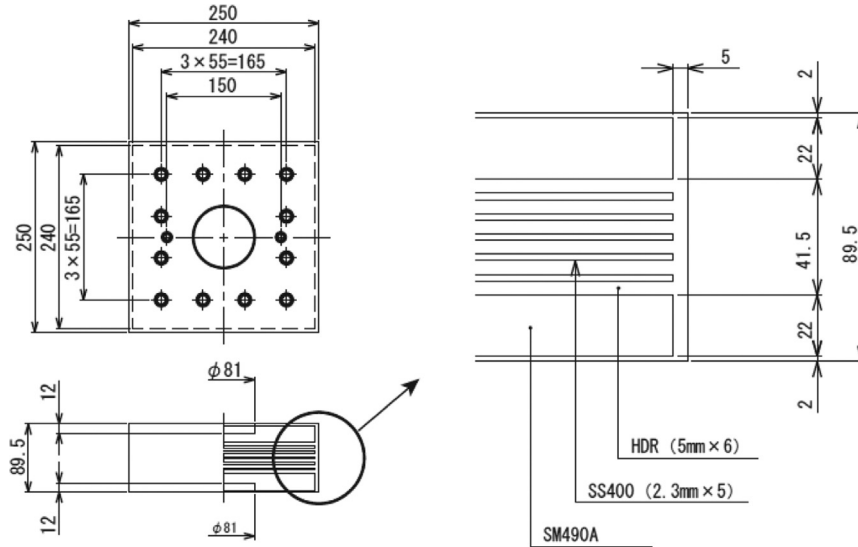


Fig. 1. Size of Type A specimen following the ISO standard ([31]) [mm] for room temperature tests.

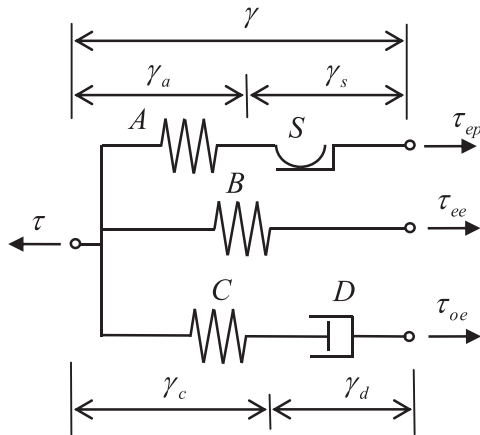


Fig. 2. Rheology model of HDRBs showing stress and strain decompositions for room temperature behavior. (after [14]). τ : average shear stress, γ : average shear strain, τ_{ee} : nonlinear elastic response, τ_{ep} : elasto-plastic response, τ_{oe} : overstress due to viscosity, $\tau = \tau_{ep}(\gamma_a) + \tau_{ee}(\gamma) + \tau_{oe}(\gamma_c)$.

represent a set of phenomena observed in full scale tests on HDRBs. The overstress (τ_{oe}) branch was modeled with a linear spring (Element C) added in series with a nonlinear dashpot (Element D). In order to identify constitutive relations of each element in the rheology model, in line with the concepts followed in Lion [15] and Amin et al. [9,10] on natural rubber (NR) and HDR, an experimental scheme comprised of three types of tests at constant strain rates, namely cyclic shear (CS) tests, multi-step relaxation (MSR) tests and simple relaxation (SR) tests were carried out at room temperature on HDRBs specimens with the standard ISO geometry. To observe the fundamental viscosity behaviors during loading and unloading, MSR tests contained multiple hold times while SR tests contained a single hold time during loading and unloading. More recently, Yamamoto et al. [16] investigated the nonlinear behavior of HDRBs under horizontal bidirectional loading at room temperature and propose an analytical model. However, no effort is known either to investigate the applicability of the existing rheology models or to propose a new model for simulating the low temperature behavior of HDRBs. Kato et al. [17] very recently proposed analytical Model for elastoplastic and creep-like room temperature behavior of HDRB.

Effect of temperature on visco-elasto-plastic phenomena in rubber is a much less investigated topic reported in current literatures. The effect of ambient temperature and the exposure history on constitutive behavior of rubber is addressed in Lion [18] and Fuller et al. [19]. A recent comprehensive review of literature together with experimental observations on natural rubber-polybutadiene rubber (NR/BR) blend is provided in Amin et al. [20]. In these studies; rate dependence, hysteresis and well-known Mullins' effect [21] were critically addressed for temperature dependence. Depending on the type and composition of the rubber, the mechanical behavior was found to be affected strongly by ambient temperature, often by temperature history and less often by the loading history. Generally, rubbers tested at lower temperatures have shown larger rate dependence, hysteresis and Mullins' effect whereas these effects got gradually diminished at temperatures above the room temperature. Furthermore, Fuller et al. [19] reports temperature history dependence of HDR due to crystallization effect on prolonged exposure to low temperature and associated increase in shear modulus. Amin et al. [20] emphasizes on the role of loading history dependence due to fundamental Gough-Joule effect, determined by the entropy elasticity and inelastic energy dissipation or hysteresis on self-heating [22–24] of large rubber devices due to quasi-adiabatic mechanical process acting on it. The later notion therefore further emphasizes the importance of thermal boundary defined mostly by the specimen size on the response of bearings. Yet, no effort in this respect is known where the fundamental constitutive behaviors observed either in HDR or HDRBs at low temperatures is investigated. This obviously restricted not only the development of a rheology model for HDRBs for seismically active cold region applications for example, Hokkaido, Japan (1968 Tokachi Earthquake) and Alaska, USA (1964 Alaska Earthquake) but also the performance prediction of existing structures in those regions.

The feat of a rheology model developed to represent a device in structural analysis is frequently judged by its ability to simulate not only the fundamental constitutive behaviors but at least also in simulating some practical loading histories that a designer would use at the design desk. Furthermore, the size of test specimen and its role on self-heating effect upon cyclic loading needs to be critically addressed at least to generate plausible conclusions on the limits of real ability of a model. In the past, this came out to be truer for HDR than other rubber-like materials when more and more test information on the former became sequentially

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