Journal of the Korean Nuclear Society
Volume 30, Number 5, pp.387~395, October 1998

Seismic Response Analyses of Seismically Isolated Structures Using the Laminated Rubber Bearings

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(Received October 2, 1996)

In general, the laminated rubber bearing (LRB), a composite structure laminated with the elastic rubber and steel plates, has a complex hysteretic nonlinear characteristics in relationships between the restoring force and shear deflection. The representative nonlinear characteristics of LRB include the change of hysteresis loop with cyclic shear deflections and the hardening effects at large shear deflection regions. Changes of the hysteresis loop of LRB with cyclic shear deflections affect the horizontal stiffness and the damping characteristics. The hardening behavior of LRB in large shear deflection region results in an increased horizontal stiffness and therefore, has a great impacton the seismic responses. In this paper, the seismic response analysis is carried out using the modified hysteretic bi-linear model of LRB, which takes into account the hysteresis loop change and the hardening behavior with cyclic shear deflection. The results on seismic responses are compared with those obtained using the widely used hysteretic bi-linear model. The new model is found to reveal the greater amount of peak acceleration response.

1. Introduction

In general, earthquakes have been treated as very important design loads for nuclear power plants including various associated structures such as building, bridge, and so forth. Especially in nuclear steam supply system, these loads dominantly control the structural design margins of systems and components. Therefore, the reduction of the seismic loads has received the worldwide attention for the sake of economy and safety of the nuclear power plants. Recently, as one of the options, the countries with advanced nuclear technology are trying to develop the seismic isolation technology using the laminated rubber bearing [1,2].

The seismic responses of seismic isolation structure are significantly improved compared with those of a non-isolated structure [3,4]. For the seismic isolation design, it is absolutely necessary to develop the numerical analysis model for a seismic isolator used in design.

The seismic isolation device considered in this paper is the laminated rubber bearing, which has high damping characteristics. This bearing shows a very complex non-linear hysteretic behavior in relationship between the restoring force and the shear deflection. There are several analysis models to represent the hysteretic behavior such as the R-O model, the rate model [5] and the simple hysteretic bi-linear model, the modified hysteretic bi-linear model [6], and so forth [7,8]. Usually, for modeling of the laminated rubber bearing, the bi-linear model is used because of its simplicity. However, it is not capable of considering acomplex behavior of the laminated rubber bearing. As shown in Fig.1, the hysteretic behavior of the laminated rubber bearing is severely changed with cyclic shear deflection [9]. This change is related to the variations of the stiffness line and the yield loads with cyclic shear deflections.

In this paper, as extension of the previous model proposed in reference 6, the modified hysteretic bi-linear model base on the simple bi-linear model, which can consider both the hysteresis loop change and the hardening behavior, is proposed. The seismic time history analyses using the proposed model of the laminated rubber bearing are carried out for a seismically isolated cylindrical tank. From the comparison of the seismic responses obtained using the proposed model and the simple hysteretic bi-linear model, it is examined if the proposed model can give more accurate results than the simple hysteretic bi-linear model.

2. Numerical Modeling of a Seismically Isolated Structure

2.1. Review of General Formulations

In general, the governing equations of motion of a seismically isolated system can be represented with mass, damping and stiffness matrix as follows:

$$[M]\{\ddot{x}_r\}+[C]\{\dot{x}_r\}+[K]\{x_r\}+\{F\}_{iso}=-[M]\{\ddot{x}_b\}\,, \quad (1)$$

where x_r indicates the relative displacement vectors to the input motion and $\ddot{x}_b$ indicates the acceleration input motion. The forcing vector, F_{iso} in equation (1) is the restoring force of a seismic isolator.

In this paper, the Runge-Kutta numerical analysis algorithm is used to solve the equation (1). To use this algorithm, the second order system of equation (1) should be transformed into the first order differential equation by using

$$z_r=\begin{Bmatrix} x_r \\ \dot{x}_r \end{Bmatrix}, \quad \dot{z}_r=\begin{Bmatrix} \dot{x}_r \\ \ddot{x}_r \end{Bmatrix}. \quad (2), (3)$$

Then, the equation (1) can be transformed into the first order differential equation with some arrangements by equations (2) and (3) as follows:

$$\{\dot{z}_r\}=\begin{bmatrix} 0 & I \\ -[M]^{-1}[K] & -[M]^{-1}[C] \end{bmatrix}\{z_r\}+\begin{Bmatrix} 0 \\ -[M]^{-1}([M]\{\ddot{x}_b\}+\{F\}_{iso}) \end{Bmatrix} \quad (4)$$

2.2. Hysteretic Bi-Linear Model of the Laminated Rubber Bearing

Fig.1 shows the experimental results of a complex hysteretic behavior for the 1/8 scaled the laminated rubber bearing, which is 15cm

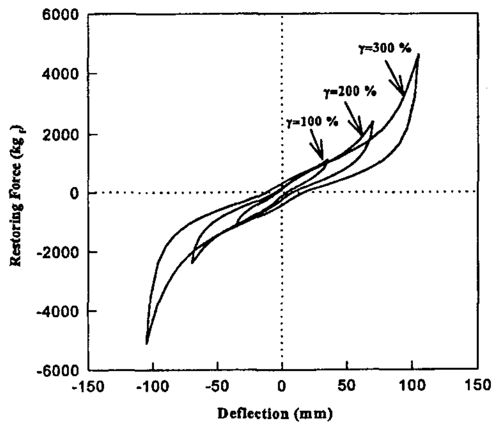


Fig. 1. Test Results of the Laminated Rubber Bearing

diameter, 29 rubber layers and 3.5cm total rubber height, for cyclic shear strain ranges of 100%, 200% and 300%. In figure, we can see that the changes of primary stiffness line and yield loads are occurred according to the maximum cyclic shear strains and the hardening behavior appears at over 100% shear strain.

For numerical analysis model using simple hysteretic bi-linear model, the forcing term in equation (4) is expressed with force equilibrium conditions when stiffness of the laminated rubber bearing follows primary stiffness line, K_1 in Fig. 2(a) as follows:

$$F_{iso} = K_1 x_r + Y, \tag{5}$$

where Y is the yield load.

When the stiffness of the laminated rubber bearing follows the secondary stiffness line, K_2 in Fig. 2(a), we can express the restoring force of the seismic isolator with considering the original coordinates shifting technique in the restoring force and displacement coordinates as follows:

$$F_{iso} = K_2(x_r - x_{shift}), \tag{6}$$

where x_{shift} is the shift value of an original coordinate, x. From equations (5) and (6), the stiffness of the laminated rubber bearing modeled by simple hysteretic bi-linear technique is just expressed with K_1 or K_2 values. The yield load, Y is a constant with $\pm$ values. In hysteretic bi-linear model, K_1 line is called as the primary stiffness line, which controls the seismic isolation frequency and K_2 line is called as secondary stiffness line, which may affect the damping characteristics of the seismic isolator. To apply this model to actual design of a seismically isolated structure, these variables should be determined by the experimental results of the mechanical characteristics of the laminated rubber bearing.

After substituting equation (5) and equation (6) to equation (4) and arranging each term, the equation (4) is rewritten as follows:

$$\{\dot{z}_r\} = \begin{bmatrix} 0 & I \\ -[M]^{-1}[K] & -[M]^{-1}[C] \end{bmatrix} \{z_r\} + \begin{Bmatrix} 0 \\ -[M]^{-1}([M]\{\ddot{x}_b\} + \{P\}_{iso}) \end{Bmatrix} \tag{7}$$

In equation (7), the stiffness matrix $[K]$ includes the stiffness of the seismic isolator, K_1 or K_2. The vector form $\{P\}_{iso}$ has Y or $K_2\ x_{shift}$ values for the degree of freedom of the seismic isolation direction at a given nodal point.

As shown in test results of Fig. 1, with increasing the cyclic shear deflections, the yield loads and the primary stiffness lines are changed, and the hardening behavior is occurred. Therefore, the simple bi-linear model shown in Fig. 2(a) is not

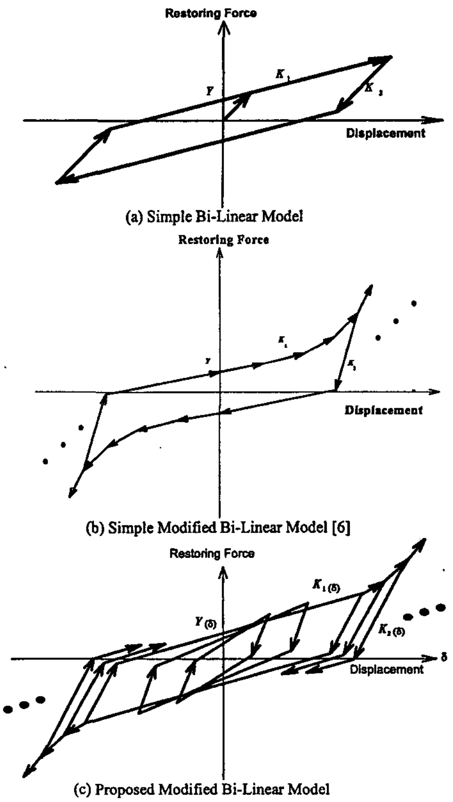


Fig. 2. Hysteretic Bi-Linear Models

valid any more to represent the detail hysteretic characteristics of the laminated rubber bearing. To consider the hardening behavior, the modified hysteretic bi-linear model has been proposed in reference [6], which is shown in Fig. 2(b). However, the changes of the yield loads and the primary stiffness lines can not considered in previous modified bi-linear model.

In this paper, as extension of the previous modified bi-linear model, the numerical model of the laminated rubber bearing using the parametric variations of the yield loads and the primary stiffness lines is proposed. Therefore, when the stiffness follows the primary stiffness line, the restoring force of the laminated rubber bearing in equation (5) can be rewritten as follows:

$$F_n(\delta)=K_n(\delta)\,\delta+Y_n(\delta)\,, \tag{8}$$

where subscript n means the nth multi-linear primary stiffness line.

In above equation (8), the primary stiffness lines, K_n and yield loads, Y_n are the functions of the maximum cyclic shear deflection, which is defined in one complete cyclic behavior. To consider the yield load variations, the following parameter equation is used.

$$Y_n(\delta)=\sum_{m=1}^{n-1} S_m\,[K_m(\delta)-K_{m+1}(\delta)]+Y_1(\delta) \qquad \text{for } n\geq 2 \tag{9}$$

In equation (9), S_m is the shear deflection for the mth point of the hardening region in Fig.2(c). The parameter equations of the stiffness lines and the yield loads can be expressed by a polynomial or any other equation forms with the maximum cyclic shear deflections. These functions can be determined based on the test results of the laminated rubber bearing.

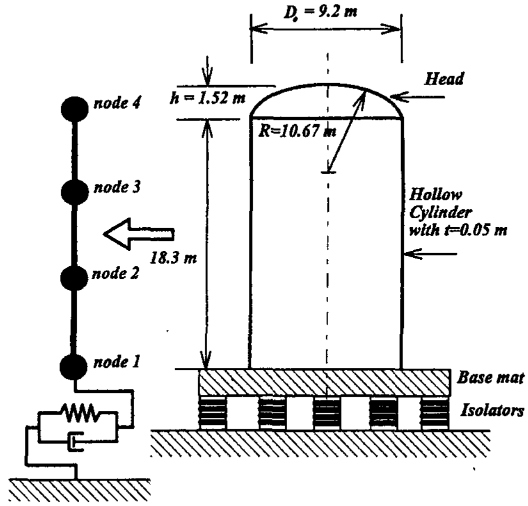


Fig. 3. Seismically Isolated Structures Used in Analysis

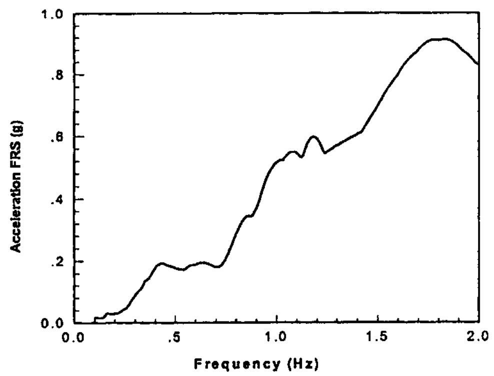
Table 1. Natural Frequencies of the Exampled Cylindrical Tank

Models	1st natural frequency	2nd natural frequency
1. Lumped mass model	14.51Hz (with head mass)	52.48 Hz
2. ANSYS 3-D model	15.17 Hz	51.03 Hz
Error between 1 and 2	4.35 %	2.84 %

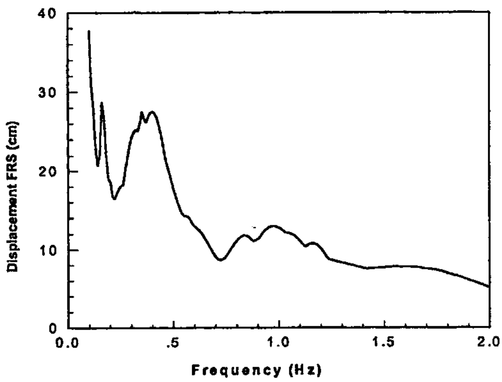
3. Examples of Application

3.1. Seismic Analysis Model

In this paper, the seismic time history analysis for a cylindrical tank is carried out. Fig. 3 shows the dimensions of the cylindrical tank and the developed seismic analysis model using the lumped mass and stiffness technique. As shown in Fig. 3, the total height of the cylindrical tank including top head is 19.82m and the thickness is 0.05m, which represents a thin shell structure similar to reactor vessel of typical LMR (Liquid Metal Reactor).



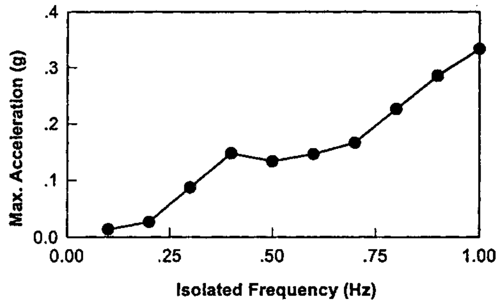
(a) Acceleration Response Spectrum



(b) Displacement Response Spectrum

Fig. 4. Response Spectrum of 1940 El Centro(NS) Input Earthquake

Table 1 shows the natural frequencies of the cylindrical tank. From table, the results for the lumped mass model are in a good agreement with those for the 3-dimensional finite element model using the ANSYS code. Therefore, the seismic analysis model is well established to represent the detailed dynamic characteristics of the cylindrical tank.



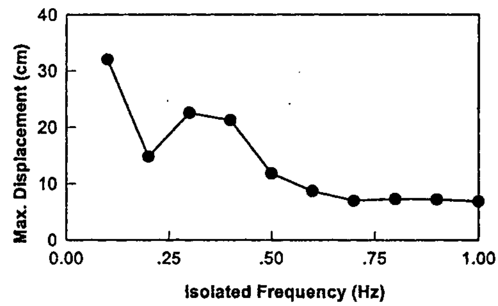
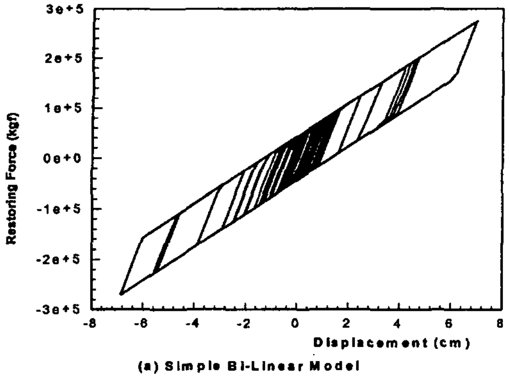


Fig. 5. Characteristics of Maximum Peak Responses Versus Isolation Frequencies

3.2. Determination of Seismic Isolation Frequency

The input ground time history used in analysis is the NS component of the 1940 El-Centro earthquake. Fig. 4 shows the response spectrum of acceleration and displacement of the input motion. In seismic isolation design, the acceleration and the displacement seismic responses are both important to determine the optimal seismic isolation frequency. As well known in a seismically isolated structure, these two responses are contrary to each other. Therefore, to find the optimal seismic isolation frequency minimizing both acceleration response and displacement response of the exampled cylindrical tank, the seismic time history analyses are carried



(a) Using Simple Hysteretic Bi-Linear Model

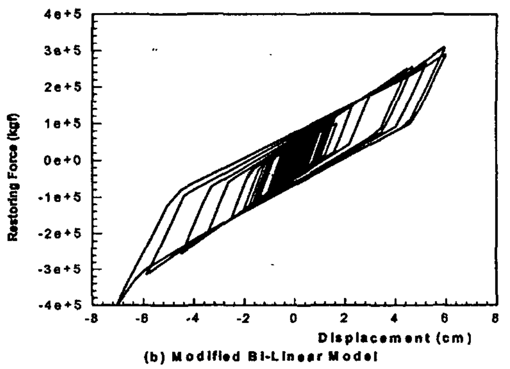
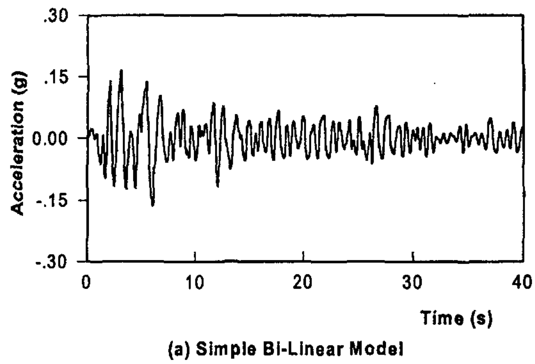


Fig. 6. Analysis Results of Non-Linear Behavior of the Laminated Rubber Bearing



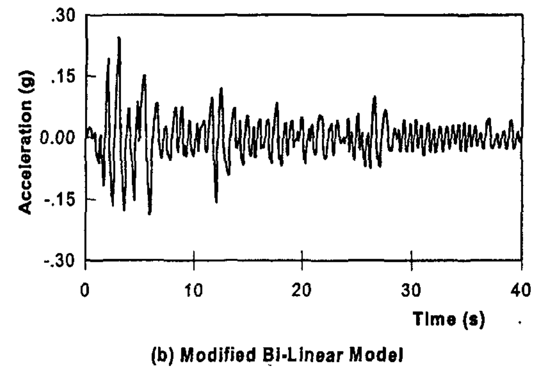


Fig. 7. Acceleration Time History Responses at Node 4

out using the simple hysteretic bi-linear model of the seismic isolator. Fig. 5 shows the maximum response spectra for each seismic isolation frequency. From these results, the optimal seismic isolation frequency can be determined as 0.7 Hz.

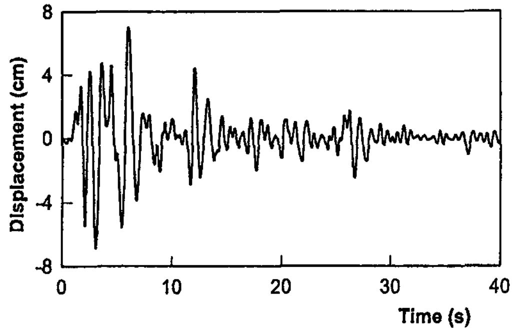
3.3. Nonlinear Seismic Time History Analysis

The nonlinear seismic time history analysis with the seismic isolation frequency, 0.7 Hz obtained from section 3.2 is carried out using both the simple hysteretic bi-linear model and the proposed modified hysteretic bi-linear model. The damping of the superstructure is assumed as 5% for all modes. The data used in simple hysteretic bi-linear model are as follows:

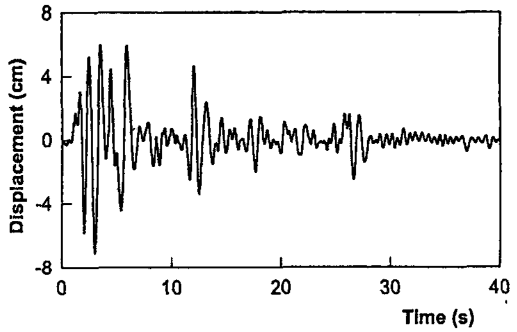
K_{s1}=3.31x10^4*kgf/cm*,
K_{s2}=1.33x10^5*kgf/cm*,
Y = 4.32x104kgf

For the modified hysteretic bi-linear model, it is assumed that this model has two hardening deflection ranges. The data used for this hardening model are as follow:

$K_{m1} = K_{s1}$, for $0.00cm \le S \le 4.57cm$
$K_{m1} = 1.2K_{s1}$, for $4.57cm \le S \le 6.10cm$
$K_{m1} = 2.5K_{s1}$, for $6.10cm \le S$



(a) Simple Bi-Linear Model



(b) Modified Bi-Linear Model

Fig. 8. Displacement Time History Responses at Node 4

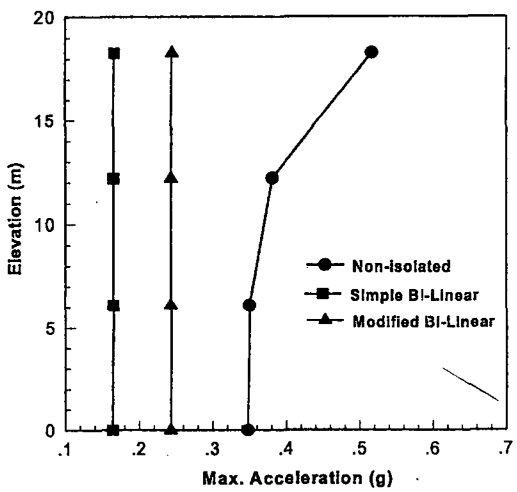


Fig. 9. Distribution of the Maximum Peak Acceleration

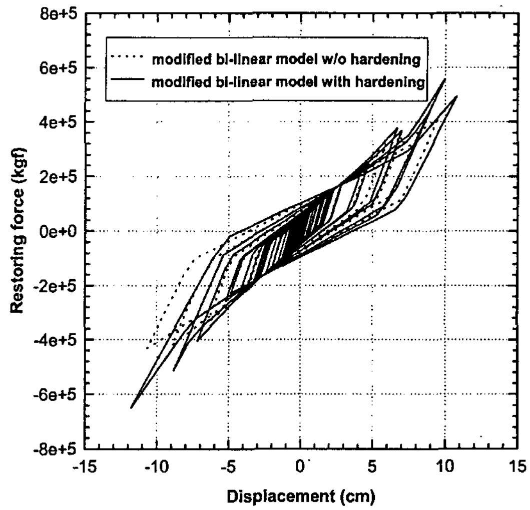


Fig. 10. Hysteratic Responses of Laminated Rubber Bearing (1940 El-Centro NS, 0.53g)

For comparison with the simple hysteretic bi-linear model, the secondary stiffness line, K_{m2} is modeled with the same value as that of the simple hysteretic bi-linear model.

For the parametric variation of stiffness lines and yield loads, the following models are used for examples.

$$\text{Yield Load}: Y = Y'(1.0 + |\delta|)$$
$$\text{Primary Stiffness Line}: K_1 = K'_1(1.0 - |\delta|)$$
$$\text{Secondary Stiffness Line}: K_2 = K'_2(1.0 - |\delta|)$$

where superscript (') means the constant values for zero shear deflection of the laminated rubber bearing. The unit of shear deflection in above parameter equations is meter.

Fig. 6 shows the hysteretic responses of the laminated rubber bearing for the 1940 El Centro (NS) input earthquake. From these results, the modified hysteretic bi-linear model has the similar behavior to that of the simple hysteretic by-linear model in global hysteretic motion but shows larger restoring forces in large deflections than those of simple hysteretic bi-linear model. This is due to the hardening model used in larger deflection regions.

Fig. 7 shows the acceleration time history responses at node 4, i.e. top head. In this result, the two models show similar waveforms but the maximum acceleration obtained using the modified hysteretic bi-linear model is slightly larger than the result obtained using the simple hysteretic bi-linear model. Fig. 8 shows the displacement time history responses at node 4. The waveforms and peak levels of displacement responses for both models are very similar.

Fig. 9 shows the distribution of the maximum accelerations along the height of the cylindrical tank. From these results, we can see that the seismic acceleration responses of seismically isolated system are significantly reduced than those of non-isolated system and this system has almost no acceleration response amplifications. And the modified hysteretic bi-linear model gives more conservative results than simple hysteretic bi-linear model.

For substantiating the proposed model, the comparison of response results obtained by using the previous modified model in ref. [6] and the proposed model is carried out. Fig. 10 shows the hysteretic responses of the laminated rubber bearing. In figure, we can see that the response prediction of the laminated rubber bearing using the proposed model gives more similar hysteretic behavior compared with actual test results shown in Fig.1 than model of ref. [6].

4. Conclusions

The laminated rubber bearing is widely used as a very useful device to reduce the seismic responses. To design the seismic isolation structure, a new numerical analysis model for the laminated rubber bearing has been proposed. The proposed numerical analysis model can consider the change of yield loads and the stiffness lines, as well as the hardening behavior in large shear deflection regions with cycling. Applications of the proposed model show comparable displacement responses but the larger peak acceleration responses than those of simple hysteretic bi-linear model. From the result, it is suggested to take into account the changes of mechanical characteristics of the laminated rubber bearing in design of seismically isolated structures because the larger computed acceleration would lead to the more conservative design.

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