Evaluation of mechanical properties considering hysteresis characteristic of high damping rubber bearing

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Abstract. Recently, laminated rubber bearings are widely used as seismic isolators for road bridges. Although many studies have been conducted on the dynamic model of High Damping Rubber (HDR) bearings, few models can reflect phenomena such as the dependency of experienced shear strain on initial history. To develop a model that can represent the dependency of the experienced shear strain of HDR and a dynamic loading test was conducted using HDR specimens. The hysteresis characteristics of HDR was measured by applying a horizontal vibration using a hybrid actuator under a constant vertical load. Based on the cyclic shear test, the mechanical properties of HDR were calculated such as absorbed energy, hysteresis loop area, equivalent stiffness, equivalent damping ratio. Dynamic analysis was also performed from the experimental results. The dynamic model applied in program analysis is a bilinear type double-target model. This model can express the nonlinear characteristics related to the initial history of HDR bearings. The parameters required for dynamic analysis were determined from the experimental results. Through this dynamic analysis, the effectiveness of the bilinear type double target model was verified. In this research, a high damping rubber specimen was used.

Keywords: base-isolation, bilinear model, high damping rubber, cyclic shear test.

1. Introduction

Since the development of laminated rubber, it began to be used as a seismic isolator in areas affected by earthquakes. The use of HDR bearings as one of the seismic isolation devices, was rapidly introduced after the 1995 Hyogo-ken-Nanbu Earthquake in Japan. In particular, the introduction of laminated rubber for seismic isolation design in the structure of road bridges, which had been severely damaged, attracted attention [1, 6]. HDR bearings have a great damping performance by mixing natural rubber and black carbon filler. These bearings are designed to be able to act as a bearing and seismic isolator without additional dampers or devices. Besides, the structure of HDR bearings are simple and have large cost advantages in terms of construction and maintenance.

HDR bearings have certain features in common, the most important of which are the energy dissipation capacity and horizontal flexibility. However, the material properties of HDR bearings have not been clarified and its dynamic behaviour is not completely understood because of a number of dependencies [18].

HDR has several dependencies because it is made by mixing rubber and carbon filler. Among the various dependencies, this study focused on the dependence of the maximum experienced shear strain. Despite numerous studies on HDR, studies on the dependence of HDR remain. Accurate analysis and research of this dependency is required for the HDR bearings to be widely used in the design of structures and isolation system. Therefore, in this research, the dynamic property of HDR was investigated through a dynamic loading test. And dynamic analysis using commercial structural analysis software developed by ARK Information Systems, INC. was performed. From the results obtained through the experiment, the effect of this dependency on HDR was confirmed. In addition, we propose a model called bilinear double target that reflects the characteristics of the initial hysteresis
characteristics. Currently, a bilinear model is mainly used as a model representing the hysteresis characteristics of laminated rubber. However, this model has limitations in that it cannot represent the dependence of HDR and the characteristics of the initial history. It is expected to more accurately understand the characteristics of HDR by proposing a modified bilinear model. In addition, there are many models that represent the hysteresis curve of HDR along with the bilinear model, but these models have a large number of parameters and are complex. In order to apply to actual design, a model that anyone can easily access is needed. In addition, objective rules for setting model parameters were established. This makes it possible to set more objective parameters and anyone will get the same result. Finally, dynamic analysis is performed through the parameters set in the experimental data. The degree of agreement between the experimental results and the results of the dynamic analysis using the bilinear double target model was analysed [18].

Many studies on the properties of HDR bearings performed through a lot of experiments and several dynamic models considering the dependency of experienced shear strain of HDR have been proposed so far. Ohtori (1995) suggested the improved double-target model that can consider the change of rigidity due to the maximum shear strain [2]. This model is characterized by dividing the skeleton curve into the initial skeleton curve and the normal skeleton curve. Takenaka (2001) proposed the HD model, which is a modified model of the bilinear model [4]. Yoshida (2014) proposed a model that can reflect the hardening phenomenon that appears in HDR bearings through experiments. Mazda (2016) suggested the bilinear type double-target model used in this dynamic analysis [14]. This model is a modification of the improved double-target model proposed by Ohtori (1995) [2]. In order to make the model easier to apply, the parameters have been simplified. And the properties of HDR have been shown more easily than other models [16]. In addition, the feasibility of this model was verified through a double lap shear test type.

In this research, an experiment was performed in which shear strain was applied under constant vertical load. Based on the results of this experiment, the validity of the bilinear type double target model was studied.

2. Experimental procedures

1.1. Cyclic shear test of HDR bearing

1.1.1. Material. The configuration of the HDR bearing used in the test is shown in figure 1. HDR specimen used in the dynamic loading test was manufactured by Yokohama Rubber Co., Ltd. In order to be able to confirm the dependency, an HDR specimen that has never been used was prepared [6, 13]. The cross-section of the HDR specimen is 110mm × 110mm, and the total thickness of high damping rubber layers is 16 mm. The thickness of the seal plate, reinforcing steel plate, rubber layer is 25mm, 2.3mm, 4mm respectively [7, 11]. The shear modulus of rubber is 0.8N/mm².

![Figure 1. HDR specimen configuration (unit: mm).](image-url)
1.1.2. Testing Apparatus. The apparatus used in the test is presented in Figure 2. The vertical load capacity of the oil pressure is 60kN, and the horizontal load capacity is 20kN. The maximum piston stroke of the hybrid actuator is ±400 mm. The 20kN hybrid actuator was used to assign the displacement to the system [18]. This actuator has a built-in load cell to measure the vertical force that the HDR specimen receives from the oil pressure. Before the dynamic loading test, the top and bottom seal plates of specimen were bolted onto the top and bottom loading plates of the test device, respectively. After imposing the vertical force using oil pressure, loading tests would be performed by the movement of the hybrid actuator. During the test, the displacement and the shear force of HDR specimen were measured. Since HDR has a dependence that appears according to temperature, a heater was used to prevent temperature change. During the experiment, the surface temperature of HDR was kept constant at 22 degrees.

![Figure 2. Test set-up: cyclic shear test.](a) Hybrid actuator (b) HDR specimen (c) Oil pressure)

1.1.3. Experiment methods. This experiment was conducted following ISO22762-1: Elastomeric seismic protection isolators – Part1: Test methods (2010) [5]. An experimental program was planned to evaluate both engineering properties and impact of dependency as shown in Table 1 [9, 12]. The loading displacements are presented in Figure 3 [7]. The loading plan was established to confirm the dependency of experienced shear strain at a fixed frequency. The frequency of sinusoidal input waves 0.5Hz is kept for all steps. The test was divided into four steps. As each step progressed, the shear strain was gradually set larger. The reason for setting this pattern is to confirm the mechanical properties and test results that depend on the experienced shear strain of the HDR specimen. In step 1, the shear strain increases the shear strain from 50% to 100%. In step 2, the amplitude of shear strain is 50% once more, to measure the displacement of the specimen that has already experienced 100% shear strain. This is a loading plan to examine the characteristics of the hysteresis that appears when a specimen that has already experienced a large shear deformation has a small deformation later [12].

| Table 1. The Loading Plan of Test |
|----------------------------------|
| **Frequencies(0.5Hz)** | **Shear strain (displacement)** |
| STEP1 | 50%(8mm) | 100%(16mm) |
| STEP2 | 50%(8mm) | 150%(24mm) |
| STEP3 | 50%(8mm) | 100%(16mm) | 200%(32mm) |
| STEP4 | 50%(8mm) | 100%(16mm) | 150%(24mm) | 250%(40mm) |
1.2. Dynamic analysis

1.2.1. Analysis condition. Analysis condition of dynamic analysis is shown in figure 4. The analytical model of the 1-mass system is shown in figure 4 (a) [1, 16]. This system is simplified by a one-degree of freedom system for dynamic program analysis purpose. The model considered consists of a mass $m$ and HDR bearing. The adequacy of the bilinear type double-target model has been checked in predicting the mechanical behaviour of the HDR specimen. From the results of the test, a dynamic program analysis of the HDR was performed by TDAP3. This software is a commercial structural analysis program developed by ARK Information Systems, INC. As an analysis model of HDR, a bilinear type double-target model was used. The model used in this research is presented in figure 4 (b) [16, 17]. This model is defined by two skeleton curves reflecting the initial history [3]. This model is characterized by dividing the skeleton curve into two as shown in figure 4 (b). Therefore, it is a model that can reflect the behaviour of the initial history of the HDR. In this research, program analysis was performed using values obtained from experimental results [20]. Several models so far have required complex parameter settings. However, this model reduced the complexity of parameter setting to make analysis easier.

1.2.2. Modeling procedure. To represent the nonlinearity of HDR, we used a bilinear double target model defined by two skeletal curves independent of them. Each parameter was set by the following procedure. The values of the experimental data were read to set objective parameters. Since the values show a similar tendency after first cycle, the component representing the initial hysteresis curve was set as the experimental value of first cycle, and the subsequent hysteresis curve was set equal to the experimental value of second cycles.

1) The first rigidity (G0) of the initial curve is determined by connecting the origin with the 15% point of the shear strain for 1cycle.

2) The second rigidity (G1) of the initial curve is determined by connecting the point of 15% of shear strain for 1cycle and the point of maximum load.
3) The second rigidity (G2) of the steady curve is determined by connecting the point of 15% of shear strain for 2cycle and the point of maximum load.

4) The unloading rigidity (G5) is determined by connecting the point of maximum displacement of 1cycle and the point of 90% of shear strain.

5) Intercept stress (td1, td2) are determined by the load at the end of each cycle.

3. Experimental result

3.1. Cyclic Shear Test of HDR Bearing

The experimental hysteresis loops of cyclic shear test of HDR are shown in figure 5 [7]. The obtained curve represented a nonlinear behavior during dynamic loading test. In this cyclic shear test, experienced shear strain dependency of HDR is clearly observed in all steps. The difference between the mechanical response of the first cycle and the following cycles is confirmed [8]. The reason is that the mechanical properties are almost identical for the shear strains already experienced due to the dependency of experienced shear strain of HDR. Therefore, it has been experimentally proved that rubber is dependent on experienced shear strain. Above 200% of shear strain, the hardening of the high damping rubber is also observed [20].

In this research, the mechanical properties of HDR specimen were evaluated by calculating equivalent stiffness and equivalent damping ratio [3]. The mechanical properties of HDR bearing are presented more clearly by comparing these parameters. When calculating the parameters, the friction force generated from the experimental device was considered. This friction force is defined as $f$. During the experiment, a friction occurred between the actuator and the sliding bed and was observed from the test results. Although this frictional force is slightly different each other, it was unified to an average value of 0.5kN for convenience of calculation. The equivalent stiffness $K_{eq}$ [3, 7] is calculated by equation (1):

$$K_{eq} = \frac{F_{\text{max}} - F_{\text{min}} - 2f}{\delta_{\text{max}} - \delta_{\text{min}}}$$

where $F_{\text{max}}$ and $F_{\text{min}}$ are the maximum and minimum restoring force; $\delta_{\text{max}}$ and $\delta_{\text{min}}$ are the corresponding displacements at $F_{\text{max}}$ and $F_{\text{min}}$ respectively. The equivalent damping ratio $H_{eq}$ [7, 17] is calculated by equation (2):

$$H_{eq} = \frac{1}{4\pi} \left( \frac{\Delta W'}{W} \right)$$

$$\Delta W' = \Delta W - 4fD$$

where $\Delta W'$ is the value excluding the frictional force generated in the experimental devices. The parameter $D$ is average value of $\delta_{\text{max}}$ and $\delta_{\text{min}}$. The elastic strain energy $W$ is calculated by equation (4). This value is the shear energy absorbed by the specimen.

$$W = \frac{1}{2} K_{eq} D^2$$
where $K_{eq}$ is the equivalent stiffness calculated in equation (1).

In all cases listed in table 2, it can be seen that the values in first cycle are larger than the values in second cycle. In addition, even with the same shear strain, it can be seen that the mechanical properties differ depending on whether they have been experienced in the past. In other words, it can be predicted that when the same shear deformation is given to HDRs in the virgin state and the same HDR that has experienced the shear deformation once, different results will be obtained. The comparisons for first cycle and second cycle of each calculated parameter for 50% shear strain are shown in figure 6 [7]. It was confirmed that the value of equivalent stiffness decreased by 35% in step2 from step1 due to the influence of the dependency, and since then, almost the same value was calculated [15]. Therefore, it was confirmed that the dependency of experienced shear strain only affected the initial history. In the result of the equivalent damping ratio, the value decreased by 25%, but after that, it was confirmed that it increased. Compared to the experimental results, it was confirmed that the characteristics of the initial history of HDR were well shown [9, 15].

| Shear strain (50%) | Elastic strain energy $W$ (kJ/mm) | Hysteresis loop $\Delta W'$ (kJ/mm) | Equivalent stiffness $K_{eq}$ (kN/mm) | Equivalent damping ratio $H_{eq}$ |
|--------------------|-----------------------------------|------------------------------------|-------------------------------------|----------------------------------|
|                    | 1Cycle   | 2Cycle   | 1Cycle   | 2Cycle   | 1Cycle   | 2Cycle   | 1Cycle   | 2Cycle   |
| STEP1              | 56.257   | 47.446   | 140.447  | 95.332   | 2.052    | 1.691    | 0.199    | 0.16     |
| STEP2              | 38.247   | 34.59    | 71.676   | 56.831   | 1.321    | 1.185    | 0.149    | 0.131    |
| STEP3              | 35.375   | 31.925   | 67.443   | 52.342   | 1.223    | 1.09     | 0.152    | 0.13     |
| STEP4              | 36.928   | 33.089   | 79.214   | 62.676   | 1.275    | 1.131    | 0.171    | 0.151    |

Figure 6. The Result of Elastic strain energy, Hysteresis loop, Equivalent stiffness and Equivalent damping ratio for each step (50% shear strain).

3.2. Comparison of the bilinear type double target model with test results

The hysteresis loops obtained from test results and program analysis results are shown in figure 7. The parameters were set from the test results. As a result, the mechanical properties of the high damping rubber were well reflected due to the parameters for the initial history considered for each case. Up to 150% shear deformation, the experimental and analysis results tend to agree well. However, it can be confirmed from the experimental results that a hardening phenomenon occurs in HDR when shear deformation of more than 200% occurs. Since the effect of hardening was not considered in this analysis, there was a difference between the experimental value and the analysis value in the shear strain of more than 200%.
4. Conclusions
In this paper, cyclic shear test with HDR specimen was carried out to understand the property of HDR and dynamic analysis was performed using the bilinear type double target model based on the test results. The engineering characteristics of HDR were evaluated. Based on the experimental result presented in this paper, the main conclusions are as follows:

1. From the cyclic shear test, the dependence of HDR on the experienced shear strain has been confirmed experimentally. A clear difference was found between first and second cycle at any shear strain.
2. It is clear that the dynamic characteristics of HDR are also that the value of first cycle is greater than the value of second cycle. In addition, it can be seen that the results vary according to the experience or not even at the same shear strain.
3. As a result of performing dynamic analysis of HDR through an objective parameter setting process, the trend was consistent when compared with the experimental results. However, it is necessary to set the parameters of the model in consideration of the hardening phenomenon occurring at high shear strain.
4. The results of the study show that the model can simulate the behavior of experienced shear strain dependency. In particular, the characteristics of the initial history of high damping rubber are well represented. The conclusions obtained as shown below.

In this research, the dynamic characteristics and dependence of HDR were confirmed through dynamic loading test, and the results of program analysis using a bilinear type double target model were confirmed.

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