Bi-Directional Experimental Hybrid Simulations of Elastomeric Isolation Bearings for Validation of Hysteretic Modeling

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SUMMARY:
Although structural responses can result in some failures as a the consequence of three-dimensional response such as coupled bi-directional inelastic response effects, current seismic performance design approaches for isolated bridges only stipulated requirements and analysis methods from past experimental results of elastomeric bearings subjected to uni-directional loading under constant vertical pressure. This study discusses hysteretic and seismic response behaviour of high damping rubber (HDR) bearings under multi-directional loading histories and earthquake excitations, and the validity of several easy-to-implement nonlinear numerical models, such as bi-linear hysteretic SDOF model and Multiple-Shearing-Spring (MSS) model. Square shape laminated rubber bearing specimens made of HDR-S which is a type of HDR are used in uni- and bi-directional quasi-static loading tests as well as hybrid simulation (pseudo-dynamic) tests. The validity of these major nonlinear dynamic analysis models in simulating the seismic response of rubber bearings with hysteretic damping is also evaluated by comparing the results of tests with that of simulations.

Keywords: High damping rubber bearing, bi-directional loading, hybrid simulation, numerical model

1. INTRODUCTIONS

The current seismic performance evaluations and design for isolated bridges, as well as those of other structures, are usually performed based on uni-directional nonlinear dynamic analysis approach, in which seismic response simulation in time domain and capacity check in one horizontal direction under constant vertical loading are conducted for design earthquakes. Accordingly, the hysteretic restoring force characteristics of the isolators used in the bridge design practice are specified and identified mostly from test data under uni-directional loading condition.

The over-simplification of these approaches may lead to failure to capture some significant features of the actual three-dimensional seismic response of structures. Although design provisions account for the safety margins for the bi-directional nature of the structural response due to seismic excitation, as well as bridge design can be checked by nonlinear numerical time history analysis, it is obvious that the validity of the numerical model to represent the nonlinear behaviour of isolators under bi-directional excitation greatly affects the reliability of the predicted response of the isolated bridge.

In the recent decade, considerable number of newly constructed or retrofitted highway bridges have extensively been designed as isolated bridge to enhance their seismic performance and safety. The bi-directional seismic isolation mechanism concept has also been increasingly adopted in these designs, promoting the study on the validity of the analysis methods in performance evaluation under bi-directional seismic action.

It has been reported in past research findings (Iwata, 1998; Yamamoto, 2009 and Kato, 2010) that the hysteretic restoring force of rubber bearings with hysteretic damping, such as that of HDR (high damping rubber bearing) or LRB (rubber bearing with lead plugs), show significant disagreement under bi-directional loading with those under unidirectional loading conditions. Especially, Iwata et al. (1998) conducted a few valuable bi-directional hybrid loading tests of circular shape HDR bearing under minor earthquakes (about half of the 1995 Kobe Earthquake in terms of PGA) in order to assure the seismic safety of an isolated pedestrian bridge. Tests results revealed that under bi-directional horizontal seismic excitation, the hysteretic curves of HDR bearings exhibited complicated behaviours such as partial hardening of tangent stiffness, pinching of hysteretic loops and rounded hysteretic shapes before and after unloading. Although in-depth finding is preferable, further detailed loading test for square shape HDR rubber bearings under severe bi-directional seismic excitation of high intensity level, or efforts in considering efficient numerical method, which can provide validity explanation and resolution for these bi-directional loading behaviours, were left as a future work.

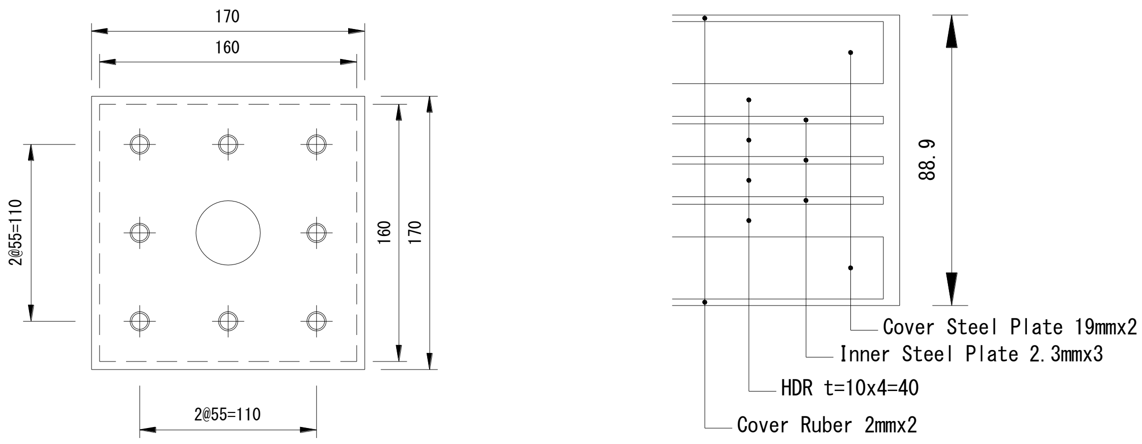
In this study, validity of the bi-directional hysteretic restoring force models for elastomeric bearings used for bridge structures is investigated by using the experimental technique of the hybrid simulation, focusing on the evaluation of bi-directional response of the elastomeric bearing and the bridge. A hybrid simulation test system with bi-directional loading of elastomeric bearings is developed, and a series of hybrid simulations are conducted to clarify the restoring force-shear displacement relationship and performance of the isolators for bi-directional horizontal earthquake excitation under constant vertical force. The elastomeric bearings tested in the hybrid simulation are high damping rubber bearings (HDR-S); several sets of earthquake acceleration inputs used as reference in bridge design in Japan are used in the hybrid simulations for unidirectional and bi-directional loading conditions.The test results are compared with predicted seismic response of the isolated bridges obtained by time history analysis using typical unidirectional and bi-directional isolator modeling techniques, namely bilinear model, multiple shear spring (MSS) model and Park's model (Park et al., 1986). The validity of these analytical models for seismic response design of isolated bridges under bi-directional horizontal seismic excitations is discussed.

2. UNI- AND BI-DIRECTIONAL LOADING TESTS

Four types of loading tests, uni-directional cyclic quasi-static loading, bi-directional quasi-static loading, uni-directional hybrid simulation (pseudo-dynamic) tests and bi- directional hybrid simulation are conducted in this study. The bearing specimen, loading system, test programme and test results o are described in this chapter.

2.1. Test specimens

Two rubber bearing specimens made of G10 grade HDR-S (a type of high-damping rubber) with shearing modulus G=1.0 N/mm are employed in this study. The plan view and cross-section in elevation are shown in Fig. 1.



(a) Plan view (b) cross-section in elevation

Figure 1. Plan view and cross-section in elevation of rubber bearing specimen

The shape of the bearings is square with plan dimensions of 160mm×160mm. The total HDR-S rubber layer thickness is 40mm.

2.2. Loading system

The quasi-static and substructure hybrid loading tests are conducted by the three-dimensional six-degree-of-freedom loading system shown in Fig. 2. The loading system includes five actuators in Z direction, three actuators in Y direction and one actuator in X direction. All actuators are pin connected between the fixed reaction frame and the rigid loading block. The specimen, as can be seen in the same figure, is clamped between the reaction beam and the rigid loading block by loading constant vertical pressure by the vertical actuator during the horizontal loadings in X and Ydirections.

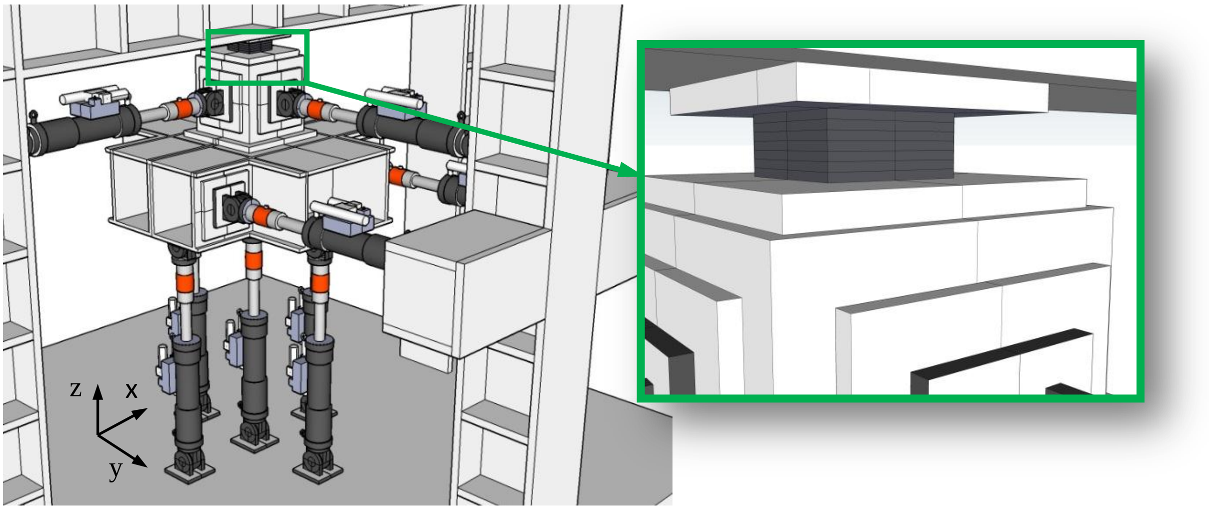


Figure 2. Loading system

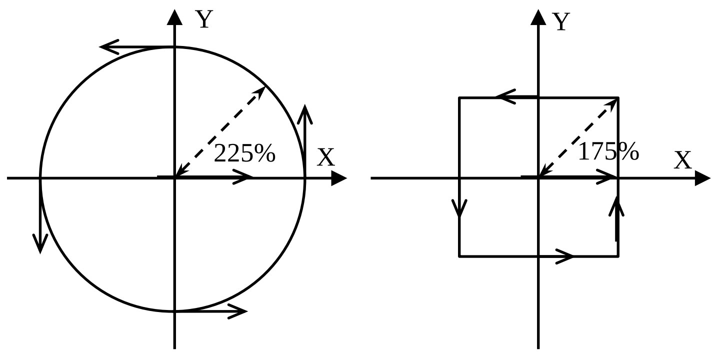
During the loading tests, the horizontal actuators in X and Y directions are controlled by displacement targets, and the vertical actuator is controlled by constant load target according to the constant pressure of the bearing specimens. Displacement and load errors due to the tilt angles of the actuators caused by the displacement of the rigid block are corrected during the load measurement and displacement control to assure the accomplished bi-directional displacements. In particular, the horizontal force measurements are corrected considering the horizontal components of tilted vertical actuator, although the small error of vertical pressure was ignored.

2.3. Test programs of quasi-static tests and hybrid simulations (pseudo-dynamic tests)

Two types of uni-directional quasi-static tests (orthogonal direction loading and oblique direction loading) and two types of bi-directional quasi-static tests (circular path loading and square path loading) were conducted in this study.

In the orthogonal uni-directional loading tests, cyclic loading target displacement values 10 mm, 20 mm, 40 mm, 60 mm and 70 mm corresponding to the shear strains of 25%, 50%, 100%, 150% and 175% were applied to the specimens in X, Y directions and in 45-degree direction in the oblique direction loading test. In the circular path bi-directional loading test, the specimen was loaded to 70 mm (175%) in X direction and loaded along a circle displacement path with radius of 70mm (175%) shown in Fig. 3(a). In the square path loading, the specimen was subjected to a square shaped displacement path with the side length of 106 mm, so that the largest deformation during the test is 70 mm (175%) in oblique direction as shown in Fig. 3(b).

A two DOF system with a single mass was employed to simulate the seismic response time history of the isolated structure subjected to two-directional horizontal ground motion excitations. Hybrid simulations incorporating uni- and bi-directional loadings of the HDR-S bearing specimens considered as 1/5 scaled elastomeric isolation bearings were conducted to look into the seismic response behavior of isolated bridges. The test program of the hybrid simulations is listed in Table 3.1. Four uni-directional and 2 bi-directional loading hybrid simulations were conducted using the bi-directional components (NS and EW) of Japan Meteorological Agency (JMA) and Japan Railway Takatori-station (JRT) records of the 1995 Kobe Earthquake as the input ground motions. The mass and initial elastic stiffness of the simulation model are determined from the constant vertical load corresponding to the compression of 6 MPa and the elastic stiffness of the bearing specimens with the consideration of the scale factor 1:5 and similitude.



(a) Circular track loading (b) Square track loading

Figure 3. Bi-directional loading tracks

Table 3.1. Program for hybrid simulations (10 pt regular)

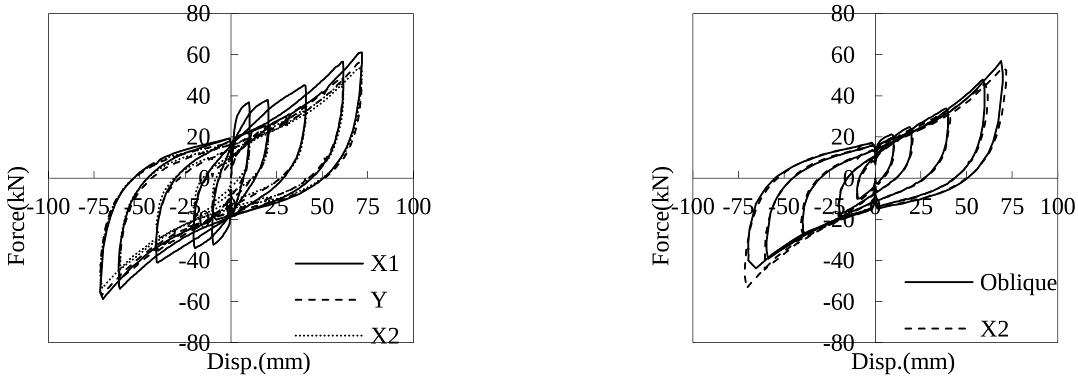
Test Name	Loading method	Input Earthquake	Ground Types	PGA (gal)
H1D-JMA-NS	Uni-directional loading	JMA	I (Hard Ground)	821
H1D-JMA-EW				598
H1D-JRT-NS		JRT	II (Moderate Ground)	611
H1D-JRT-EW				615
H2D-JMA	Bi-directional loading	JMA	I (Hard Ground)	821
H2D-JRT		JRT	II (Moderate Ground)	615

2.4. Test result of uni-directional cyclic loadings

The first specimen was used for the sequence of four uni-directional loading tests: (1) X direction loading; (2) Y direction loading; (3) 45-degree oblique direction loading and (4) X direction loading. The loading in the X direction was conducted twice to confirm the degradation effects due to the virgin cyclic loading as shown in Figs. 4(a) and (b). The first of all loading (X1) shows larger restoring force than the others, and this virgin loading affected both hysteretic curves of the second X direction loading (X2) and the Y direction loading (Y), as can be seen in Fig. 4(a). Hysteresis curve obtained by 45-degree oblique direction loading shows an agreement with that in X direction loading (X2), hence the horizontal shear behaviour of HDR-S bearings can be considered as isotropic.

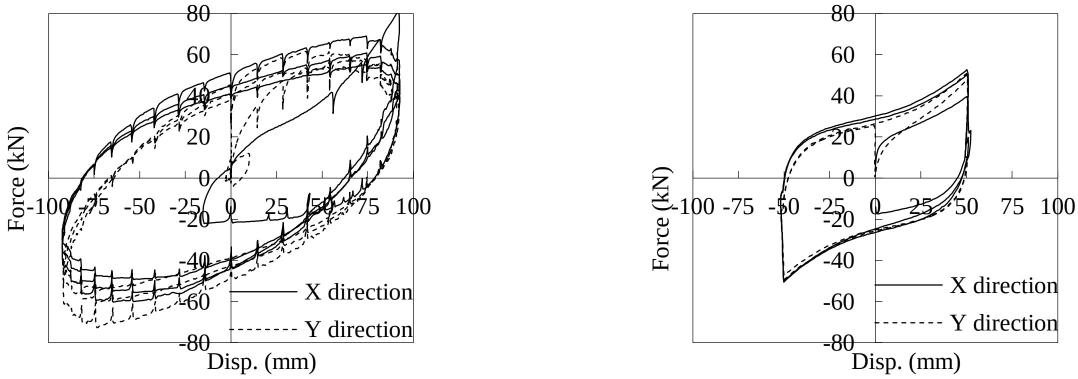
2.5. Test result of bi-directional circular and square path loadings

The hysteretic force-deformation relations of the specimens subjected to the circular and square displacement paths are shown in Figs. 5(a) and (b), respectively. Both specimens for these two tests were preloaded to eliminate the virgin loading effect. Swelling effects can be observed from these figures by comparing that of uni-directional loading. A smooth rounded shape appears in the hysteretic curve due to circular loading. The load of hysteretic curves due to bi-directional loading at zero displacement is greater than that of uni-directional loading. These features appear due to the contribution of the interactive hardening effect of the two orthogonal components of the bi-directional loading.



(a) Loading in X and Y directions (b) Loading in orthogonal and oblique directions

Figure 4. Hysteretic force-displacement relationship by uni-directional loading



(a) Circular path loading (b) Square path loading

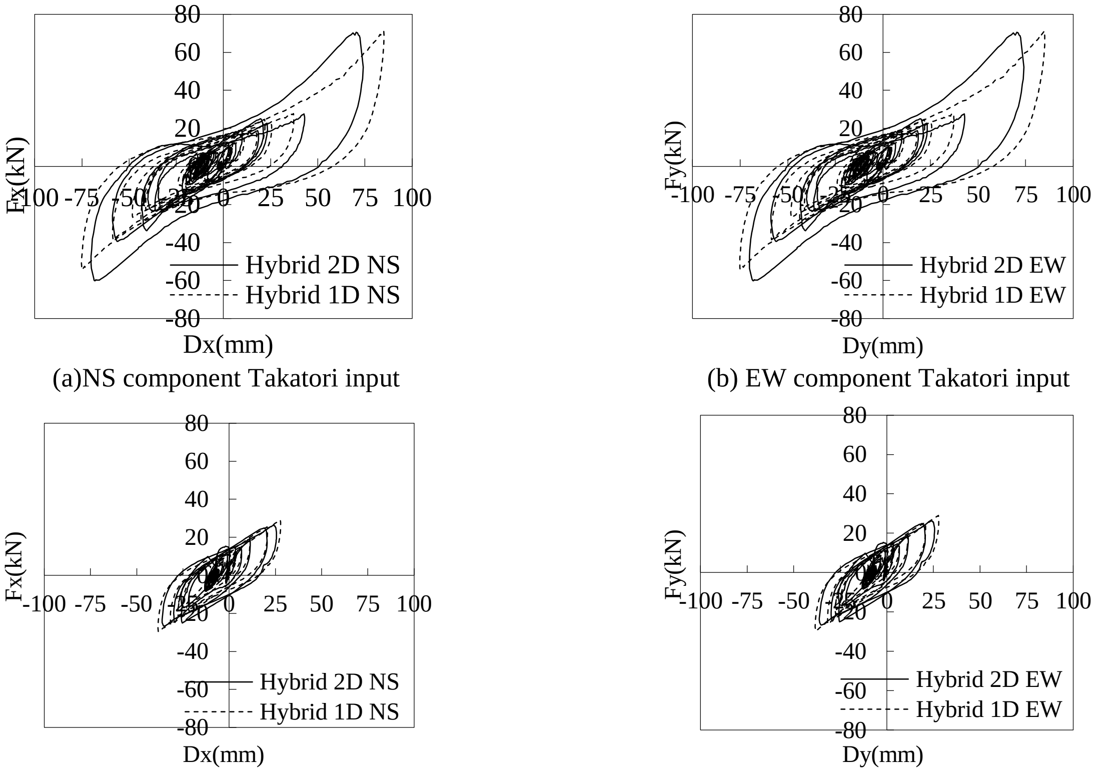
Figure 5. Hysteretic force-displacement relationship by bi-directional loading

2.6. Result of uni- and bi-directional hybrid loading tests

The responses obtained from the uni- and bi-directional loading hybrid simulations of isolated bridges under JMA and Takatori excitations are shown in Figs. 6 (a)~(d), in which solid and broken lines correspond to bi- and uni-directional loading, respectively. The hysteretic curves due to bi-directional loading indicates the onset of hardening effect at a smaller displacement than that due to uni-directional loadings, as a consequence of larger shearing strain caused by the combination of deformation of the elastomeric bearing in both directions. This difference has not been observed in the result of hybrid simulation using JMA record input, as the response to this ground motion is too small to lead to hardening.

3. NUMERICAL ANALYSIS OF HDR BEARINGS UNDER BI-DIRECTIONAL LOADING

Numerical models intended for use in design of new structures or in evaluation of existing structures are usually required to be efficient as well as effective. Three representative simple numerical models, namely the bilinear hysteretic model, the bilinear type MSS model and bi-directional hysteretic model proposed by Park et al. (1986) are used to obtain the hysteretic response subjected to bi-directional displacement paths and nonlinear seismic response under bi-directional earthquake excitations. Their validity in evaluating seismic response of isolated bridges under bi-directional excitation is discussed by comparing the calculated response with the test results.



(a)NS component Takatori input

(b) EW component Takatori input

(c)NS component JMA Kobe input

(d) EW component JMA Kobe input

Figure 6. Hysteretic force-displacement relationship obtained by hybrid simulations

3.1. Description of numerical models

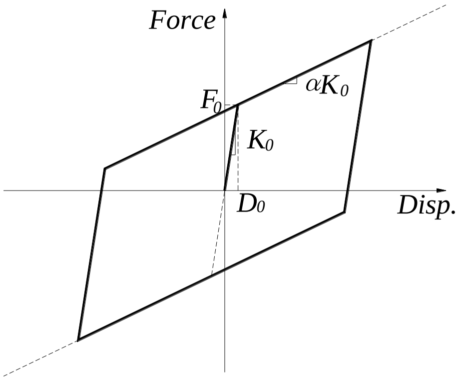
3.1.1 Bilinear hysteretic model

The bilinear model, as shown in Fig. 7(a), is a standard nonlinear hysteretic model for Lead Rubber Bearings (LRB) or HDR bearings specified in the current highway bridge design code in Japan (Japan Road Association, 2002.a, 2002.b). Key parameters, yield displacement δ_0, elastic stiffness K_0 and post-yield stiffness ratio α are determined from the result of quasi-static test X2 shown in Fig.4. The identified values are δ_0=3.5 mm, K_0=6 kN/mm and α=0.081.

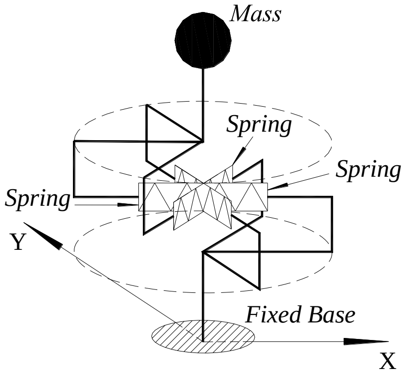
3.1.2 MSS model

MSS model has been frequently utilized in numerical analysis for three-dimensional seismic response of structures (Wata etc., 1985). Schematics of MSS model are shown in Fig. 7(b). This model consists of multiple horizontally distributed shearing springs with an identical hysteretic character, which is the bilinear model in this study, and with an equiangular layout. The deformation of each spring i, denoted by d_i, under bi-directional displacement δ_x and δ_y can be found by its orientation angle with respect to the X axis, and expressed by Eqn. 3.1. The nonlinear spring force f_i is calculated according to a bilinear type hysteretic spring force-deformation relation defined by the key parameters d_0, k_0 and α similar to the bilinear hysteretic model, so that the bi-directional horizontal restoring force of the two-dimensional system F_x and F_y can be determined by integrating the spring forces of all springs in X and Y directions as expressed by Eqns. 3.2 and 3.3. The three key parameters d_0, k_0 and α are determined so that the resulting MSS model and the corresponding bilinear hysteretic model share the identical yield displacement, initial stiffness and post-yield stiffness ratio under uniaxial loading. The yield spring deformation d_0 and elastic spring stiffness k_0 are calculated from Eqns. 3.4 and 3.5, respectively.

$$d_i = \cos\theta_i\, \delta_x + \sin\theta_i\, \delta_y \tag{3.1}$$
$$F_x = \sum \cos\theta_i\, f_i \tag{3.2}$$
$$F_y = \sum \sin\theta_i\, f_i \tag{3.3}$$
$$k_0 = K_0 / \sum \cos^2\theta_i \tag{3.4}$$
$$d_0 = \delta_0 \sum \cos^2\theta_i \,/ \sum \cos\theta_i \tag{3.5}$$



(a)Bilinear Model



(b) MSS Model

Figure 7. Hysteretic force-displacement relationship by hybrid simulations

3.1.3 Park's model

Park et al (1986) proposed a two-dimensional hysteretic model based the one-dimensional SDOF model proposed by Wen et al (1976). According to Park's model, the two-dimensional force-displacement relationship of an elastomeric bearing can be expressed by following equations to describe a smoothed kinematic hardening behavior.

$$F_x = \alpha K_0 \delta_x + (1-\alpha) K_0 Z_x \tag{3.6}$$
$$F_y = \alpha K_0 \delta_y + (1-\alpha) K_0 Z_y \tag{3.7}$$

where the variables Z_x and Z_y are determined by following differential equations.

$$\dot{Z}_x = A\dot{\delta}_x - \beta\left|\dot{\delta}_x Z_x\right| Z_x - \gamma\dot{\delta}_x Z_x^2 - \beta\left|\dot{\delta}_y Z_y\right| Z_x - \gamma\dot{\delta}_y Z_x Z_y \tag{3.8}$$
$$\dot{Z}_y = A\dot{\delta}_y - \beta\left|\dot{\delta}_y Z_y\right| Z_y - \gamma\dot{\delta}_y Z_y^2 - \beta\left|\dot{\delta}_x Z_x\right| Z_y - \gamma\dot{\delta}_x Z_y Z_x \tag{3.9}$$

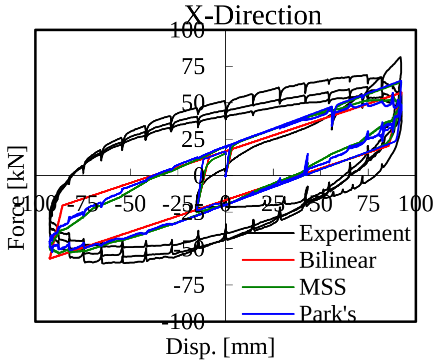
Generally, the parameter A is unity (A =1), and the parameters β and γ share the same value (β= γ). As mentioned in the work of Park (1986), Z_n, the limit value of Z_x and Z_y, is determined by parameters A, β and γ by Eqn. 3.10, and is equivalent to the yield displacement δ_0 as $Z_n \approx \delta_0$, hence the value of β (=γ) can be found by Eqn. 3.11.

$$Z_n = \sqrt{A/(\beta+\gamma)} \tag{3.10}$$
$$\beta = \gamma = (2\delta_0)^{-1} \tag{3.11}$$

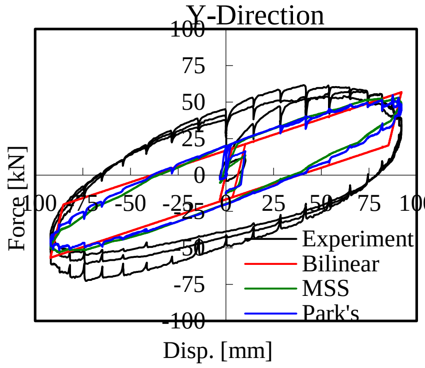
3.2. Comparison of numerical models and test results

3.2.1 Bidirectional quasi-static loading

Comparison of the hysteresis loops obtained by bi-directional quasi-static loading tests and by simulations is shown in Fig. 7 (Circular path loading) and Fig. 8 (Square path loading) in X-, Y-directions, respectively. From hysteretic loops under the circular path loading, the difference between the experimental and analytical results is remarkable and this difference is far greater than those among the analytical results with the three models including the conventional unidirectional bilinear model.

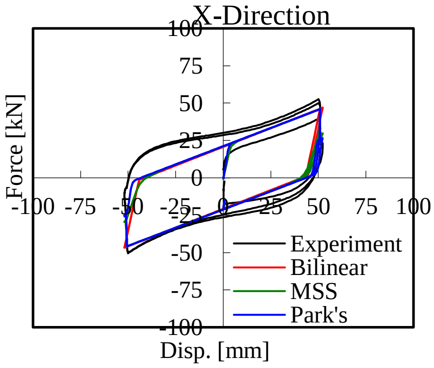


(a) X direction

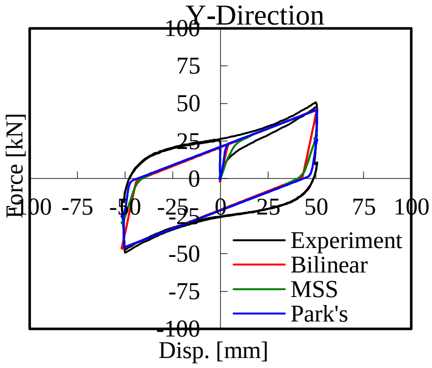


(b) Y direction

Figure 7. Comparison of numerical models and test results : circular path loading

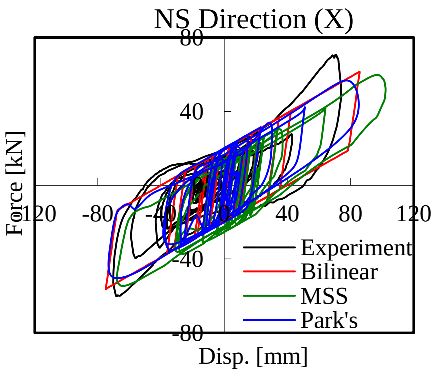


(a) X direction

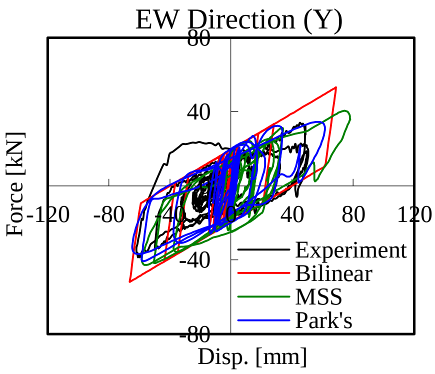


(b) Y direction

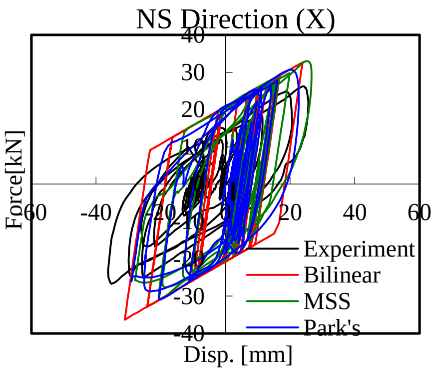
Figure 8. Comparison of numerical models and test results : square path loading



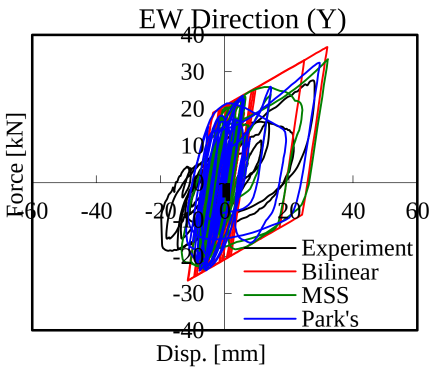
(a)NS component by JRT



(b) EW component by JRT



(c)NS component by JMA



(d) EW component by JMA

Figure 9. Comparison of numerical models and test results : hybrid simulation

One reason of this result can be attributed to the higher maximum shear strain in the circular path loading test (225%), compared with that of the square path loading test (175%).

3.2.2 Bidirectional seismic excitation results

Comparison of the hysteresis loops of the isolator under bi-directional seismic excitation by hybrid and numerical simulations is shown in Fig. 9. In each analytical result, the restoring force are overestimated within a smaller deformation range and underestimated for large greater deformation. The difference between the experimental and analytical results within the range of large deformation may be related to the hardening of elastomeric bearings, which generally becomes notable in the shear strain range exceeding 175%.

On the other hand, in terms of the maximum response displacement, the errors compared with experimental results are limited to 10%~30%, which are regarded as acceptable to some extent for the design purpose. Compared with the unidirectional bilinear model in which the bidirectional interactions are neglected, it is observed that analytical results of the MSS model and the Park model can represent the character of experimental hysteresis loops more properly. However, the difference among the three models is not so clear. As to the maximum response displacement, errors between experimental and analytical results by the JR Takatori record are smaller than those by the JMA Kobe record. For the former case, smaller error is observed also in the bi-directional absorbed hysteretic energy, which can be used as an indicative parameter for the evaluation of accuracy of the model.

For improved bidirectional modeling with greater accuracy, appropriate representation of the hardening behavior related to bi-directional strains is required.

4. CONCLUDING REMARKS

Loading tests, hybrid and numerical simulations of high damping rubber bearings subjected to uni- and bi-directional horizontal displacement paths and seismic excitation were conducted in this study. Four uni-directional loading tests in different directions demonstrated that the virgin load hardening effect vanishes in the oblique or orthogonal directions after the first uni-directional loading and hysteretic behaviour of the square-shaped elastomeric bearing obtained by the oblique direction loading is similar to that by the standard uni-directional loading. Notable difference in hysteretic curves was observed by comparing the results of uni- and bi-directional loading. Bi-directionally loaded specimen showed larger restoring force and energy absorption. This difference may be caused by the hardening effect in a large strain range of the elastomeric bearing which causes large bi-directional deformation. The hysteric curves obtained by hybrid simulation with bi-directional loading indicate the onset of the hardening effect at a smaller displacement than the case of unidirectional loading.

Numerical simulations using bilinear model, MSS model and Park’s model were conducted to compare with the tests results in order to investigate their validity in the evaluation of the seismic performance of isolated bridges under bi-directional excitation. The accuracy of these methods is almost acceptable in 10% to 30% difference in peak response displacement evaluation. However, the difference among these methods is negligible. The difference between the experimental and analytical results in a large displacement range can attributed to the hardening of elastomeric bearing which can be more severe in bi-directional loading due to the increased level of strain by the combined orthogonal components of deformation. Development of numerical models according for the hardening behavior related to the bi-directional strains is motivated in future research.

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