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DEVELOPMENT OF HYBRID SIMULATION SYSTEM FOR THE RUBBER BEARINGS UNDER THE LOW TEMPERATURE ENVIRONMENT

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Abstract

In these 25 years after the Kobe Earthquake in Japan, rubber bearings have been widely used for bridges to ensure its seismic performance. The seismic performance of bridges with rubber bearings is commonly evaluated by numerical simulation owing to the rapid development of the simulation techniques and application software. In the numerical model, rubber bearings usually modeled by a bilinear hysteresis loop. This model may have the modeling error about the nonlinearity of the material, loading history dependency, and temperature changes. Especially under cold environment, the initial stiffness of the material is considerably high and the stiffness decreased as increasing internal temperature by cyclic loading. For the formulation of such complexity, a number of loading test cases and careful considerations are required for the modeling. The interaction between the variation of the bearing characteristics and the response of whole structures is also concerned. For these problems, a substructured hybrid simulation can be an effective solution for the evaluation of the seismic performance of the entire bridge system with a combination of numerical simulation and physical experiment. Whole of structures including steel and/or concrete members, which are enough formulated numerically, are modeled in FEM software. The rubber bearings with the above complexity are tested simultaneously in loading facilities.

A substructured hybrid simulation system for the rubber bearings under the low temperature environment was developed in this study. The hybrid simulation system utilized an open-source pseudo-dynamic simulation system UI-SIMCOR and a sub-program that could cooperate with the existent loading facility in a cold room was developed. The capacity of the loading facility was 300kN for static loading and it was able to operate in -30 degrees in Celsius. To enhance the usability of the system, another sub-program was also developed for the application of a versatile FEM software.

A simulation for a single bridge pier model with one rubber bearing was performed. A 10m height reinforced concrete bridge pier was modeled in a FEM software. A rubber bearing was installed at top of the pier and mass of the superstructure was added above the bearing. The rubber bearing was a small size specimen made of newly developed high damping rubber with low nonlinearity and the bearing was an experimental part of the hybrid simulation system.

As a model case, a simulation at -30°C was conducted on a base-isolated bridge. As a result, it was possible to incorporate into the response analysis that the hysteresis loop of the bearing changed as the vibration progressed.

Keywords: hybrid simulation; laminated rubber bearing; low temperature environment

1. Introduction

Since the 1995 Kobe Earthquake, the number of bridges adopting seismic isolation structure in addition to the conventional seismic structure has been increasing, and research and development of seismic isolation and seismic control devices have been actively conducted. Seismic isolation bearings using laminated rubber are one of the leading options for improving the seismic performance of bridges and are widely used.

The mechanical properties of rubber bearings are obtained by cyclic loading experiments at constant amplitude [1]. In seismic response analysis, seismic isolation rubber bearings are often modeled using a bilinear model based on the hysteresis loop at the fifth cycle [1]. It has been known from previous studies that the mechanical properties of rubber bearings are temperature dependent [2]. As a result of loading experiments, the equivalent stiffness at low temperature is higher than at normal temperature. In addition, rubber bearings generally have the characteristic that the horizontal force gradually decreases by cyclic loading with a constant amplitude, and this change becomes large in low temperature environments. If seismic response analysis is performed to evaluate the seismic response of a bridge in a low temperature environment, the difference in hysteresis characteristics due to the temperature in the fifth cycle can be expressed by a bilinear model. However, it cannot express the characteristic that the horizontal force gradually decreases as the vibration progresses.

A substructured hybrid simulation that combines structural experiments and numerical analysis is one method of incorporating such ever-changing hysteresis characteristics into seismic response analysis [3]. Therefore, a hybrid simulation system that enables loading tests of rubber bearings for the low temperature environment was developed in this study. In this paper, we describe the outline of the system and report the results of a hybrid simulation in a low temperature environment on a bridge with seismic isolation rubber bearings as a model case.

2. Substructured hybrid simulation system

In this study, UI-SimCor [4] which have been

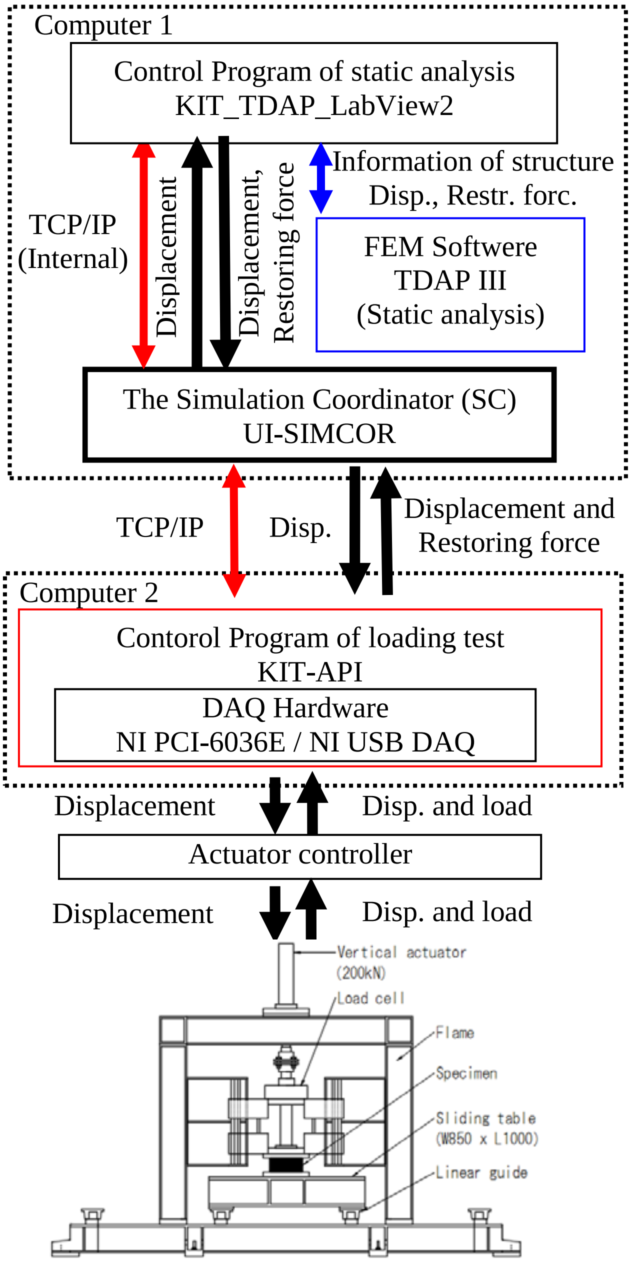


Fig. 1 - The hybrid simulation system

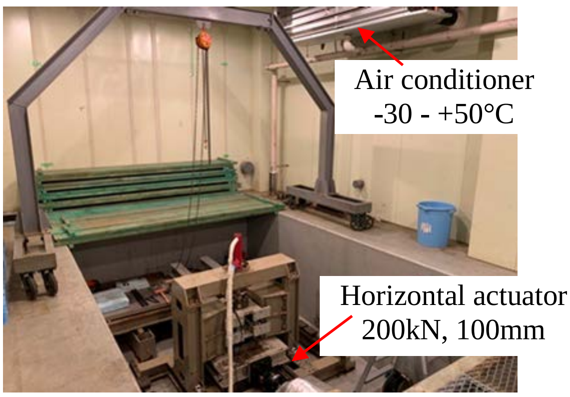


Fig. 2 - Experimental equipment

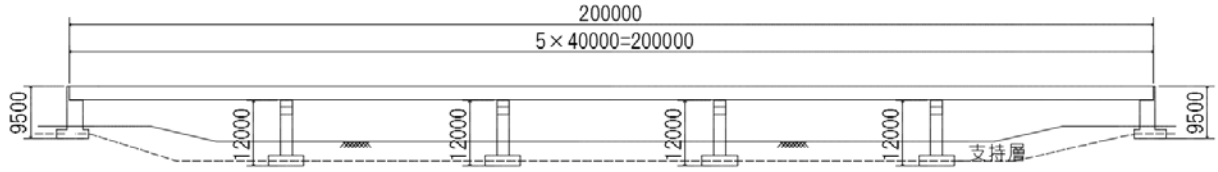
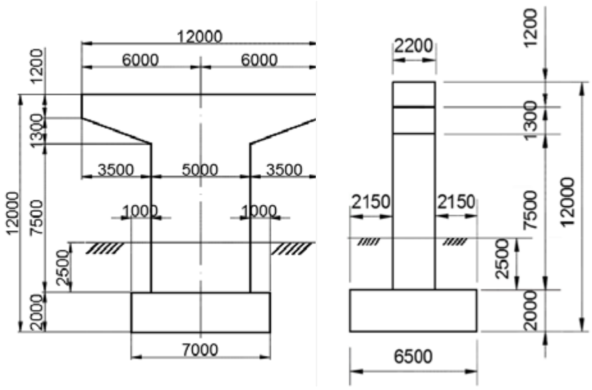


Fig. 3 - Target bridge [6]

developed in University of Illinois at Urbana-Champaign for NEES project was utilized to establish the substructured hybrid simulation system in cold environment. UI-SimCor offers the simulation coordinator (SC) and SC controls hybrid simulation entirely. Users can develop their original loading and/or structural calculation program and these programs can be integrated into the hybrid simulation via control program with a communication protocol.

The system configuration in this study is shown in Fig. 1. The authors [5] have developed the hybrid simulation system to calculate the seismic response of a girder model with a damper. In previous study, the loading facility used an actuator that loaded vertically. In this study, we use a biaxial loading facility that applies shear deformation to the specimen by applying horizontal pressure to the specimen while applying a downward vertical compressive stress to the specimen. The capacity of the loading facility was 300kN for static loading and it was able to operate in -30 degrees in Celsius. To enhance the usability of the system, another sub-program was also developed for the application of a versatile FEM software.



(a) Front view (b) Side view

Fig. 4 - Target pier

Table 1 - Specifications of rubber bearings

Rubber type	HDReX
Nominal shear modulus	G12
Size	600mm×600mm
Thickness of one rubber layer	14mm
Number of rubber layers	8
Total thickness of rubber layer	112mm
Number of rubber bearings	5

3. A hybrid simulation for low temperature environment

3.1 Target bridge

In this study, we focus on road bridges with seismic isolation rubber bearings as described in Reference [6]. Fig. 3 shows a general view of the target bridge. This bridge was designed based on the 1996 edition of the Specifications for highway bridges in Japan. This bridge is a 5-span continuous steel I-girder bridge with a length of 200m, and uses reinforced concrete piers. The T-shaped piers of the bridge have a direct foundation on the 1st type of ground in Reference [1]. Each pier equips 5 seismic isolation rubber bearings. Table 1 shows the specifications of the rubber bearing. The type of rubber bearing and the shear modulus were adjusted to the specimen used in this study. HDReX which is a high damping rubber bearing was used.

3.2 Analytical model

In this study, in order to simplify the analysis, one substructure and the superstructure supported by the substructure were considered as one design vibration unit, and the pier shown in Fig. 4 was used as an

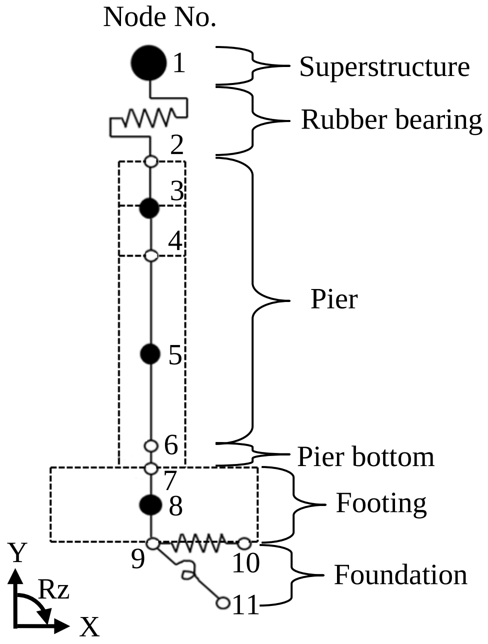


Fig. 5 - Analytical model

analytical model. Fig. 5 shows the overall view of the analytical model. The superstructure is one mass point. Since the failure mode of the reinforced concrete bridge pier is the type that precedes bending failure, a nonlinear model that can express the nonlinear behavior of bending was used. An asymmetric maximum point-directed bilinear (Takeda-type) model with a complete elasto-plastic skeletal curve of bending moment-curvature relation was applied to the plastic hinge section of the bottom of pier, and the bending behavior of the pier was expressed. The plastic hinge length was calculated from Reference [1]. Other elements were modeled by linear beam elements, and the ground was modeled by a linear spring element connecting nodes 9 and 10, and a rotary spring element connecting nodes 9 and 11. Rubber bearings are not modeled for loading experiments.

Table 2 - Node coordinate and mass

Node No.	Height (m)	Mass	
		X direction (t)	R_Z direction (t m)
1	10.000	600.0	-
2	10.000	-	-
3	8.900	140.0	-
4	7.000	-	-
5	3.750	206.3	-
6	0.993	-	-
7	0.000	-	-
8	-1.000	227.5	876.8
9	-2.000	-	-
10	-2.000	-	-
11	-2.000	-	-

Table 3 - Specifications of pier

Node No.	Section area (m^2)	Moment of inertia (m^4)
2 - 3	26.4	10.65
3 - 4	18.7	7.45
4 - 5	11	4.44
5 - 6	11	4.44
7 - 8	45.5	160.2
8 - 9	45.5	160.2

Table 4 - Specifications of foundation

Node No.	Stiffness
9 - 10	1397 (kN/m)
9 - 11	17259 (kNm/rad)

In the hybrid simulation system, static response analysis using TDAPIII [7] which is a general commercial FEM software is performed on the computer 1 shown in Fig. 1, using the calculation module below the pier top. And using the loading facility via the computer 2 and the control unit, the loading test above the pier top is used as the experimental module.

Table 2 shows the coordinates and mass of the nodes in the model. The mass was set at the center of gravity of the superstructure and the members of the pier. In this study, the vibration is applied in one horizontal direction along the bridge axis. In the X axis direction, which is the bridge axis direction, only

Table 5 - Specifications of specimen

Rubber type	HDReX
Nominal shear modulus	G12
Size	170mm×170mm
Thickness of one rubber layer	7mm
Number of rubber layers	3
Total thickness of rubber layer	21mm
Number of specimen	1

nodes 10 and 11 that are the ground are fixed. In the R_Z direction, the superstructure (node 5), nodes 10 and 11, were fixed.

Table 3 shows the specifications of pier and Table 4 shows the specifications of foundation.

3.3 Analytical conditions

The Rayleigh damping is used for damping other than bearings. Assuming that the damping ratio of each member is 0% for rubber bearings, 2% for piers, and 10% for foundation-ground, a damping rate proportional to strain energy is considered. In calculating the natural frequency, the rubber bearing used the equivalent stiffness obtained by a loading test with a shear strain of 175% at +23°C. As a result, the damping ratio was 0.016 for the natural frequency of 0.724 Hz in the first mode, and 0.054 for the natural frequency of 3.500 Hz in the second mode. The numerical analysis of the simulation used the α-OS method [8-10], and the damping parameters were $\alpha = 0.00$, $\beta = 0.25$, and $\gamma = 0.50$. This is consistent with the Newmark β method ($\beta = 0.25$, $\gamma = 0.50$).

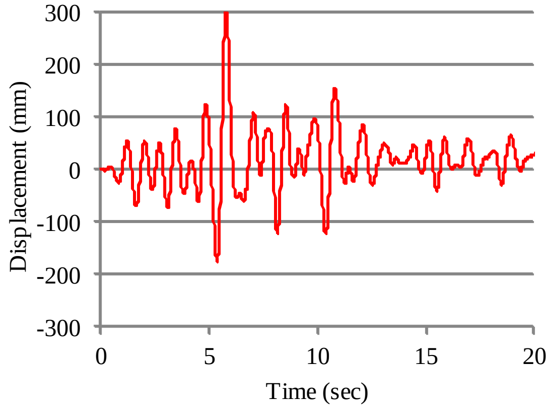


Fig. 6 - Displacement of superstructure

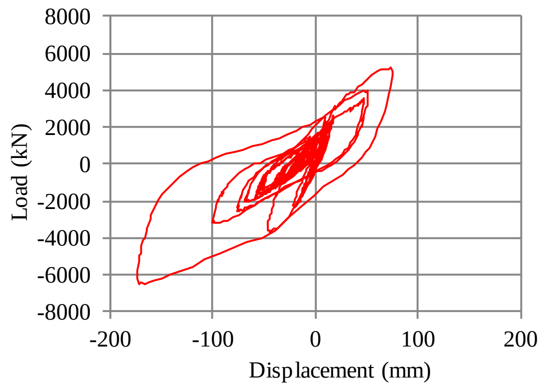


Fig. 7 - Hysteresis loop of rubber bearing

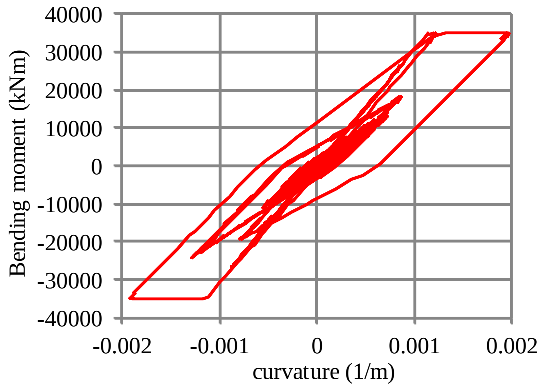


Fig. 8 - Hysteresis loop of pier bottom

The input ground motion was JMA Kobe NS during the 1995 Kobe Earthquake. The time step of the simulation was 0.01sec. However, the simulation was performed 20 seconds from the start of the large amplitude. Therefore, the number of steps in the simulation was 2000. The waiting time for the actuator to follow the commanded displacement in each step described in Chapter 2 was set to 0.8 sec.

Table 5 shows the specifications of the specimen. Because the specimen is smaller than the bearing of the analytical model, the displacement and the load applied the specimen are adjusted so that the shear strain and the shear stress of the rubber bearings become equivalent. The vertical compressive stress applied to the specimen was set to $3.3N/mm^2$ calculated from the mass of the superstructure and the size of the rubber bearings.

3.4 Result

We considered the earthquake response of the bridge pier at -30°C as one case. From the results, Fig. 6 shows the displacement of the superstructure, Fig. 7 shows the load-displacement relation of the bearing, and Fig. 8 shows the bending moment-curvature relation of the pier base.

From Fig. 7, the maximum shear strain of the bearing was 155%. When the deformation of bearing is small, the equivalent stiffness is large. After the maximum deformation, the equivalent stiffness becomes smaller.

Fig. 8 shows that the nonlinear hysteresis characteristic of the pier base can be expressed.

4. Conclusion

In this study, in order to reflect the change of the hysteresis characteristic of the rubber bearing to the seismic response, a hybrid simulation system using experimental equipment capable of loading test at low temperature was developed. The hybrid simulation system was developed by using open source UI-SimCor and combining it with a program that operates a loading facility in a low temperature room.

As a model case, a simulation at -30°C was conducted on a base isolated bridge. As a result, it was possible to incorporate into the response analysis that the hysteresis loop of the bearing changed as the vibration progressed.

5. Acknowledgements

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