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Hybrid simulation for seismic performance evaluation of SPR-S bearing at low temperatures

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1. Introduction

The spring confined Pb high damping rubber bearing (SPR-S bearing) is a type of elastomeric bearing consisting of laminated high damping rubber and lead plugs wrapped around by steel springs, and the energy dissipation performance of SPR-S bearing is enhanced compared with the conventional LRB and HDR bearings. As a common problem with LRB and HDR bearings, there is a technical concern on the performance degradation of SPR-S bearings under low temperature environments, and the temperature rise caused by the self-heating of high damping rubber and lead plugs can also affect the seismic performance of SPR-S bearing. Although the influence of the low temperature condition on the seismic performance of natural rubber bearing, high damping rubber bearing and lead rubber bearing are known by the past studies, that of SPR-S bearing involving thermal-mechanical interaction between HDR and lead plugs has not been examined. The hysteresis behavior of SPR-S bearing and the seismic response of the isolated bridge with SPR-S bearing under low temperatures still need to be explored in order to introduce the SPR-S bearing to the cold earthquake-prone regions in the future. In this study, the cyclic shear loading tests and hybrid simulation using a loading system with the ability to control the environmental temperature are carried out, and the low temperature effect on the seismic response of the SPR-S bearings isolated bridge is evaluated according to the obtained hysteresis loops of the SPR-S bearing and the pier top displacement.

2. Experimental condition

(1) Test specimen

The 1/6 scaled SPR-S bearing specimen was used in the experiment, as shown in **Fig. 1**. The effective dimensions of specimen are 240×240 mm, one rubber layer thickness is 5mm and the total rubber thickness is 30mm, one steel plate thickness is 3.2mm and the total steel thickness is 19.2mm, and the shear modulus of rubber material is 1.2 N/mm^2. There are four lead plugs with a diameter of 34.5 mm respectively distributed on the four corners of the SPR-S bearing specimen.

(2) Loading apparatus

The loading apparatus is shown in **Fig. 2**. In the horizontal direction, the specimen was controlled by displacement with a constant rate of 10mm/s and the maximum horizontal force and displacement capacity of the loading apparatus are ±400kN and ±200mm, respectively. In the vertical direction, the specimen was loaded by a constant axial stress of 6 MPa, and the maximum vertical force and displacement capacity of the loading apparatus are −2000/+1000kN and ±150mm, respectively.

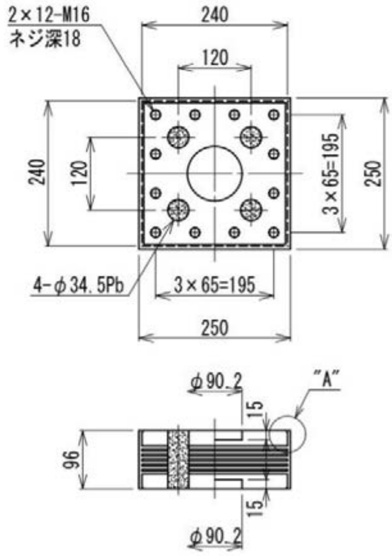


Figure 1. Test specimen

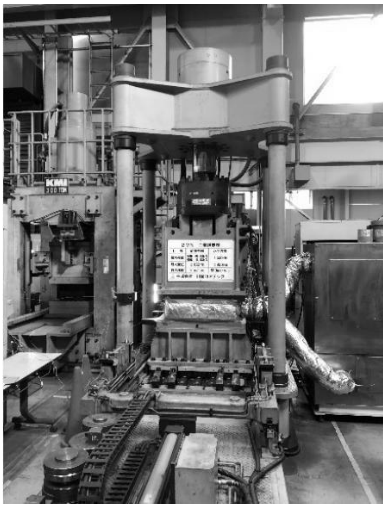


Figure 2. Loading apparatus

(3) Temperature control

Both the cyclic loading tests and hybrid simulation were conducted at room and low ambient temperatures: 23ºC, 0ºC and −20ºC. Only the SPR-S bearing specimen was placed within an insulation chamber, and the inner temperature of the chamber was controlled by delivering the continuous flow of cold air through the cooling system, as shown in **Fig. 3**. Furthermore, as the loading apparatus's temperature was basically the same with the air temperature, two insulation plates were installed on the upper and lower surface of the SPR-S bearing specimen to prevent the energy loss from the SPR-S bearing specimen to the loading apparatus, as shown in **Fig. 4**. However, the shear key was installed at the center of upper insulation plate to transmit the shear force to the SPR-S bearing specimen, hence, there was a small amount of energy loss from the specimen to the loading apparatus through the shear key.

The temperature of high damping rubber was measured by four thermocouples with two installed within the center of the fourth rubber layer, and two installed on the outer surface of the specimen. The temperature of lead plug was measured by three thermocouples with one inserted in a hole between the lead plug and high damping rubber with a depth of 50 millimeter, one attached to the upper surface center of the lead plug, and one inserted in the lead plug with a depth of 50 millimeter, as shown in **Fig. 5**.

Before each test, the SPR-S bearing specimen was placed within the insulation chamber and cooled by the cooling system for at least one day, then the test was started until the temperature of SPR-S bearing specimen reached the expected value.

Figure 3. Cooling system

Figure 4. Insulation plate (on the upper surface of specimen)

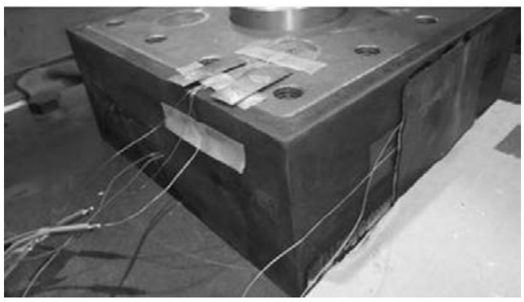
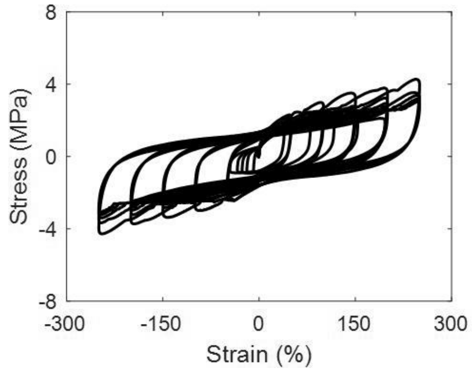


Figure 5. Thermocouples installed on the specimen

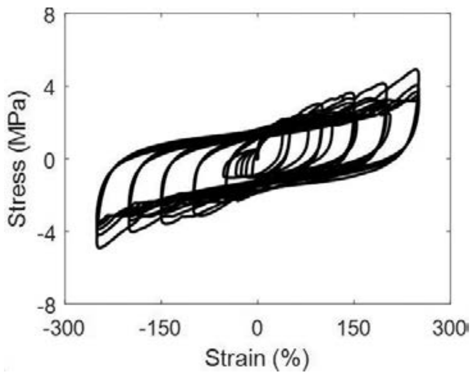
3. Cyclic shear loading test

The shear strain amplitudes for the cyclic loading test were 50%, 100%, 150%, 200% and 250%, from the smallest strain amplitude to the highest strain amplitude, and 5 cycles were repeated at each strain amplitude.

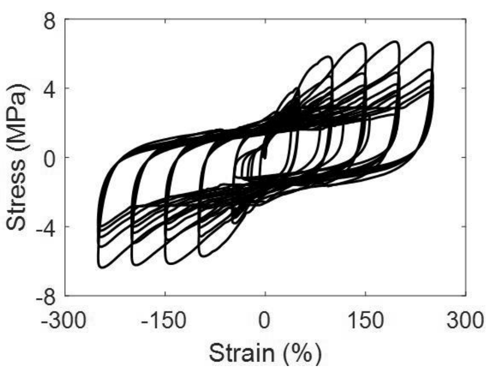
The shear strain-stress relationship of specimen at different temperatures is shown in **Fig. 6**. It can be seen that the stiffness is larger at lower temperature and higher strain level, and the stress of specimen for the first loop is obviously bigger than that of the next four loops caused by the Mullins effect, which is the same as expected.



(a) 23ºC



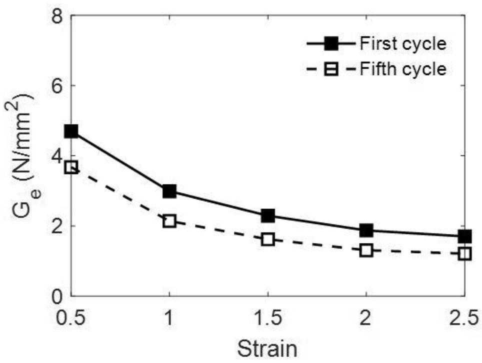
(b) 0ºC



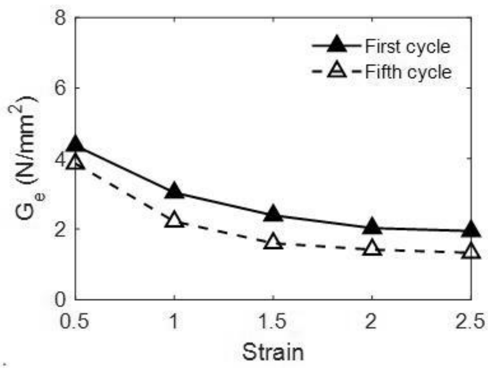
(c) −20ºC

Figure 6. Shear strain-stress relationship of SPR-S bearing in cyclic loading

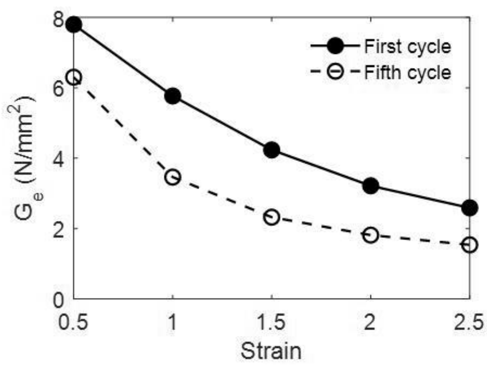
The equivalent shear modulus of SPR-S bearing specimen at different temperatures and shear strain amplitudes of the first and fifth cycles is shown in **Fig. 7**. It is observed that the equivalent shear modulus decreases as the shear strain increases, and the the equivalent shear modulus among different temperatures tends to be same as the shear strain increases, meanwhile, the equivalent shear modulus of the first cycle is higher than that of the fifth cycle at the same strain level, which may be caused by the self-heating of the SPR-S bearing. On the whole, the equivalent shear modulus at 0ºC and 23ºC is almost identical, and the equivalent shear modulus of the first cycle at −20ºC is distinctly higher than that at 0ºC and 23ºC.



(a) 23ºC



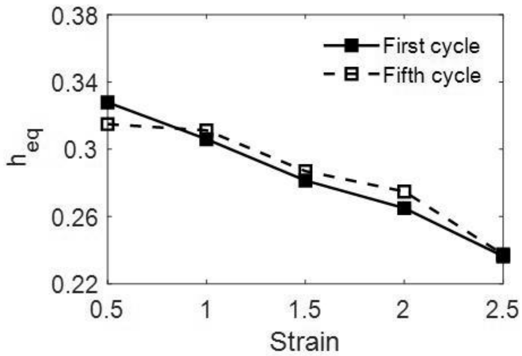
(b) 0ºC



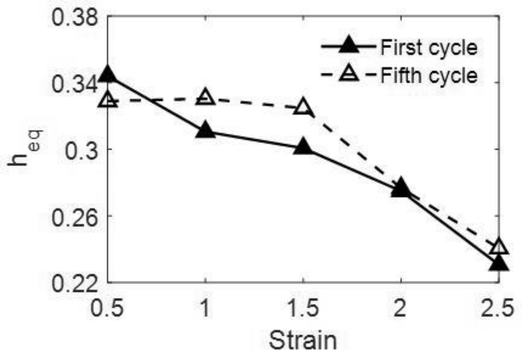
(c) −20ºC

Figure 7. Equivalent shear modulus vs. shear strain

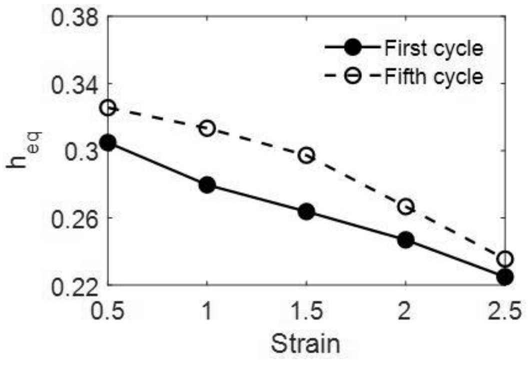
The equivalent damping ratio of SPR-S bearing specimen at different temperatures and shear strain levels for the first and fifth cycles is shown in **Fig. 8**. It can be observed that the equivalent damping ratio decreases as the shear strain increases, and the the equivalent damping ratio among different temperatures tends to be same as the shear strain amplitude increases. However, different from the equivalent shear modulus, the equivalent damping ratio of the first cycle is almost smaller than that of the fifth cycle at the same strain level.



(a) 23°C



(b) 0°C



(c) −20°C

Figure 8. Equivalent damping ratio vs. shear strain

4. Hybrid simulation

The hypothetical SPR-S bearing isolated bridge and the simplified 2-DOF system model of the bridge are shown in **Fig. 9**. The first period of the hypothetical isolated bridge is 1.498 sec, and the Level 2, Type II, ground type-II accelerogram 1 specified in Design Specification of Highway Bridges (Japan Road Association, 2017) was input as the seismic wave.

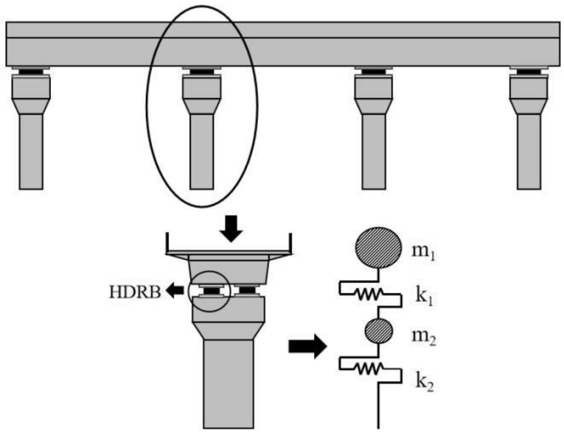
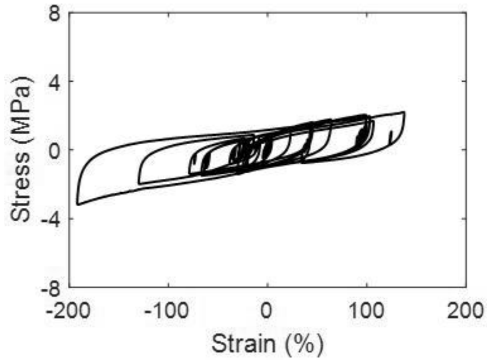
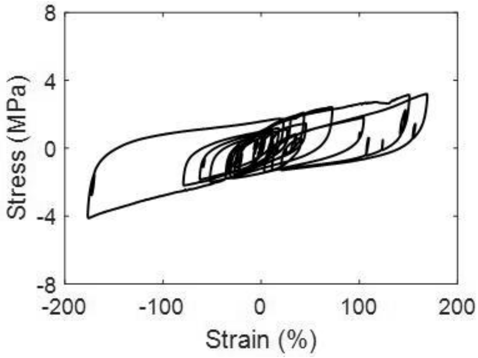


Figure 9. Hypothetical bridge and simplified 2-DOF model

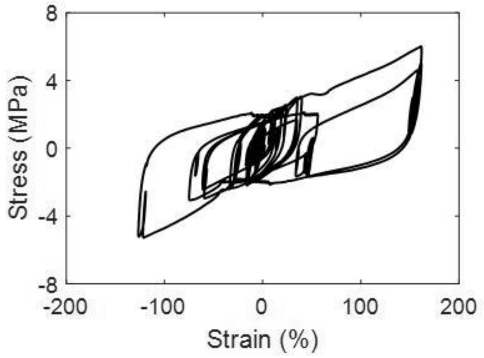
The hysteretic shear strain-stress relationship of SPR-S bearing at different temperatures in hybrid simulation is shown in **Fig. 10**. It is observed that stiffness and maximum shear stress are higher at lower ambient temperatures, and the maximum strain at −20°C is reduced by a factor of 0.844 compared with the result at 23°C. The pier top displacement at room and low temperatures is shown in **Fig. 11**. It can be seen that the pier top displacement is higher at lower temperatures, and the maximum pier top displacement at −20°C is increased by a factor of 2.162 compared with the result at 23°C.



(a) 23°C

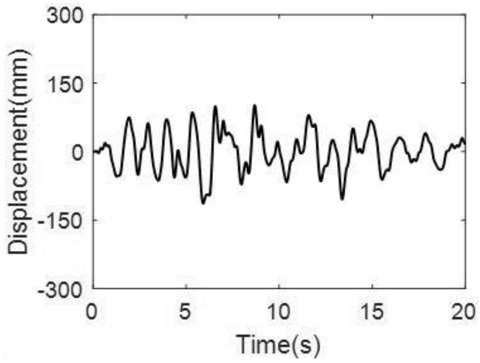


(a) 0°C

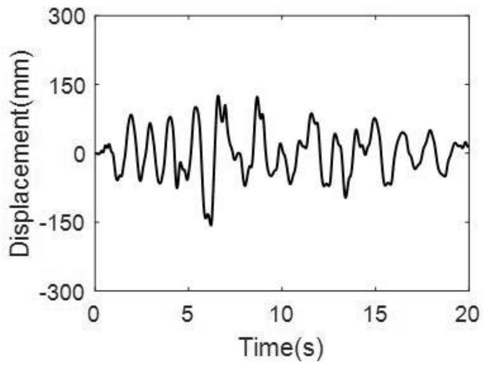


(b) −20°C

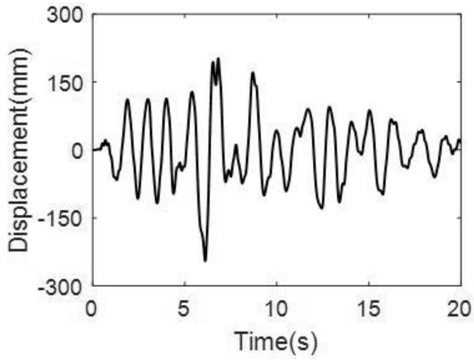
Figure 10. Shear strain-stress relationship of SPR-S bearing in hybrid simulation



(a) 23°C



(b) 0°C



(c) −20°C

Figure 11. Pier top displacement

5. Conclusions

In this work, cyclic shear loading tests and hybrid simulation at ambient temperature of −20°C, 0°C and 23°C were conducted to investigate how the seismic performance of the SPR-S bearings is influenced by the low temperatures. The following main conclusions can be obtained according to the experimental results.

In the cyclic shear loading tests, the stiffness of SPR-S is larger at lower ambient temperature and higher strain level, and both the equivalent shear modulus and equivalent damping ratio among different temperature tend to be same as the shear strain increases due to the self-heating. The hysteresis loops of SPR-S bearing at 0°C are similar to those at 23°C, and show an obvious difference from the results at −20°C.

In the hybrid simulation, the stress of SPR-S bearing and pier top displacement are higher at lower ambient temperatures. Furthermore, the seismic performance reduction of the SPR-S bearings at low temperature is evaluated though the test results, it is found that the maximum shear strain of bearing is reduced by a factor of 0.844 and the maximum pier top displacement is increased by a factor of 2.162 at −20°C compared with the test results at 23°C.

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