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Experimental study on temperature dependence of the mechanical properties of rubber isolation bearings

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Abstract

Base isolation is an efficient method to reduce the vulnerability of structures in high seismic risk zones. Laminated rubber bearings have become the mainstream isolation devices due to their simple structure and stable performance. As the core component, the performance of the isolation bearings greatly affects the safety and reliability of the isolation system. The influence of temperature on the mechanical properties of the rubber isolation bearings is one of the most prominent factors. In order to study the influence of temperature on the dynamic characteristics of rubber isolation bearings, a series of cyclic shear tests (CS), simple relaxation tests (SR) and multi-step relaxation tests (MSR) were carried out on two scaled rubber isolation bearings LRB200-G3 and LNR200-G3, five temperature conditions range from -30 ℃ to 20 ℃ and different levels of shear strain were considered. Test results of CS tests show that the maximum shear stress value of the hysteresis curve and the area enclosed by the curve gradually decrease with the increase of temperature, and the large displacement hardening of the bearings is more significant at lower temperatures. The influence of temperature on the equivalent stiffness and yield force of lead rubber bearings LRB200-G3 is very significant, while those of rubber bearing LNR200-G3 have relatively small temperature dependence. The results of SR tests and MSR tests show that the instantaneous value of the bearings' shear stress at various shear strains under fast loading shows an obvious temperature dependence. And during the stress relation stage of each shear strain, the equilibrium stress of the bearings also has a significant temperature dependence. All these observations indicate that the mechanical properties of the rubber isolation bearings have significant temperature dependence, which should be considered in the design of isolation structures.

Keywords: elastomeric bearings; temperature; loading-rate dependent; experimental study; mechanical properties;

1. Introduction

Different from the traditional seismic design of the structure, the design of isolation structure is to ensure the safety and reliability of the structure from the perspective of "reducing the seismic energy input to the superstructure". Because of its advanced concept, New Zealand, the United States, Japan and other countries have carried out a lot of relevant research, and obtained a lot of research results. At present, isolation technology has been widely used in engineering structures, and a large number of buildings using this technology have successfully withstood the test of earthquake [1].

The isolation devices are installed between the foundation and the superstructure to form an isolation layer, a centralized controllable weak layer of the isolation system, the performance of the isolation bearings greatly affect the safety and reliability of the isolation system. After decades of development, laminated rubber bearings have become the mainstream isolation devices due to their simple structure and stable performance [2]. The basic mechanics performance of the bearings, include horizontal stiffness, yield force and damping characteristics, etc., many scholars have conducted a lot of research on the mechanical properties of laminated rubber bearings, and proposed various numerical models [3-5].

China lies between the Pacific seismic belt and the Eurasian seismic belt, the peak acceleration of ground motions in most territories is greater than $0.1 m/s^2$, the seismically active areas are widely distributed and the climate conditions are quite different. Although isolation technology has been widely used in these areas, the adaptability of rubber isolation bearings and isolation systems to the seasonal temperature changes in these areas is still a little-known issue. At present, there is no clear stipulation in the relevant codes, and the influence of temperature has not been considered in the design of rubber bearing isolation system, so the rationality of the design results cannot be determined.

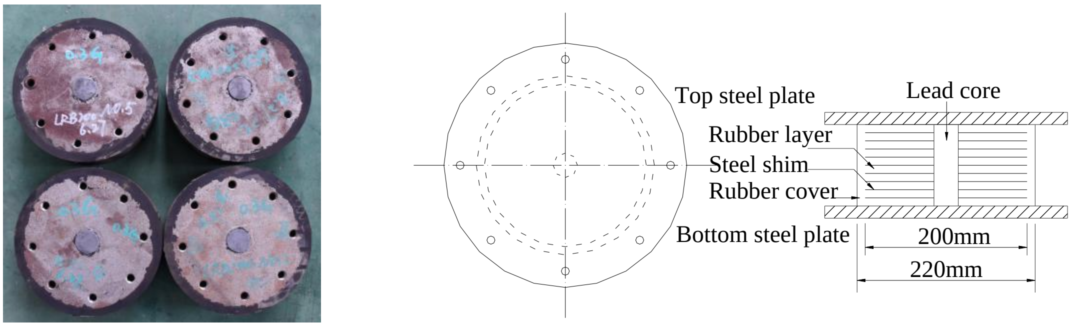
A large number of scholars such as Roeder et al. [6], Yakut and Yura [7], Fuller [8] and Cardone [9], etc. have conducted experiments on the behavior of rubber at different temperatures. It has been found that rubber will harden at low temperatures, and the effects of temperature on the mechanical properties of rubber cannot be ignored. In order to explore the performance of rubber bearings at different temperatures, some scholars have carried out experimental research on the temperature dependence of rubber bearings [10-12]. The experimental results show that temperature, especially low temperature conditions, will have a significant impact on the mechanical properties of rubber bearings, which will cause great changes in the dynamic characteristics of the isolation structure. The influence of temperature on the performance of rubber bearing mainly includes: the transient changes in performance of rubber and lead at ambient temperature; the crystallization hardening of rubber and lead core in the low temperature environment for a long time; the influence of the internal temperature changes caused by the hysteretic energy dissipation; the influence of seasonal temperature changes on the service life of the bearings. Based on the experimental research, some scholars have carried out some theoretical research on the temperature effect of the bearings and established some mathematical models [13-18]. However, due to the variety of rubber bearings and different material properties, those calculation models are not widely accepted.

In order to study the influence of temperature on the dynamic characteristics of rubber bearings and isolation structures, so as to accurately grasp the mechanism of structural damage and reasonably evaluate the performance of the structure, a series of experimental studies were carried out on the low modulus and high damping rubber bearings developed by our research group. In the experiment, five temperature conditions range from -30 ℃ to 20 ℃ were considered. And three loading schemes were implemented, namely cyclic shear test (CS), simple relaxation test (SR) and multi-step relaxation test (MSR).

2. Specimen and test apparatus

Two specimens with diameter of 200mm were used in this paper, which were numbered LRB200-G3 and LNR200-G3, respectively, the suffixes G3 in the bearing names represent that the shear modulus of rubber materials is 0.3MPa. Among them, LRB200-G3 is lead-rubber bearings and LNR200-G3 is rubber bearings.

The geometric parameters of the bearings are shown in Table 1, and the photograph of the bearings are shown in Fig. 1. The steel plates used in the bearings is Q235, and the rubber used in the bearings is the high performance natural rubber with high damping and low shear modulus developed by our research group.

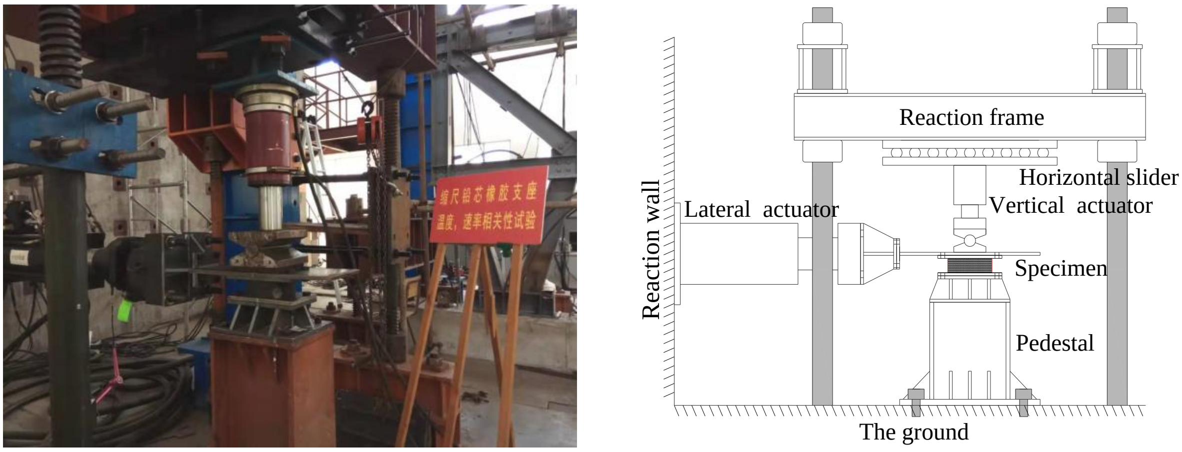


(a) (b)

Fig. 1 Photograph(a) and Schematic(b) of the specimen.

Table 1 Geometric parameters of test specimen.

Main parameters		LRB200-G3	LNR200-G3
Rubber shear modulus	N/mm^2	0.3	0.3
Bearing diameter	mm	220	220
Lead diameter	mm	30	---
Rubber layer thickness	mm	1.5	1.5
Number of rubber layers	layer	15	15
Inner steel shim thickness	mm	2	2
Total rubber thickness	mm	22.5	22.5
Total Bearing Height	mm	70.5	70.5



(a) (b)

Fig. 2 Photograph(a) and Schematic(b) of the test system

The compression-shear test apparatus used in this study is shown in Fig. 2. The vertical load mechanism is assembled by a hydraulic jack and a horizontal sliding device. The maximum output of the jack is 1000kN, and the pressure can be compensated automatically. The stroke of the horizontal sliding device is ±200mm. The horizontal load is provided by an actuator with a rated output of 250kN.

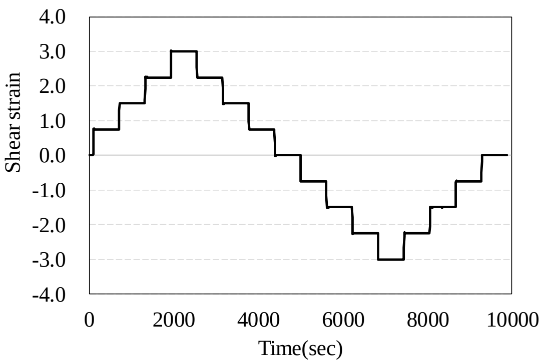
3. Test conditions

The behaviors of rubber bearings at different temperatures that are expected to occur over the lifetime of an isolation structure was studied. Tests were conducted on the bearing specimens in accordance with the procedures outlined in ISO 22762-1.2005 [19]. The test conditions are shortly described in Table 2. In all the tests, the vertical surface pressure of the bearings was constant at 5MPa(157kN). The shear strains considered in the tests were 100%(±22.5mm), 200%(±45mm), 300%(±67.5mm), the loading speeds considered were 1.5mm/s, 7.5mm/s, and the test temperatures considered were -30℃, -20℃, -10℃, 0℃, 20℃.

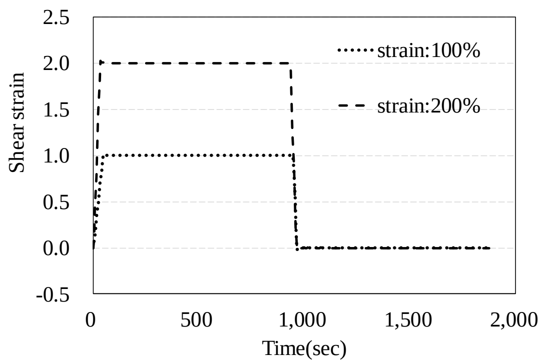
Table 2 Test conditions.

Test protocol	Max shear strain γ^1(%)	Test temp. (℃)	Loading velocity(mm/s)	Hold time of each strain(s)	Repetitions
CS	100%	-30, -20, -10, 0, 20	1.5	--	3
CS	200%	-30, -20, -10, 0, 20	1.5	--	3
CS	300%	-30, -20, -10, 0, 20	1.5	--	3
MSR	300%	-30, -20, -10, 0, 20	7.5	600	1
SR	100%, 200%	-30, -20, -10, 0, 20	7.5	900	1

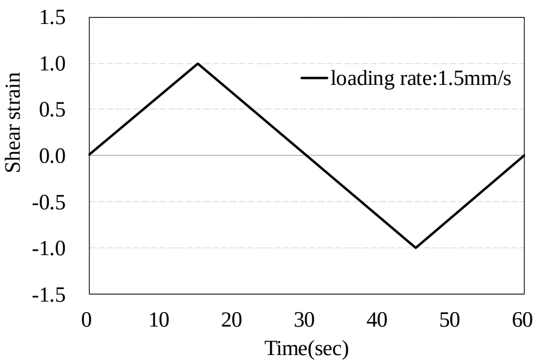
Shear strain γ is calculated as $\gamma = u/h$, where u is the shear displacement, h is the total rubber thickness (Table 1, 22.5mm).



(a) MSR



(b) SR



(c) CS

Fig.3 Loading curves of MSR, SR, and CS tests:

(a)MSR test.

(b)SR tests with shear strains of 100%, 200%

(c)CS tests with loading rates of 1.5 mm/s.

The different temperatures of the specimens were provided by the temperature control box. For each temperature condition, the bearings was placed in the temperature control box for 24 hours, and the refrigeration temperature was set 2℃ below the target test temperature. During the loading process, the bearing was surrounded by a foam insulation box with a small amount of dry ice inside. Figs.3 shows the loading curves of the cyclic shear test (CS), simple relaxation test (SR) and multi-step relaxation test (MSR) Among them, Fig.3(a) shows the loading curves of CS tests with loading rate of 1.5mm/s. Each CS loading curve was loaded 3 times. Fig. 3(b) shows the loading curves of SR tests with shear strain of 100% and 200%, the holding time after loading and unloading is 900s. Figs.3(c) shows the loading curves of MSR tests, which is a segmented cyclic loading test with a maximum shear strain amplitude of 300%, after each section of shear strain loading is completed, the load is paused for 600s.

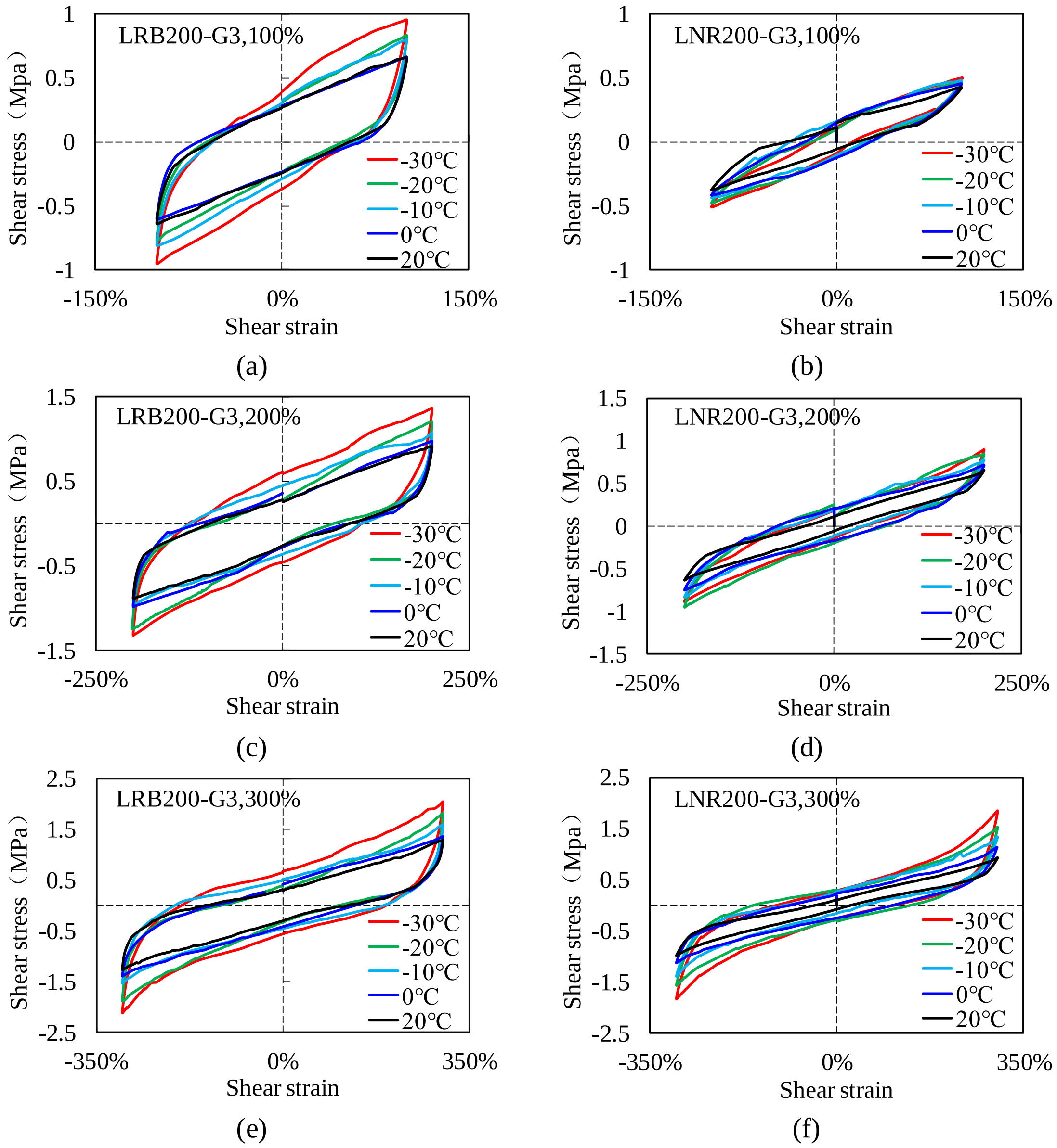


Fig.4 Hysteresis curvs at different temperatures and shear strains.

4. Experimental results and Discussion

3.1 Hysteresis curves obtained from CS tests

Based on the CS tests of the two specimens at 5 temperature conditions and 3 shear strains, a lot of curves were obtained, and the third cycle of the hysteresis curves at each test condition were taken for study.

Fig.4 shows the comparison of hysteresis curves at different temperatures. Among them, (a), (c) and (e) are the hysteresis curves of LRB200-G3 at shear strains of 100%, 200% and 300%. And (b), (d) and (f) are the hysteresis curves of LNR200-G3 at shear strains of 100%, 200% and 300%, respectively. For LRB200-G3, it is visible that the hysteresis curves of each shear strain are fuller at lower temperatures. As the temperature increases, the maximum shear stress value of the hysteresis curve and the area enclosed by the curve gradually decrease. The comparison of hysteresis curves of LNR200-G3 shows that, when the shear strain is 100%, the influence of temperature on the shape of the hysteresis curve is not obvious. With the increase of shear strain, the hysteretic curves at low temperature and room temperature has significant differences, characteristics such as the area enclosed by the curve and the maximum shear stress increase as temperature decreases. At -30℃~-20℃ and shear strain 300%, both ends of the hysteretic loops are significantly upturned, showing an inverse S-type, which indicates that the large displacement hardening of the bearing is more significant at lower temperatures. Comparing the hysteresis curves of LRB200-G3 and LNR200-G3 at different shear strains, it can be found that the curve of LRB200 is fuller than LNR200 and the sensitivity to temperature of LRB200 is more significant. This is mainly because LRB200 contains a lead core, indicating that the mechanical behavior of the lead core also has an obvious temperature correlation.

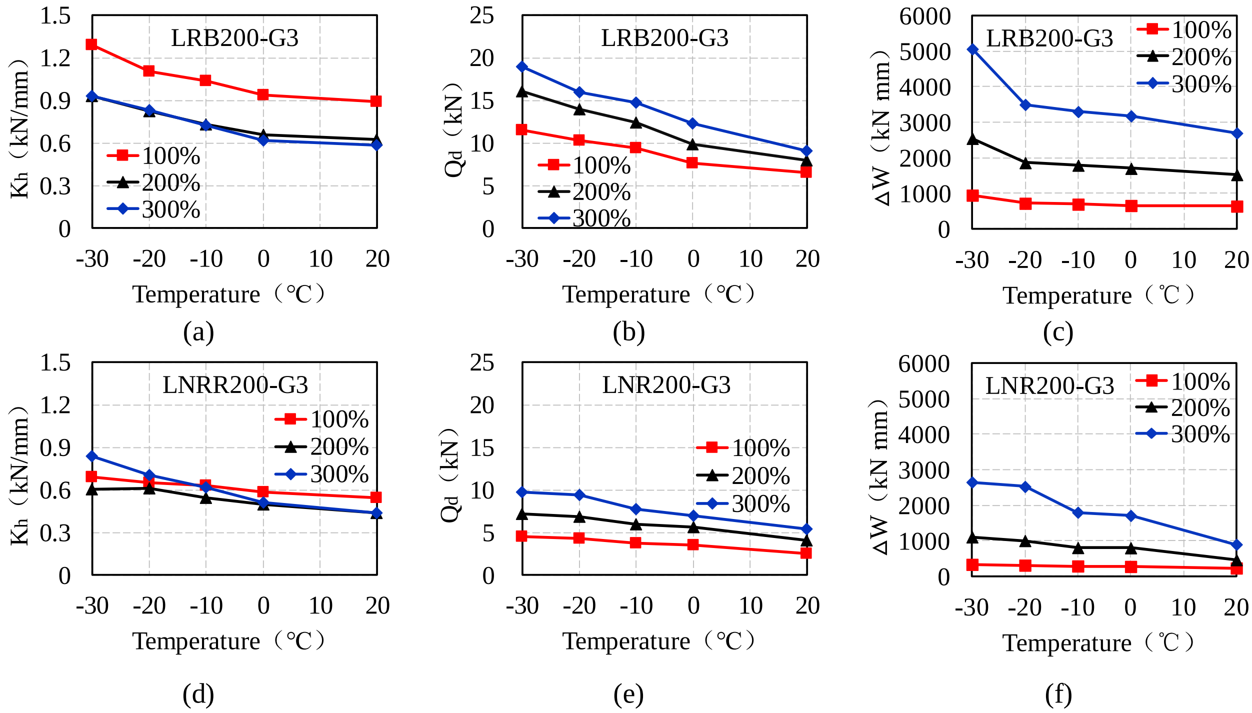


Fig.5 Curves of K_h, Q_d, and ΔW varying with temperature at different shear strains

In order to quantitatively describe the temperature dependence of the mechanical properties of the bearings, parameters such as the equivalent stiffness K_h, the yield forces Q_d and the hysteretic energy dissipation ΔW were obtained by identifying the hysteretic curvs as indicated in the ISO 22762-1:2005[19]. The curves of these mechanical parameters varying with temperature are shown in Fig.5.

As shown in Fig. 5(a), for LRB200-G3, K_h decreases with the increase of temperature. When the shear strain is 100% and the temperature is -30 ℃, K_h reaches its maximum value of 1.29kN/mm. When the shear strain is 300% and the temperature is 20 ℃, K_h reaches its minimum value of 0.59kN/mm. The ratio of the maximum value to the minimum value is 2.19. This phenomenon indicates that the influence of temperature on the equivalent stiffness of lead rubber bearings is very significant. Fig. 5(d) shows that the K_h of LNR200-G3 also increases with the decrease of temperature, but the decrease is smaller than that of LRB200-G3.

According to Fig. 5(b) and Fig. 5(e), the yield force of LRB200-G3 and LNR200-G3 also increases with the decrease of the temperature. And the yield force of LRB200-G3 is larger and changes more significantly with the temperature. Fig. 5(c) and Fig. 5(f) illustrate that temperature have a visible effect on the hysteretic energy dissipation of the bearings. Under each temperature condition, ΔW increase with the increase of shear strain. When the shear strain is constant, ΔW decreases with the increase of the test temperature.

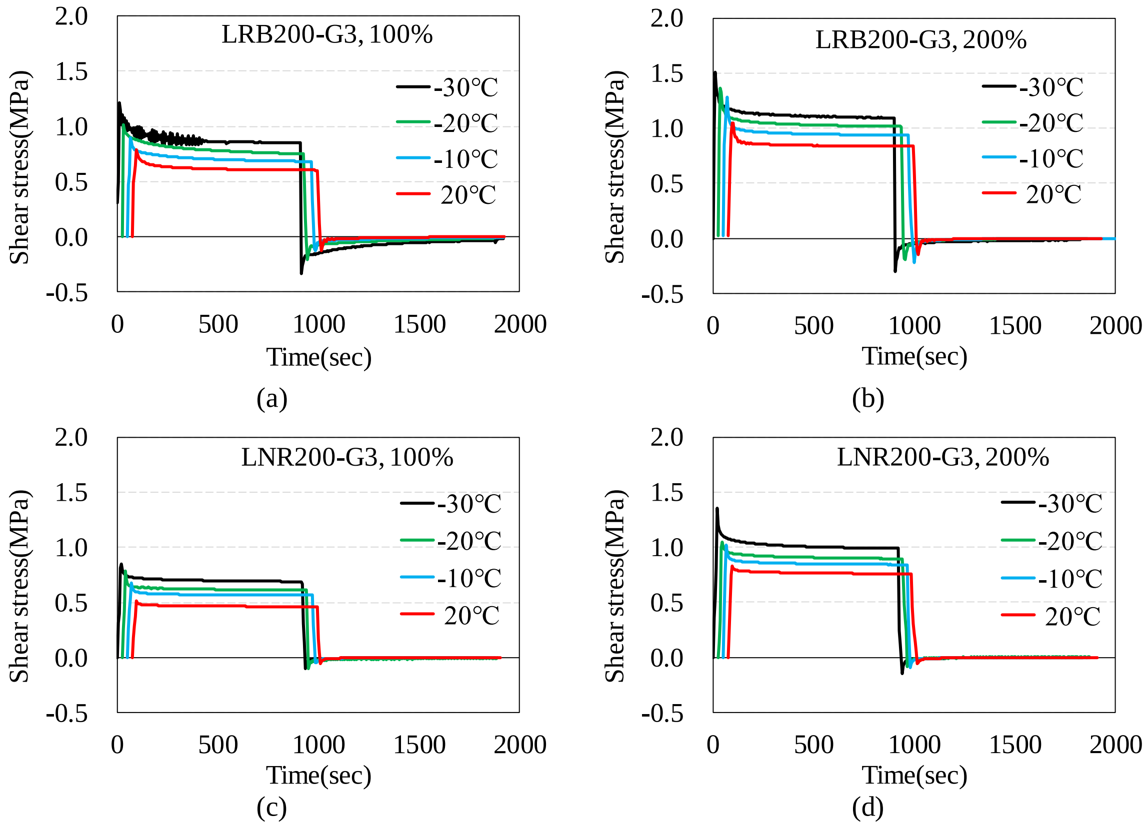


Fig.6 Stress histories obtained from SR tests at different temperatures and shear strains

The relaxation response of two specimens were studied through a series of SR tests with three shear strain levels at different temperatures. The loading rate of SR tests was 7.5mm/s. The stress histories are plotted in Fig.6. Stress relaxation curves with the same strain at different test temperatures are compared in the graphs. Fig.6(a) and (b) are the comparison of stress histories of LRB200-G3 with shear strains of 100% and 200%. Fig.6(c) and (d) are the stress histories comparison of LNR200-G3 with strain of 100% and 200%, respectively. As loaded, the shear stresss of the bearings rush to a relatively high instantaneous value, and the comparison shows that the instantaneous shear stress is higher at lower temperatures for each strain amplitude. During the loading pause phase, the shear stress drop rapidly from the instantaneous value in the first few seconds. Then as the time of loading pause increases, the stress asymptotically converge to relatively lower stable values, which can be approximated as the rate-independent equilibrium stresses. For both specimens under different shear strains, the equilibrium shear stresses at the end of the loading pause phases shows a slightly temperature dependence. While the equilibrium shear stresses are similar to each other at the end of the unloading pause phases, the temperature correlation is not so obvious. What's more, for LRB200-G3, the equilibrium shear stresses of the loading pause phases at different temperatures are greater than those of LNR200-G3, which indicates that the temperature dependence of LRB200-G3 in equilibrium stress and instantaneous stress is more significant than that of LNR200-G3.

MSR experiments were implemented to present the temperature dependence of the bearings' equilibrium state, which were supposed to be able to simulate the equilibrium response of the bearings due to the viscosity property by applying infinitely slow loading rate. Fig.7 illustrates the stress curves observed in MSR tests at different temperatures. Each of the curve in the figures show significant stress value drops at the suspension stage of each shear strain. The magnitude of stress relaxation at each shear strain for LRB200-G3 is larger than that for LNR200-G3. And for both specimens, the peak stress and stress relaxation magnitude at each applied strain are larger at lower temperatures. All these observations indicated that the mechanical properties of the bearings have significant temperature dependence.

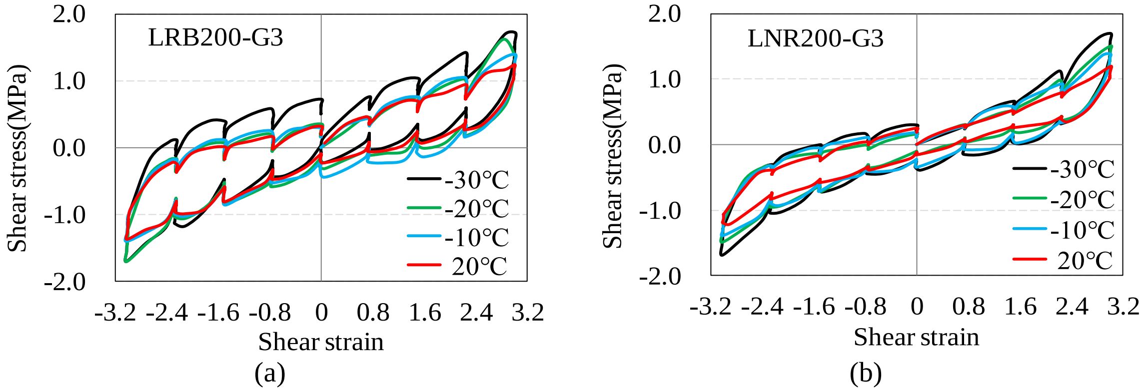


Fig.7 Stress-strain curves obtained from MSR tests, (a) LRB200-G3 and (b) LNR200-G3

5. Conclusion

In order to study the temperature dependence of the rubber bearings' mechanical properties. A series of experimental studies on two low modulus and high damping rubber bearings LRB200-G3 and LNR200-G3 were carried out. There were three kinds of loading schemes, namely cyclic shear test (CS), simple relaxation test (SR) and multi-step relaxation test (MSR). And five temperature conditions range from -30 ℃ to 20 ℃ were considered in those tests. The main conclusions obtained through analysis and comparison of experimental results are as follows:

(1) Comparison of hysteresis curves obtained at different temperatures in the CS tests show that, for both bearings, the maximum shear stress value of the hysteresis curve and the area enclosed by the curve gradually decrease with the increase of temperature. In addition, the comparison of hysteresis curves under large shear strain conditions shows that the large displacement hardening of the bearings is more significant at lower temperatures.

(2) The hysteresis curves of the lead rubber bearing LRB200-G3 is much fuller than that of rubber bearing LNR200-G3, which show that, in addition to rubber, the temperature dependence of the mechanical properties of the lead core is also significant.

(3) The influence of temperature on the equivalent stiffness and yield force of lead rubber bearings LRB200-G3 is very significant, while those of rubber bearing LNR200-G3 have relatively small temperature dependence.

(4) The comparison of relaxation curves obtained from the SR tests and MSR tests shows that, for both bearings under different shear strains, the equilibrium stresses at the end of the loading pause phases shows obvious temperature dependence. For LRB200-G3, the equilibrium stresses at different temperatures are greater than those of LNR200-G3, indicating that the temperature dependence of the LRB200-G3's equilibrium stress is more significant than that of LNR200-G3.

6. Acknowledgements

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