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Experimental Study on Properties of High-damping Rubber Damper

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Abstract

Viscoelastic damper is a kind of widely-used energy dissipation device, which can be equipped in building structures for wind or earthquake vibration control. However, the poor energy dissipation capacity of viscoelastic damper becomes a limit in it's practical application. To solve this problem, a new high-damping rubber material has been developed and used to produce high-damping rubber dampers (HRD). In this paper, to study the performance of HRD, three HRDs have been produced. The deformation correlation of HRD have been test as well as the frequency correlation and the fatigue property through controlling the loads with different frequency and strain amplitude, variation law of HRD mechanical properties including storage shear modulus, loss shear modulus,the maximum damping force and equivalent viscous damping ratio have been study under different conditions. The results show that the HRD has a good energy dissipation capacity with full hysteresis curve and high equivalent viscous damping ratio; The mechanical properties of HRD has a certain relevance to strain amplitude and loading frequency. The mechanical property parameters decrease with increasing loading laps in the fatigue tests, wherein the storage shear modulus, loss shear modulus and the maximum damping force reduce rapidly until the eleven lap, and then gradually slow.

Key words: energy dissipation; HRD; deformation and frequency correlation; fatigue performance; test

1. Introduction

As an effective passive control device, viscoelastic damper have been first applied successfully in high-rise building for reduction of wind-induced response in the field of civil engineering. Then a number of researchers studied on the viscoelastic dampers through experimental and theoretical method. As the advantages of good performance of energy consumption, simple configuration, low cost, and easy to maintain etc, viscoelastic damper has been gradually widely used in high-rise buildings, large span structure, bridge and tower systems to mitigate both wind and earthquake vibrations[1]. The mechanical properties of viscoelastic damper mainly depends on a viscoelastic material, which are typically copolymers or glassy substances. Early material of polymer molecules is sensitive to frequency and temperature, thus the mechanical properties of viscoelastic damper has a obvious correlation with frequency as well as temperature, and has great influence on performance of damper's energy dissipation[2-4]. In order to improve the mechanical properties of viscoelastic dampers, Japanese scholars proposed the use of silicon-based and isoprene rubber to produce high damping viscoelastic dampers, which has lower frequency correlation and could provide higher damping compare to common viscoelastic damper, showing good deformation properties and energy dissipation capacity[5-10].

The current production of viscoelastic dampers mainly are propylene, styrene-based rubber polymer materials in China.And there are many researchers have studied on the viscoelastic dampers in recent years[11]-[14]. However, problems still remain such as smaller energy loss factor and obvious frequency and temperature dependence, which seriously hampered the application and development of viscoelastic dampers in structural earthquake and wind induced vibration control. Therefore, high-performance materials developed with our own intellectual property rights to produce viscoelastic dampers become particularly urgent and important. In order to improve the mechanical properties of viscoelastic dampers, three HRDs have been produced by a new formulation of isoamyl high damping rubber material. The experimental studies on the individual components of HRDs are conducted to exam the properties of deformation correlation as well as frequency correlation and fatigue performance.

2. Specimen design

High-damping rubber damper is a twin shear type device, which is consist of three steel plates and two rubber damping material layers. Wherein the dimension of each high damping rubber layer is 400x400x25mm; the external constraint steel plate thickness is 12mm, the intermediate steel plate thickness is 19mm. Fig.1 shows the detailed dimension drawings of HRD.

In this paper, three HRD Specimens have been produced to study the mechanical properties of HRDs:The first HRD Specimen is used to study the properties of deformation correlation; the second is used to study the frequency-dependent properties; the third is for fatigue properties experimental study. Fig.2 shows the experimental specimens of HRD.

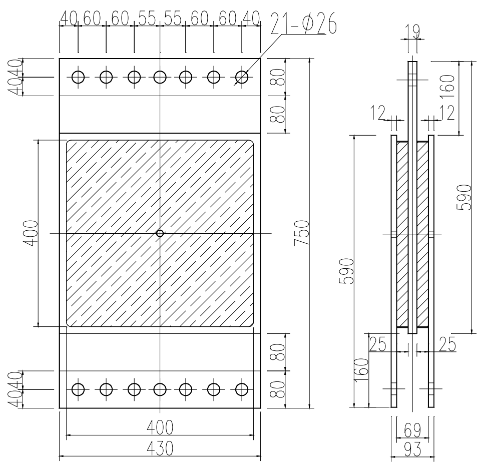


Fig.1 The Detailed Dimension of HRD

Fig.2 High-damping Rubber Damper

3. Loading system

High-damping rubber damper test apparatus consists of servo actuator, reflexive force steel structure and control system, as shown in Fig3. Actuator maximum dynamic load is 100 tons, the maximum stroke displacement is ±600mm, the operating frequency range of 0.01Hz to 5Hz, the maximum working pressure is 28MPa.

The mainly measure content during the HRD test including damping force and shear deformation, wherein damping force feedback from the actuators to the control system and shear deformation obtained by displacement sensor which measuring the relative displacement between the external constraint steel plate and intermediate steel plate. Test process requires strict control of the temperature of HRD, and the measurement of rubber surface temperature through an infrared scanner. All tests were conducted at room temperature.

Test loading cases are formulated through control indicators including loading frequency and displacement amplitude. Sinusoidal excitation method is adopted, in accordance with the law of varying sine wave input displacement $u(t)=u_0\sin(\omega t)$ to control the loading system. Loading cases of three HRDs are shown in Table 1. Due to the limited maximum dynamic load of actuator, specimen HRD-I under shear deformation γ=150% only loaded at frequency of 0.1Hz , specimen HRD-II test at shear deformation γ=100% at 2.0Hz was canceled, for the protection of the loading equipment.

Fig.3 The loading system

Tab.1 Loading cases

<table>
<tr><th>Speci-mens</th><th>Ambient temperature</th><th>Shear deformation</th><th>Amplitude (mm)</th><th>Frequency (Hz)</th><th>Cycles</th><th>Content</th></tr>
<tr><td>HRD-I</td><td rowspan="4">23±3 (ºC)</td><td>25%, 50%
75%, 100%
150%</td><td>6.25, 12.5
18.75, 25
37.5</td><td>0.1, 0.3
0.5, 1.0</td><td>5</td><td>Deformation correlation</td></tr>
<tr><td>HRD-II</td><td>25%, 50%
100%</td><td>6.25, 12.5
25</td><td>0.1, 0.3
0.5, 1.0
2.0</td><td>5</td><td>Frequency correlation</td></tr>
<tr><td rowspan="2">HRD-III</td><td>25%, 50%
75%</td><td>6.25, 12.5
18.75</td><td rowspan="2">0.3</td><td>5</td><td>Conventional performance</td></tr>
<tr><td>100%</td><td>25</td><td>30</td><td>Fatigue property</td></tr>
</table>

4. Test results and analysis

According to *Technical specification for seismic energy dissipation of buildings (JGJ297-2013)* [15] on the mechanical properties of viscoelastic dampers, the mainly examining property indicators including the damping force $P_{\max}$, storage shear modulus G', loss shear modulus G'' and loss factor η. As the high damping rubber damper is made of non-linear high damping materials of which hysteresis curve shape is very different than oval, the equivalent viscous damping ratio ξ is used to evaluate the energy dissipation capacity of HRD instead of loss factor [10]. The mainly mechanical property indicators of HRD are defined as follows:

(1) Shear strain is $\gamma = u_0 / t$, where u_0 is shear displacement of the damper, t is viscoelastic layer thickness of the damper;

(2) Storage shear modulus is $G' = \tau' / \gamma$, where $\tau' = P' / A$, where P' is the force corresponding to the maximum displacement, where A is the area of viscoelastic layer;

(3) Loss shear modulus is $G'' = \tau'' / \gamma$, where $\tau'' = P'' / A$, where P'' is the force corresponding to zero displacement;

(4) The maximum damping force is $P_{\max} = (|P_{\max}^{+}| + |P_{\max}^{-}|)/2$, where $P_{\max}^{+}$ and $P_{\max}^{-}$ is positive and negative maximum damping force;

(5) Equivalent viscous damping ratio is $\xi = \Delta W / 4\pi W$, where ΔW is the area of hysteresis curve of damper, where $W = P' u_0 / 2$ is strain energy corresponding to maximum deformation.

According to *Dampers for vibration energy dissipation of buildings (JG/T209-2012)*, the 3rd lap of hysteresis curves will be used in the calculation of the mechanical properties of dampers as given in (1) to (5) under various conditions[16].

4.1 Specimen consistency verification

For verify the consistency of three HRD specimens, a verification test procedure that consists of 5 load cycles at shear deformation of 25% at 0.3Hz was applied for three HRD specimens during formal tests to compare the differences of mechanical properties. The loading cases of verification test procedure will not affect the mechanical properties of the subsequent tests, which is the part of formal tests. Fig.4 shows shear displacement-damping force curves of three HRD specimens for consistency verification under the same loading condition.

Table 2 shows mechanical properties parameters of storage shear modulus, loss shear modulus, the maximum damping force and equivalent viscous damping ratio of three specimens.

The results observed that three HRD specimens are consistent with small difference and stable mechanical properties whose hysteresis curves substantially in coincidence. The maximum average relative difference of various property parameters is shear storage modulus only reached 6.75%. Therefore, these three HRD specimens could be used for deformation correlation, frequency correlation and fatigue properties study respectively.

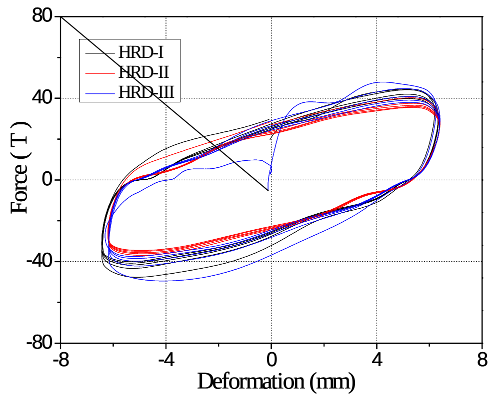


Fig.4 Hysteresis curve of different HRD specimens (γ=25% f=0.3Hz)

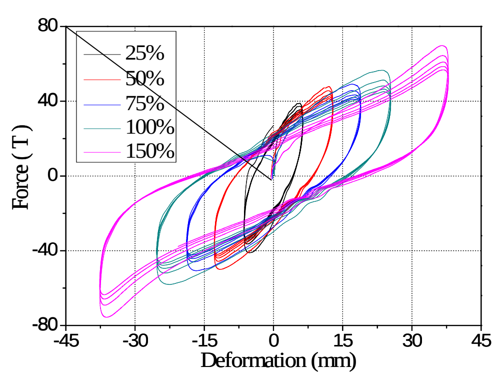
Tab.2 Mechanical properties of different HRD specimens

Specimens	G'/MPa	G''/MPa	P_{max}/T	ξ
HRD-I	6.64	5.91	37.36	0.36
HRD-II	7.60	6.54	40.58	0.35
HRD-III	7.48	6.43	39.86	0.36
Average relative difference	6.75%	6.47%	5.33%	1.85%

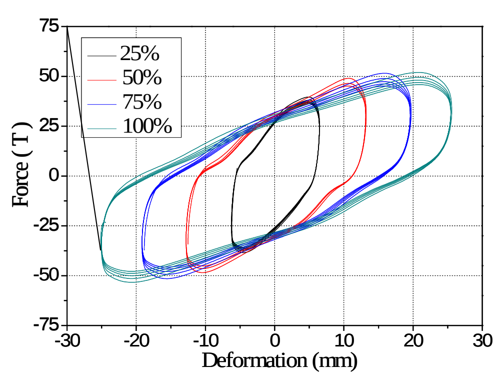
Where average relative difference $\delta = 100\% \times (\frac{II - I}{II} + \frac{III - I}{III} + \frac{II - III}{II})/3$

4.2 Deformation correlation

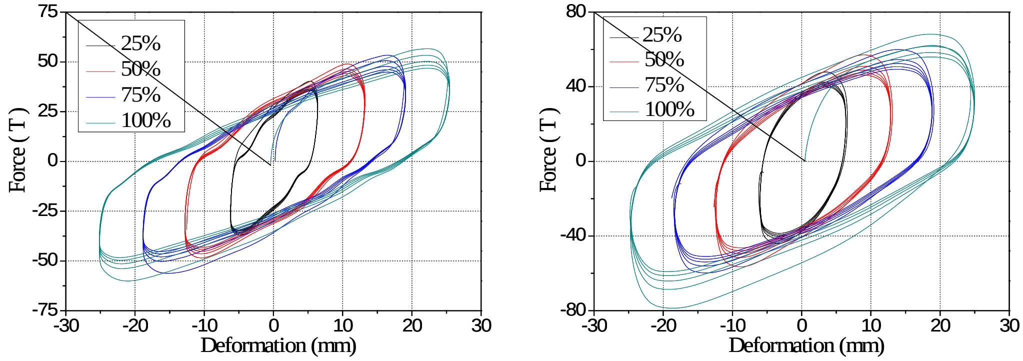
In order to investigate the effects of shear deformation on the mechanical properties of HRD, shear tests were conducted on HRD-I at up to four specific and common shear deformations of 25%, 50%, 75%, 100%, and 150% at frequencies of 0.1Hz, 0.3Hz, 0.5Hz, 1.0Hz respectively. Fig. 5 illustrate the typical force-deformation curves under various shear deformations for the HRD at four frequencies of 0.1Hz, 0.3Hz, 0.5Hz, and 1.0Hz. Moreover, Fig.6 plots the variation of storage shear modulus, loss shear modulus, the maximum damping force and equivalent viscous damping ratio for HRD with shear deformation at different loading frequencies.



(a) loading frequency $f = 0.1Hz$

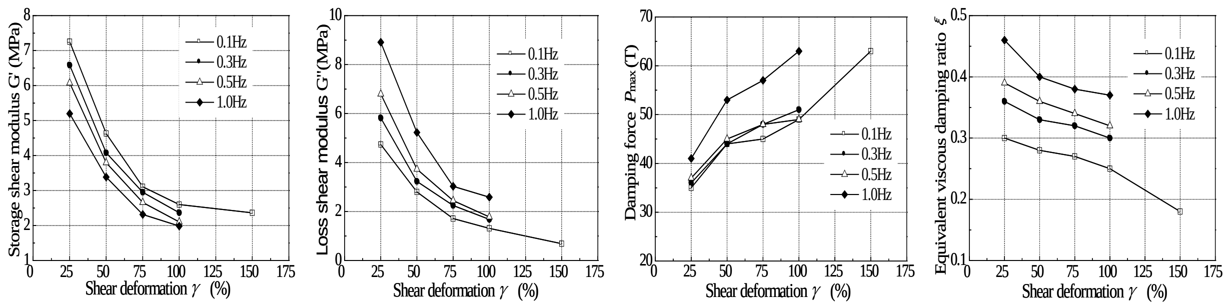


(b) loading frequency $f = 0.3Hz$



(c) loading frequency $f = 0.5Hz$ (d) loading frequency $f = 1.0Hz$

Fig.5 Hysteresis curve of HRD-I under various shear deformations at different frequencies



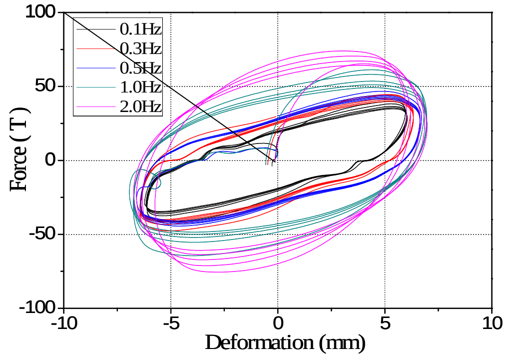
(a) (b) (c) (d)

Fig.6 variation of (a) storage shear modulus, (b) loss shear modulus, (c) the maximum damping force and (d) equivalent viscous damping ratio with shear deformation

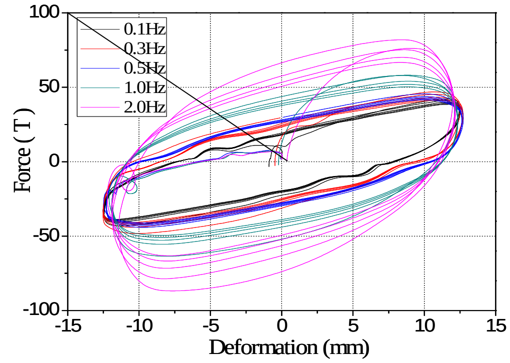
The results show that the HRD has stable performance as the variation of mechanical properties with shear deformation at different frequencies are consistent. The storage shear modulus, loss shear modulus and equivalent viscous damping ratio decreases and the maximum damping force increases with increasing shear deformation. In addition, the storage shear modulus and loss shear modulus shear decreases gradually slow with increasing shear deformation after reaches deformation of 75%. The hysteresis curves of HRD-I shown in Fig.5(a) at shear deformation of 150% at 0.1Hz illustrate the phenomenon of slightly hardening, and the equivalent viscous damping ratio began to decrease rapidly. However, the equivalent viscous damping ratio of HRD is still above 0.18 which have higher equivalent viscous damping ratio than traditional viscoelastic damper and showing a good energy dissipation capacity. On the other hand, the hysteresis curve of HRD is more full and better energy dissipation capacity with increasing loading frequency.

4.3 Frequency correlation

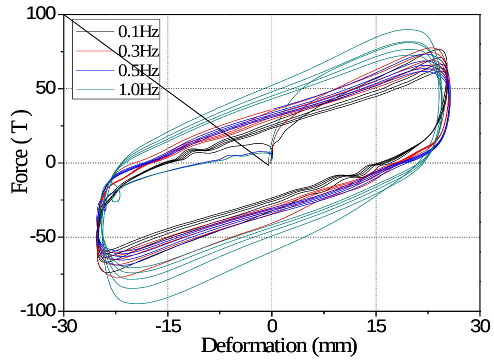
In order to investigate the effects of loading frequency on the mechanical properties of HRD, frequency tests were conducted on HRD-II at up to five specific and common frequencies of 0.1Hz, 0.3Hz, 0.5Hz, 1.0Hz, and 2.0Hz at shear deformations of 25%, 50%, and 100% respectively. Fig. 7 shows the typical force-deformation curves under various frequencies for the HRD at three shear deformations of 25%, 50%, and 100%. Moreover, Fig.8 plots the variation of storage shear modulus, loss shear modulus, the maximum damping force and equivalent viscous damping ratio for HRD with loading frequency at different shear deformations.



(a) Shear deformation $\gamma = 25\%$

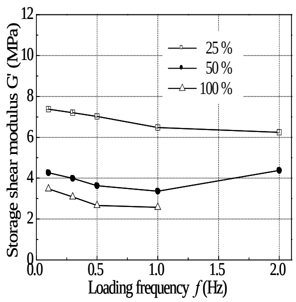


(b) Shear deformation $\gamma = 50\%$

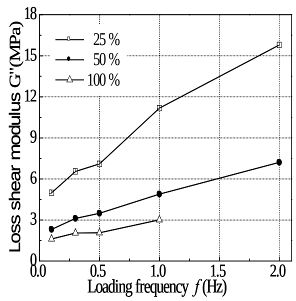


(c) Shear deformation $\gamma = 100\%$

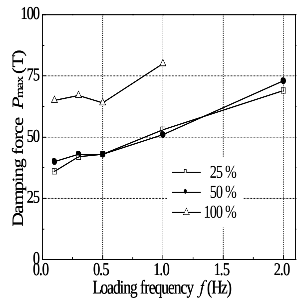
Fig.7 Hysteresis curve of HRD-II under various frequencies at different shear deformations



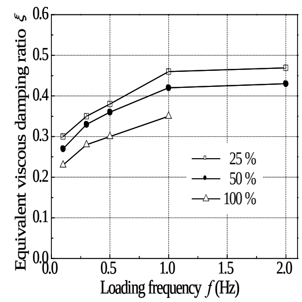
(a)



(b)



(c)



(d)

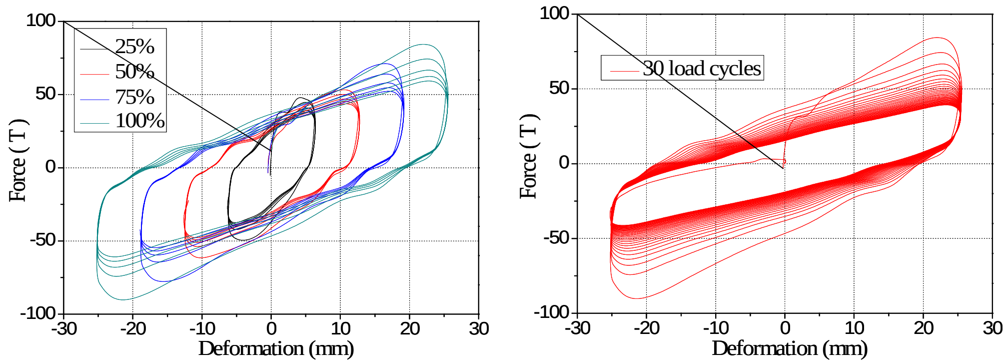
Fig.8 Variation of (a) storage shear modulus, (b) loss shear modulus, (c) the maximum damping force and (d) equivalent viscous damping ratio with loading frequency

The results reveal that loss shear modulus, the maximum damping force and equivalent viscous damping ratio increases and storage shear modulus decreases with increasing frequency at shear deformation of 25% across the frequency range of 0.1-1.0Hz. In addition, the hysteresis curve of HRD is more full and better energy dissipation capacity with increasing loading frequency.The mainly variation trendy of mechanical properties with loading frequency at shear deformations of 50% and 100% shows consistent with shear deformation of 25%. Further more, the storage shear modulus and equivalent viscous damping ratio become stable, the maximum damping force and loss shear modulus increased continuously at loading frequencies varying from 1.0Hz to 2.0Hz. However, the hysteresis curve area began to appear pronounced attenuation with the increase of loading laps at deformation of 25% and 50% at frequency of 2.0Hz. The properties seem to be more frequency sensitive at smaller shear deformation. In other words, the properties vary less at deformation of 100% than they do at 25% and 50% across the frequency range of 0.1-2.0Hz. The HRD-II shows good energy dissipation performance whose minimum equivalent viscous damping ratio above 0.23.

4.4 Fatigue property

Before fatigue test, a deformation correlation test was conducted on HRD-III specimen to research the conventional performance, with a frequency of 0.3Hz, to obtain target deformation of 25%, 50%, and 75%. Fig.9 (a) shows the hysteresis curves of HRD-III at each shear deformation, wherein the hysteresis curves at deformation of 100% obtained from the first five laps of fatigue cyclic loading test. It can be seen that the hysteresis curves of HRD-III is symmetrical and full, the variation of properties with shear deformation shows consistent with HRD-I.

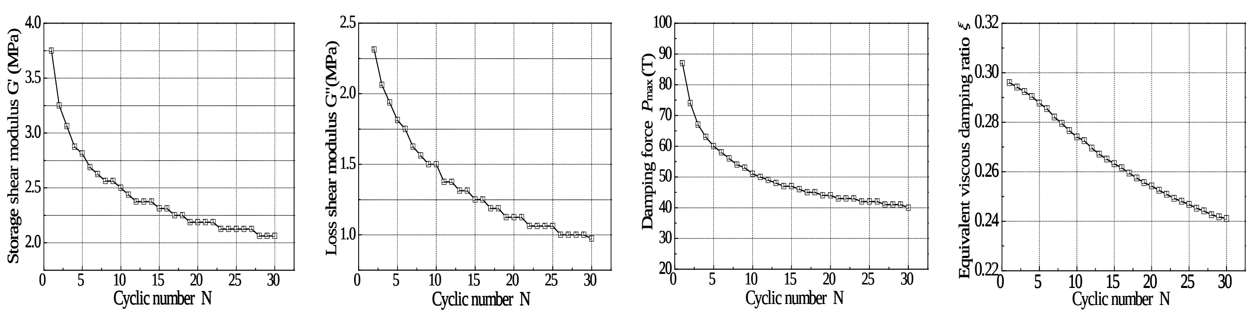
The HRD-III was put on hold for 30 minutes after deformation correlation test, until the damper temperature lowered to ambient temperature stability. In order to investigate the fatigue property of HRD, cyclic loading that consists of 30 load cycles at shear deformation of 100% at frequency of 0.3Hz were applied. The 30 laps cyclic loading hysteresis curves shown in Fig.(b) illustrate the hysteresis curve area, which signifies the energy dissipation, decrease with increasing cyclic number.



(a) (b)

Fig.9 Hysteresis curve of (a) deformation correlation test and (b) fatigue test

Fig.10 plots the variation of storage shear modulus, loss shear modulus, the maximum damping force and equivalent viscous damping ratio for HRD with cyclic number at deformation of 100% at 0.3Hz. Moreover, table 3 shows the value of mechanical properties in fatigue test at third and thirty lap. The results show that storage shear modulus, loss shear modulus, the maximum damping force and equivalent viscous damping ratio decreases with increasing cyclic number. Wherein the shear storage modulus, loss shear modulus and damping force in the first 10 laps decreased rapidly , and then gradually slow.The equivalent viscous damping ratio varies from 0.29 at third lap to 0.24 at thirty lap, which corresponds to a 17.24% decrease. While the same decrease is 32.65%, 52.91% and 39.74% in storage shear modulus, loss shear modulus and the maximum damping force respectively. However, The HRD shows good energy dissipation performance whose minimum equivalent viscous damping ratio above 0.24 after 30 load cycles.



(a) (b) (c) (d)

Fig.10 Variation of (a) storage shear modulus, (b) loss shear modulus, (c) the maximum damping force and (d) equivalent viscous damping ratio with cyclic number

Tab.3 Value of mechanical properties in frequency test

Cyclic number	G'/MPa	G''/MPa	P_{max}/T	ξ
3	3.06	2.06	67.34	0.29
30	2.06	0.97	40.58	0.24
Attenuation ratio	32.65%	52.91%	39.73%	17.24%

5. Conclusions

Three high-damping rubber damper specimens have been produced in this paper, which is made of a new formulation of isoamyl high damping rubber material. And cyclic loading experiments are conducted to study on the deformation correlation, frequency correlation and fatigue property of HRD. The conclusion is as follows:(1) The HRDs have full hysteresis curves with high equivalent viscous damping ratio, showing good energy performance;(2) The storage shear modulus, loss shear modulus and equivalent viscous damping ratio decreases and the maximum damping force increases with increasing shear deformation; (3) The shear modulus loss, the maximum damping force and equivalent viscous damping ratio increases, small changes in the storage shear modulus and the hysteresis curves are more full with increasing loading frequency; (4) The mechanical property parameters decreases with increasing cyclic number in the fatigue tests, wherein the shear storage modulus, loss shear modulus and damping force in the first 10 laps decreased rapidly, and then gradually slow. However, the mechanical properties parameters have greater attenuation in the fatigue tests and fatigue properties need to be further improved and enhanced.

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