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STUDY ON LRB PERFORMANCE OF HIGH-RISE BASE-ISOLATED BUILDING DURING STRONG WIND

Osamu KOCHIYAMA[1], Masayoshi IKENAGA[2], Takahito NAKAMURA[3], Shuhei KANEKO[4]
Yasuo TAKENAKA[5], Kazuhide YOSHIKAWA[6], and Akira WADA[7]

SUMMARY

The purpose of this study is to investigate the characteristics of LRB's (: Lead Rubber Bearing) installed in a high-rise building, during extended strong wind excitation by experiment and analysis. Firstly, the experiment for a five-hour-long wind load test on this LRB isolation system was performed. Results indicated no dramatic increase in the temperature inside the LRB. Secondly, to establish a relationship for wind load amplitude dependency, a 2-hour-long sinusoidal load test was performed. Results obtained, indicated characteristics for the temperature inside an LRB to increase, as well as providing a valuable insight into the residual deformation resulting. Furthermore, the experimental results and the heat analysis corresponded well. It was found that the performance of LRB, which is installed in a high-rise building, is hardly influenced by strong wind load.

INTRODUCTION

Recently, application of base-isolation for high-rise buildings has increased. Many high-rise base-isolated buildings have a greater ratio between wind load and yield load in the seismic isolation interface than comparative middle-rise base-isolated buildings. This greater ratio requires careful attention to wind response when designing high-rise base-isolated buildings, due to the possibility of large creep deformation caused by wind load with certain seismic isolation materials. Building designers would also do well to have knowledge about temperature changes caused by repeated plastic deformation of lead plugs due to wind force. Using both experimental and analytical testing, we investigated the response of a lead rubber bearing to simulated typhoon scale wind forces, as well as the internal temperature change of a test specimen caused by repeated plastic deformation of the lead plug. 2-hour continual dynamic load tests combining a constant horizontal load and sinusoidal wave load was also conducted, in order to grasp

[1] Oiles Corp.,Tochigi, Japan, kouchiyama@oiles.co.jp
[2] Oiles Corp.,Tochigi, Japan, ikenaga@oiles.co.jp
[3] Oiles Corp.,Tochigi, Japan, ta.nakamura@oiles.co.jp
[4] Oiles Corp.,Tokyo, Japan, s.kaneko@oiles.co.jp
[5] Kajima Corp., Tokyo, Japan, takenaka-yasuo@kajima.com
[6] Kajima Corp., Tokyo, Japan, yoshikawa-kazuhide@kajima.com
[7] Prof.,Tokyo Institute of Technology, Tokyo, Japan, wada@serc.titech.ac.jp

qualitatively the effect of wind load amplitude in a dynamic wind load time-history test. In the past, there have been a number of reports related to repeated wind loading tests using lead rubber bearings. However, only a few have dealt with temperature changes inside lead rubber bearings. This report investigates those characteristics through experimental testing.

RESPONSE WAVE DYNAMIC LOADING TEST

1.1 Simulated Base-Isolated Building and Dynamic Wind Load Wave

The base-isolated building shown in Figure 2 is a reinforced concrete, 25-story, 80-meter tall building having an aspect ratio of approximately 3, supported by 38 ϕ 1000mm diameter LRBs. The wind load wave was created to simulate a large-scale typhoon passing near the high-rise base-isolated building seen in Figure 2. The duration time was set to be five hours. Wind loading tests of LRB were conducted under two cases for maximum wind speed. A predicted wind load waveform associated with a 100-year return period (maximum wind speed of 51.70m/s), and a predicted wind load waveform associated with a 1,000-year return period (maximum wind speed of 63.63m/s).

1.2 Creation of a Simulated Waveform

The predicted wind load waveforms associated with a 100-year and a 1,000-year return period used in our testing are based on a calculation of the wind force exerted on an isolation apparatus as a simulated typhoon passes a simulated isolation building (Figure 2). We established a scenario for the simulated typhoon to exert wind force on the isolated building for a total of five hours, including a 150-minute approach, a 45-minute of top-speed wind, and a 105-minute departure.

1.3 Test Specimen

The test specimen shown in Figure 1 is a ϕ 500mm diameter LRB which is reduced in scale by one-half from real scale. Table 2 indicates the internal composition of the test specimen.
Figure 3 shows a hysteresis curve for the test specimen under a 100% shear strain overlaid with a design-use modified bi-linear and rubber shear stiffness. Each characteristic value showed Kd=0.82kN/mm for post yield stiffness and Qd=66.0kN for post yield load.

1.4 Test Methodology

During our tests, a constant face pressure of 12MPa (axial force of 2262kN) to the test specimen was applied. In order to maintain a consistent shear strain across each LRB, an input wave at the projected net area ratio of 1/4, which was explained at section 1.2, was applied. Dynamic wind load tests via load control for the input wind load wave were conducted. During the load-control tests, the feedback load cell in the test equipment was situated in a position so as not to be affected by friction force.

Table 2 Specification

	Assumed Real Scale LRB	Half-scale LRB
Rubber	NR	
Outer Dia [mm]	1000	500
Lead Plug Dia. [mm]	200	100
Total Thickness of Rubber Layer [mm]	204	102
S1	41.7	
S2	4.9	

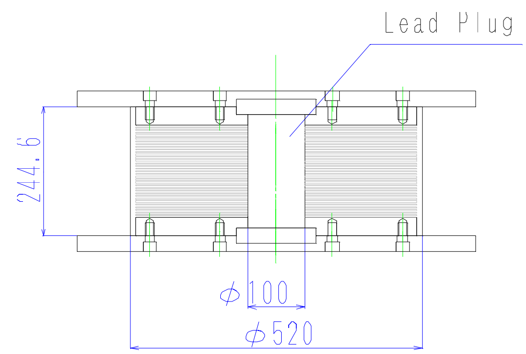


Fig.1 Specimen (Half-scale)

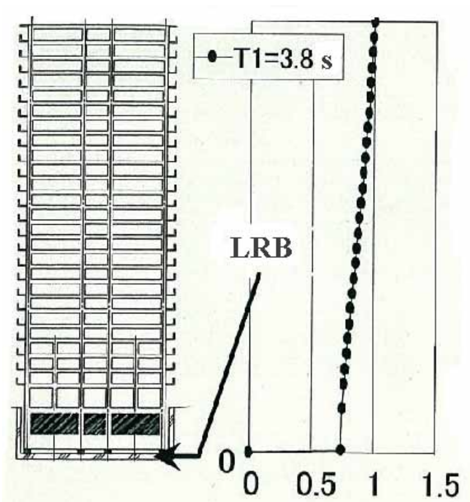


Fig. 2 Simulated High-Rise Base-Isolated Building

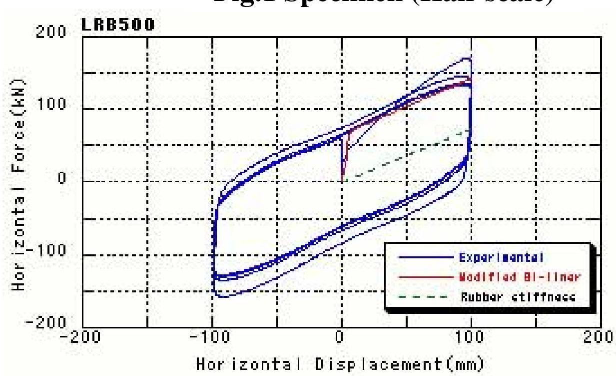
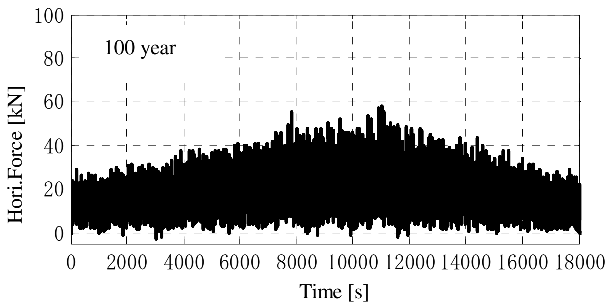


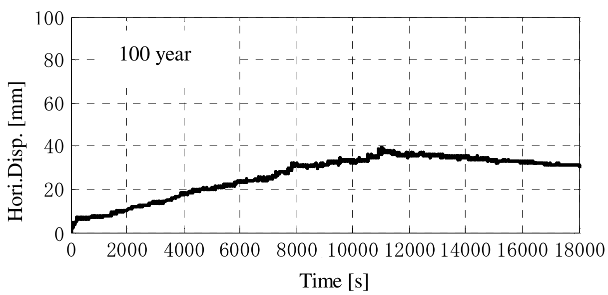
Fig. 3 Basic Sample Performance

1.5 Test Results

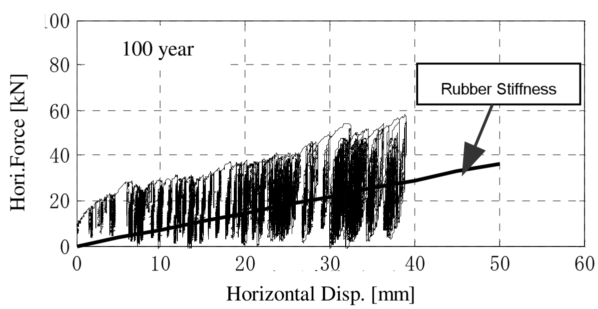
Figures 4 and 5 show the respective test results for the predicted wind load waveforms associated with a 100-year and 1,000-year return period. The maximum deformation for the dynamic wind load tests shown in Figures 4 (b) and 5 (b) is at approximately 12,000 seconds at the vicinity of the input wave peak. Recovery began once the peak passed. After the conclusion of the dynamic wind load test, the vertical load was maintained at test levels, which resulted in residual deformation recovery back to 25mm, measured at approximately 12 hours after test conclusion. The maximum deformation during the dynamic wind load test was 39.1mm for the predicted wind load waveform associated with a 100-year return period, and 61.6mm for the predicted wind load waveform associated with a 1,000-year return period. Converting this displacement magnitude to real-scaled LRB from the proportionate measurements of the test specimen resulted in a 123.2mm value for the predicted wind load waveform associated with a 1,000-year return period. As shown in Figures 4(c) and 5(c), the core of the Fig.3 Basic Sample Performance load amplitude for the test specimen is almost equivalent to the restoring force of the rubber. This is because for the original point of the lead plug plastic strain, the wind force mean component and the rubber restoring force move across a common displacement range. As shown in Figures 4(d) and 5(d), the temperature change for the lead plug core over the course of dynamic wind load testing was 16.5℃ to 17℃ for predicted wind load waveform associated with a 100-year return period, and 16.5℃ to 17℃ for the predicted wind load waveform associated with a 1,000-year return period, almost no change.



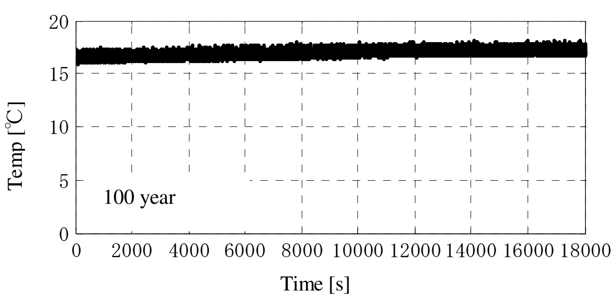
(a) Horizontal Force



(b) Horizontal Displacement

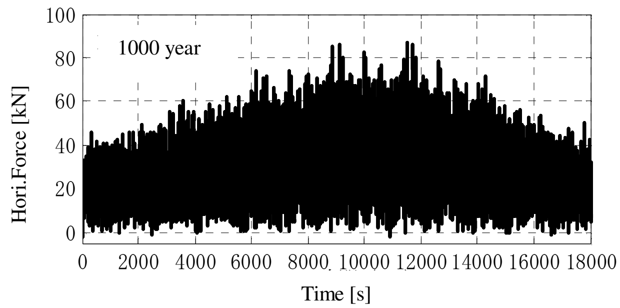


(c) Hysteresis Loop

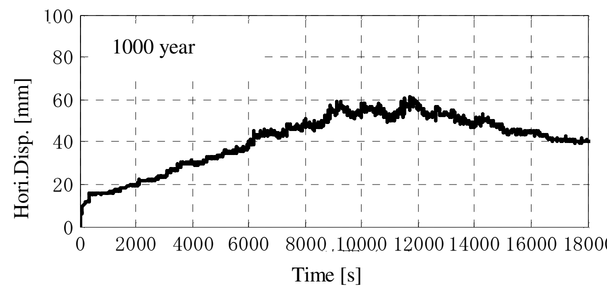


(d) Temperature at Center of Lead

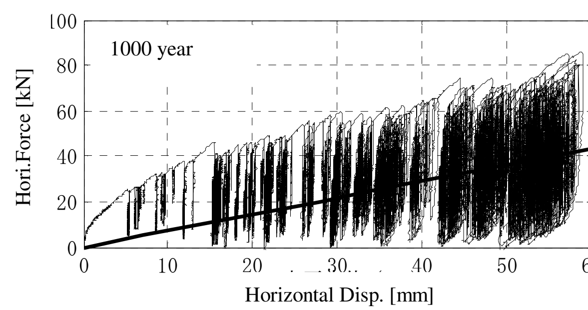
Fig. 4 Test Results for 100-Year Return Period Predicted Value



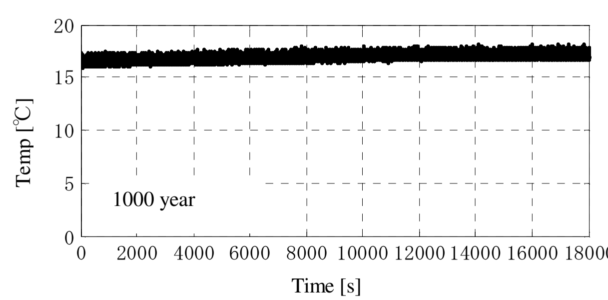
(a) Horizontal Force



(b) Horizontal Displacement



(c) Hysterisis Loop



(d) Temperature at Center of Lead

Fig. 5 Test Results for 1000-Year Return Period Predicted Value

1.6 Simulation Analysis for Wind Response Dynamic Loading Tests

Simulations utilizing convenient methods for estimating winds response (Ref.1) were conducted, taking into account the creep propensity of the LRB. As shown in Figure 6, the simulations were conducted by separating the wind load into a static component and a dynamic component.

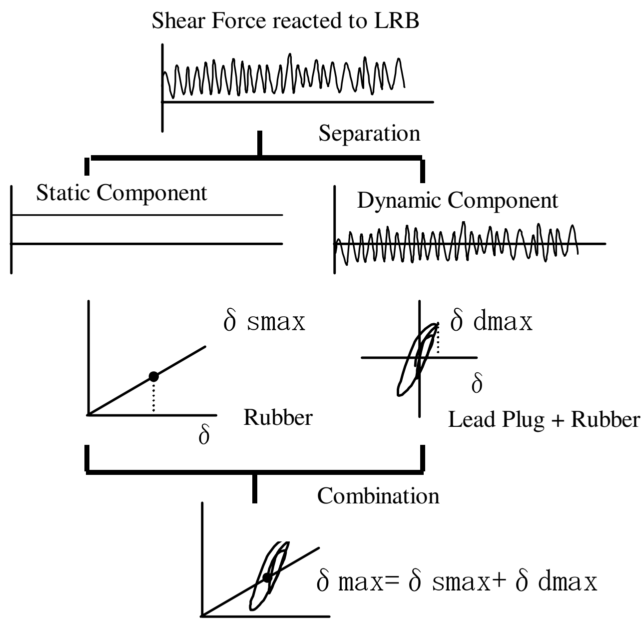
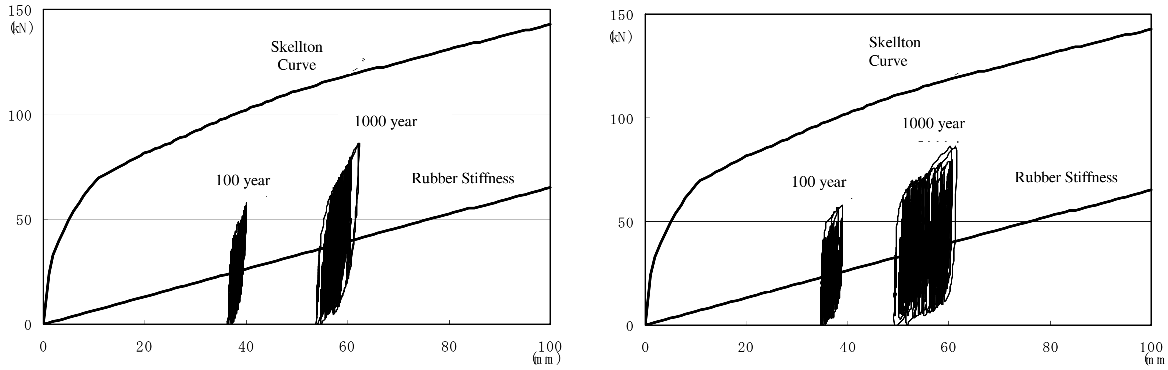


Fig.6 Convenient method for estimating wind response

By subtracting the static load from the dynamic load obtained from the wind response dynamic loading tests, the static component and the dynamic component were separated. The rubber stiffness for applying to the static component was not the design value, but rather the experimental value 0.654kN/mm (face pressure σ =12MPa (2261.9kN) and shear strain γ =±100%（102mm） .The analytical model for applying dynamic component was a modified HD model along with design values for the various specifications. Also, the coefficient of a modified HD model for small amplitudes of horizontal deformations was used γ =0.5. Figure 7(a) showed analytical and Figure 7(b) showed experimental hysteresis loop results for dynamic wind loading tests. Simulation analysis was conducted between 10,800 seconds and 12,000 seconds, the time band in which testing deformation is larger.



(a) Analytical Results **(b) Experimental Results**

Fig. 7 LRB Shear Force - Deformation Relationship

Comparing the experimental value and the simulation results for LRB shear strain shows near matching numbers, with the maximum analytical value for the dynamic wind load test for a predicted wind load waveform associated with a 100-year return period being 40mm, while the experimental result was 39mm. The maximum analytical value for the dynamic wind load test for a predicted wind load waveform associated with a 1,000-year return period was 62mm vs. a 62mm value from the experimental results.

SINUSOIDAL WAVE DYNAMIC LOADING TEST

In order to qualitatively grasp the effect of wind load amplitude on the previously introduced time history dynamic wind load test, we conducted two-hour continual dynamic load tests combining constant horizontal load and sinusoidal load. The effects of the load amplitude of the input wave, the test frequency, and constant horizontal force were experimentally investigated. Real-time measurements of temperature changes inside the LRB were also conducted.

2.1 Testing Conditions

Extended (two-hour) continual dynamic load tests on combined static and sinusoidal horizontal wave loads were conducted, experimentally investigating characteristics given off from fluctuated load components for the wind response wave. The face pressure (axial force 2262kN) was constant at σ =12MPa, and the fluctuated load component and frequency were changed as Table2 so that a comparison of constant horizontal load: Q and sinusoidal horizontal load amplitude: ΔQ was $\Delta Q/Q=1$ (Figure 8). For the sinusoidal wave test period: T=3 seconds, we changed the load amplitude from 13±13kN to 66±66kN.

Table2 Test Condition

σ : 12MPa		Q± ΔQ [kN]				
		13±13	33±33	44±44	66±66	0±66
f [Hz]	0.22	-	-	○	-	-
	0.33	○	○	○	○	○
	0.5	-	-	○	-	-

Test conditions are shown in Table 1. (characteristic value=66kN, which was equivalent to the LRB yield load). In order to clearly observe the internal temperature change within the lead rubber bearing during dynamic wind load testing, we inserted a temperature sensor inside the lead rubber bearing. The position of the temperature sensor is shown in Figure 10.

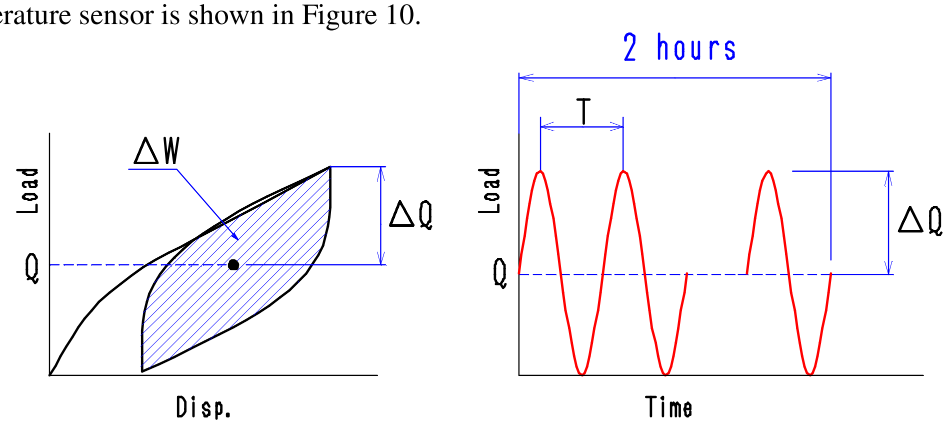
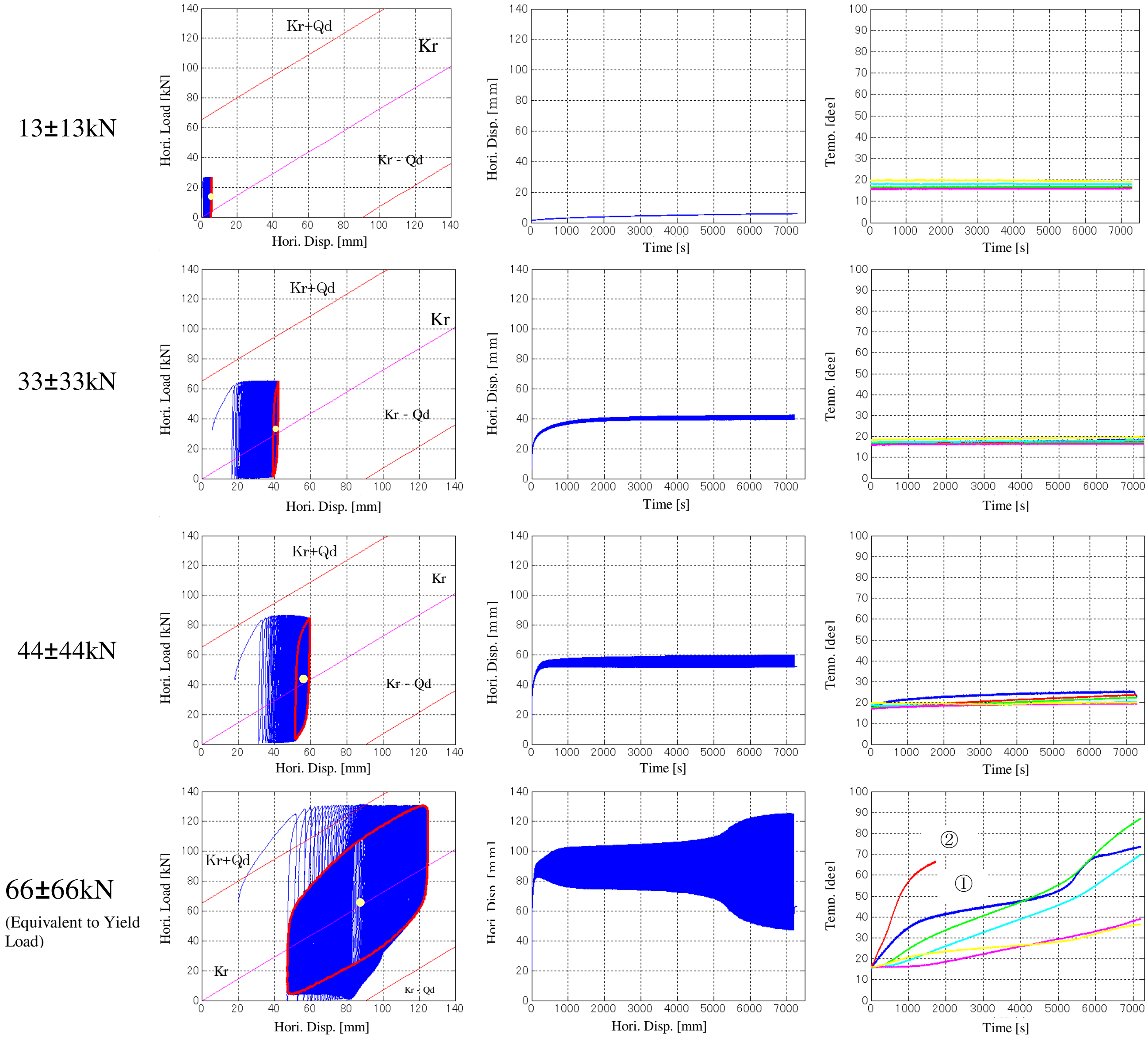


Fig. 8 Sinusoidal Wave Dynamic Load

2.2 Load Amplitude Dependence

Figure 9 shows the test results. The point in the central area of the hysteresis loop indicates the load – displacement center point for the last hysteresis loop cycle, while the solid lines indicate the respective Kr±Qd, derived by adding horizontal stiffness(:Kr) of the rubber portion only and LRB yield load equivalent: Qd. The center of the hysteresis loop displacement amplitude increases steadily from the start of testing, eventually becoming a constant value (Figure 9(b)); however, the time needed to become a constant decreases as the horizontal load gets larger, whereas the time needed increases when the horizontal load is a smaller value, such as 13±13kN. The temperature inside the lead rubber bearing showed relatively little increase at Q±ΔQ=13±13kN, 33±33kN for the two-hour test. For 44±44kN, initial temperature: 18℃ increased to 27℃. The lead plug internal temperature for the 66±66kN test rose rapidly. Since the temperature sensor at ② in the plug core was broken during testing, the ultimate temperatures reached after two hours of testing could not be measured; however, making an estimate based on the temperature trends at ① in the upper section of the lead plug, it should be that the temperatures of the lead plug core subsequent to the temperature sensor breakage would have leveled off. Without respect to the size of the load amplitude, the central point of the hysteresis loop after two hours of testing approaches the Kr value of the rubber only. When the maximum value of the amplitude is less than a value equivalent to the LRB yield load, a stable hysteresis loop is depicted, once the center point reaches the vicinity of the Kr. For Q±ΔQ=66±66kN, the progression of the time history horizontal amplitude in Figure 9(b) is stable around 5,000 seconds; however, it increases sharply after that. At the same time the energy absorption caused by lead plug plastic deformation increases, resulting in rising lead plug temperatures (② in Figure 9(c)). For the large load amplitude Q±ΔQ=66±66kN, the temperature at lead plug: ① rose from 17℃ at the beginning of the test to 74℃ after two hours. The surface temperature of the specimen rose from 17℃ at the beginning of the test to 39℃ at the end of the test. While the temperature at the top of lead plug:② increased at 5,000 seconds after the start of the test, the ultimate temperature leveled off and stayed at a stable value. With respect to the load amplitude of the equivalent value of the yield load, the displacement amplitude of the LRB demonstrated stable behavior at the end of the test. Confirming the performance of the lead rubber bearings before and after this series of tests, there were little characteristic changes of the LRB.



(a) Displacement - Load (b)Time-Horizontal (c) Time - Temperature

Fig.9 Sinusoidal Wave Test Result

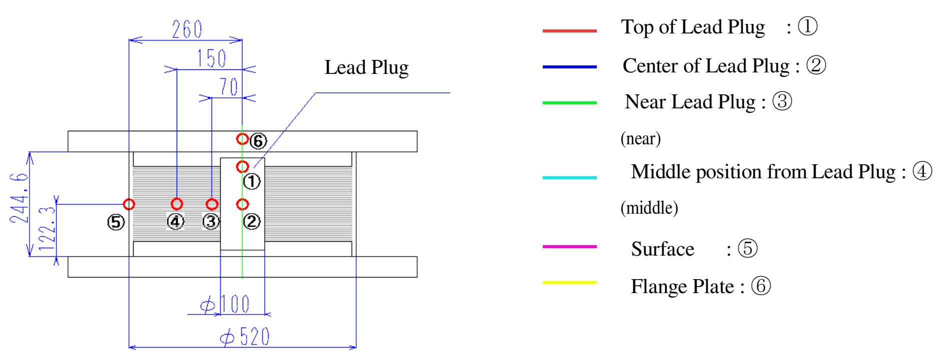


Fig.10 Measuring Point of Temp.

Figure 11 shows the changes in the accumulated absorbing energy of the hysteresis loops. Similar to the discussion above, at a load amplitude (66±66kN) equivalent to yield load: Qd, accumulated absorbing energy increases markedly, but does not increase radically at lower conditions.
It was calculated that an approximation from the results of the accumulated absorbing energy of the hysteresis loops of the combined static and sinusoidal horizontal wave loads, indicated by broken lines. When the load amplitude is in excess of 5,000 seconds at 66kN, we encounter a discrepancy between the experimental results and our approximation. At lesser load amplitudes, we see almost no discrepancy, indicating that our approximations provide a sufficient description. Therefore, we believe that we can reasonably estimate the time history accumulated absorbing energy of hysteresis loops for other load amplitude conditions not tested on the ϕ 500（f=0.33Hz） LRB used in our experiments.

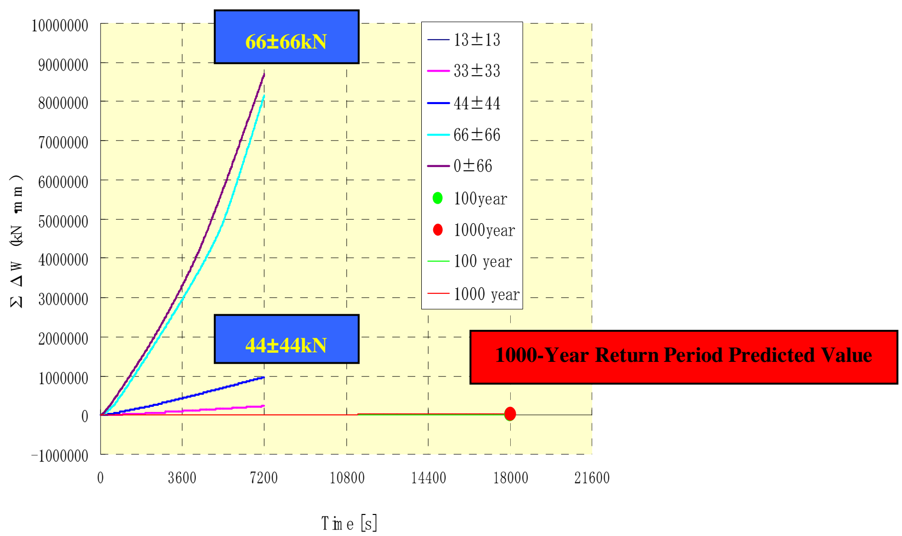


Fig.11 Accumulated Consuming Hysteresis Energy

2.3 Zero-Point Focused Sinusoidal Wave Dynamic Load Test

Figure 12 shows the results of two-hour continual force testing focused on zero-point 0±66kN which does not have an added constant horizontal load. In comparison to an added constant horizontal load (Figure 12(a) 66±66kN), the horizontal displacement amplitude relative to a time history focus is somewhat larger with an added constant horizontal load. The increase in internal LRB temperature is somewhat smaller when not adding a constant horizontal load. Qualitatively, the two hysteresis loops draw an almost matching history, and it was regarded that it is possible to separate the constant load component and the fluctuated load component for further analysis.

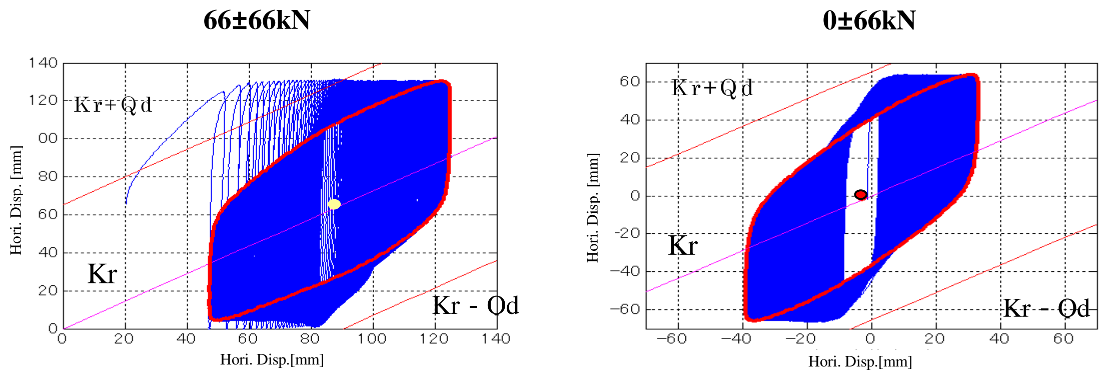


Fig.12 Effect of Static Wave Factor

2.4 FEM Heat Analysis

The heat generation conditions set for the analytical model assumed that only the plug area would generate heat caused during horizontal testing. In other words, we converted the absorbed energy of the hysteresis loop (: ΔW) obtained via dynamic load testing of ϕ 500LRB to a heat release value, applying the changing values over a given time history to the lead plug.

Figure 14 shows the analytical and experimental results of load amplitude: 66±66kN. The analytical value was somewhat lower than the experimental value; however, they were extremely closely matched both qualitatively and quantitatively.

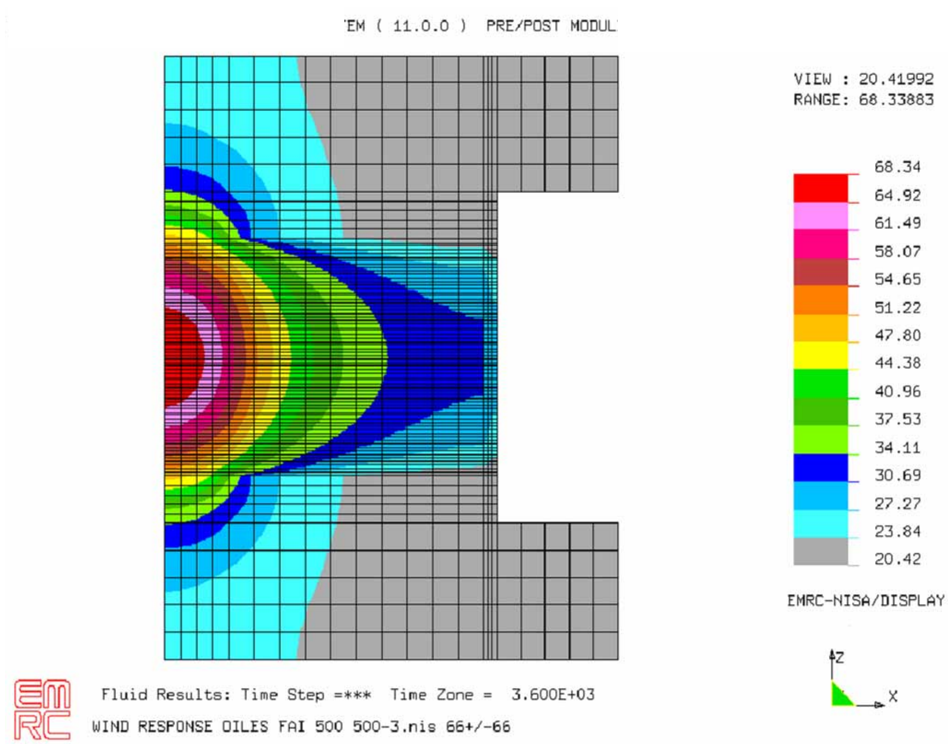
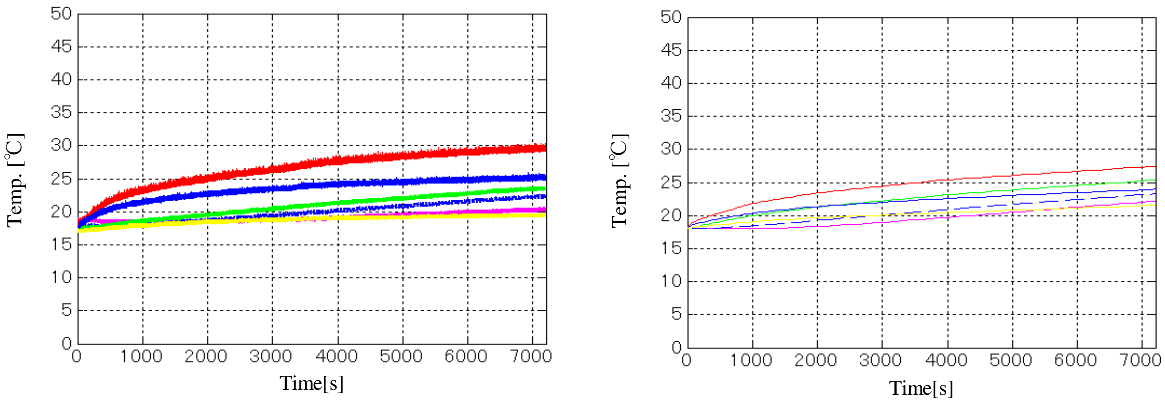


Fig.13 FEM Heat Analysis



(a) Experimental Result (b) FEM Analytical Result

Fig.14 FEM Heat Analysis and Experimental Result

CONCLUSION

The following results based on our time history LRB dynamic wind load tests were obtained.

1. The center of the load amplitude for the test specimen under dynamic wind loading test was very nearly the same as the restoring force of rubber.
2. The maximum deformation of LRB for the predicted wind load waveform associated with a 1,000-year return period was 61.6mm, or 123.2mm when converted to real-scaled LRB.
3. Internal and external temperature of LRB did not change a significant amount during dynamic wind loading test.

In addition, dynamic loading tests for wind load with LRB were conducted, and confirmed the following:

4. The central point of the hysteresis loop generated by long-term fluctuating sinusoidal wave loads approaches the horizontal shearing rubber stiffness value: Kr; this point never exceeded the Kr value.
5. The greater the load amplitude, the less time it takes for the mean component of the horizontal displacement to stabilize.
6. As long as the lead plug does not reach the equivalent yield load of LRB (where γ =100%) for the LRB to the fluctuating sinusoidal wave load, temperature inside the LRB including the lead plug dose not increase much.
7. If the horizontal load applied to the LRB reached the equivalent LRB yield shear load (where γ =100%), the lead plug generated heat, and horizontal amplitude increased. However, stability was ultimately reached, at which point no great fluctuations occur.
8. As the frequency increases, the temperature inside the LRB increased; however, there were no great differences between the hysteresis loop and the horizontal displacement characteristics.
9. Dynamic wind loading tests with zero-point focus and tests with added constant horizontal force result were in similar qualitative and quantitative results.

The following via FEM Thermal Analysis were confirmed:

10. The experimental and analytical values for temperature changes over time inside the LRB were both qualitatively and quantitatively the same and it was possible to successfully estimate the actual time history temperature distribution inside the LRB.

AKNOLEDGEMENT

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REFERENCE

1. Takenaka, Y., et al., "Convenient Method for Estimating Base-Isolated Tall Building Response To Strong Winds Incorporating Creep Characteristics of Lead-Plugged Rubber Bearing", Journal of Struct. and Constr. Eng., Transactions of AIJ, No.561, 89-94, Nov., 2002
2. Suzuki, Y., et al., "Dynamic Loading Test for Isolator at Base-Isolated Tall Building against Typhoon", Proceedings of 16th National Symposium on Wind Engineering, JAPAN, pp417-422, 2000