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STUDY ON BASED-ISOLATION OF WOODEN HOUSES BY HEAT HARDENING PORYURETHANE RUBBER

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SUMMARY

This paper investigates effectiveness and mechanical characteristics of heat hardening polyurethane rubber (PUR) for viscoelastic dampers in based-isolated and vibration controlled wooden houses. Since PUR shows low stiffness and high damping compared with the conventional viscoelastic materials, it is suitable for based-isolated device for small-scale structures such as wooden houses. In addition, PUR is not expensive so it is possible to build up based-isolated system in low cost. From the results of sinusoidal loading tests of PUR, the mechanical characteristics are estimated. PUR has frequency dependency, strain dependency, temperature dependency, and axial pressure dependency. Especially in them, axial pressure dependency is important. Because there is the problem of axial pressure dependency that equivalent stiffness of PUR increases with the increment of pressure, when it is used as based-isolation device. The Kelvin-Voigt model is build up based on the results of test. In this study, laminated PUR bearing is proposed to control axial pressure. From the results of vibration test for the laminated PUR bearing, low equivalent stiffness and high equivalent viscous damping factor is observed even if axial pressure exists. The results of seismic response analysis show the effectiveness of laminated PUR bearings for based-isolated structures.

INTRODUCTION

The purpose of a based-isolated structure is not transfer1ing energy of an earthquake to an upper structure. A structure is separated from the ground by the isolator and absorbs energy of earthquake with dampers. Therefore, based-isolation devices are required for vertical strength, low stiffness, and high damping. However, the usual based-isolation devices for wooden house are difficult for realization of these points. Because weight of wooden house is small, it is difficult to lengthen a natural period. And the cost for

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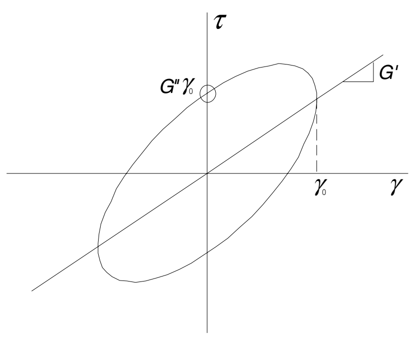
based-isolation devices becomes high. Since PUR shows low stiffness and high damping compared with the conventional viscoelastic dampers, it is suitable for based-isolated device for small-scale structures such as wooden houses. In addition, PUR is not expensive so it is possible to build up based-isolated system in low cost. It is inserted between base of house and ground sill. The role of isolator and damper is available by PUR. In this study, based-isolation device using PUR is proposed.

VISCOELASTIC MATERIAL

Fundamental Mechanical Characteristic

Viscoelastic material is the high polymer material having the character of viscosity and elasticity. Viscocity means that material shows reactive force by viscous resistance proportional to speed. Elasticity shows the force proportional to deformation. Recently, in a field of architecture, it is spreading widely as viscoelastic damper aiming for energy absorption in vibration control structure. Viscoelastic material can absorb vibration energy by resistance with histerisis loop (Fig.1). This damper performs high energy absorption from small amplitude such as vibrations of wind and traffic to large earthquake. For that reason, it is effective in vibration control of structure.

Fundamental mechanical characteristic of PUR is represented by equivalent stiffness (K_{eq}), equivalent damping coefficient (C_{eq}), and equivalent damping factor (h_{eq}). Resisting force of viscoelastic material is proportional to cross section area (A_s) and shear thickness (d). Fundamental mechanical characteristic of PUR is able to be estimated by small-sized test piece. Therefore, it can be estimated shape factor.



$$K_{eq} = \frac{A_s}{d} G'$$

$$C_{eq} = \frac{\eta K_{eq}}{\omega}$$

$$h_{eq} = \frac{1}{4\pi} \cdot \frac{\Delta W}{W} = \frac{\eta}{2}$$

Loss factor $\eta = \tan\delta = \frac{G''}{G'}$

γ_0 : Maximum shear strain

ΔW : Absorbed energy

Fig.1 Histerisis loop of viscoelastic material

Mechanical characteristic can be divided into viscosity and elasticity. In case of sin wave, shear stress (τ) can be represented as $\tau = G' \gamma_0 \, sin(\omega t) + G'' \gamma_0 \, cos(\omega t)$ with storage modulus (G') and loss modulus (G''). In this numerical expression, the first term of the equation shows elasticity, and second shows viscosity.

SIN WAVE VIBRATION TESTS OF PUR

Outline of Experiment

It is known that fundamental mechanical characteristics of viscoelastic materials are influenced by temperature, frequency, and share strain. In this study, PUR is developed for based-isolation device of wooden house. So, it is necessary to investigate fundamental mechanical characteristics and dependencies. Fig.2 shows test piece (section: 50*50mm, thickness: 5, 10, 20, 40mm). When it use for wooden house, several tens of PUR (section: 100*100mm) set between base and ground sill. Therefore, in this test, four test pieces are tested as one set.

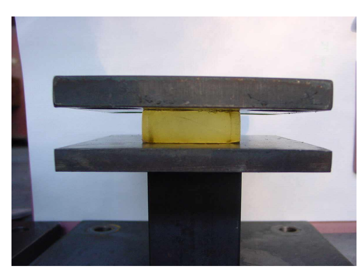


Fig.2 Test piece

Loading system is shown in Fig.3 and Fig.4. For adding axial pressure equally, four test pieces are fixed on the ground sill, and weights are set on them. In addition, two supports are set to the both sides of weights in order to restrict rotation. Both sides of load cell are pin joint. The number of cycles is at least 10 times. Parameters of loading are frequency (0.2~5Hz), shear strain (20~300%), temperature (-20~60 deg.), and axial pressure (0~1.0N/mm^2). Observed values of load and displacement are averaged in 2 to 10 cycles. Measurement terms are load, displacement, temperature. In the case of the test with a weight, shear stress and strain are calculated using thickness and sectional area of test piece after setting a weight.

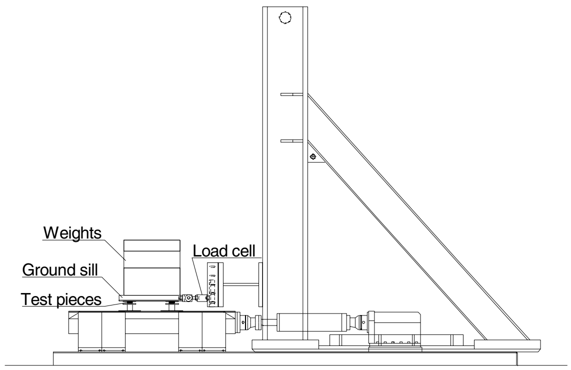


Fig.3 Loading system

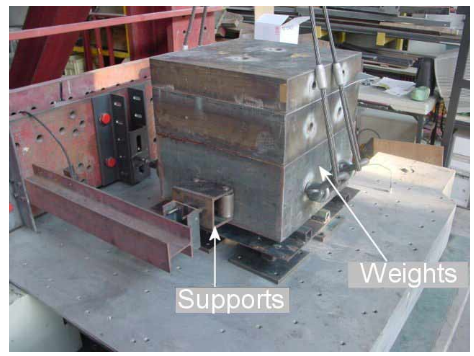


Fig.4 Experimental condition

Test Results

Histerisis loop

Fig.5 shows histerisis loop (thickness: 5mm, frequency: 1Hz, axial force: 0 or 10kN, temperature: 20deg of Celsius.). Strain-softening characteristic is observed.

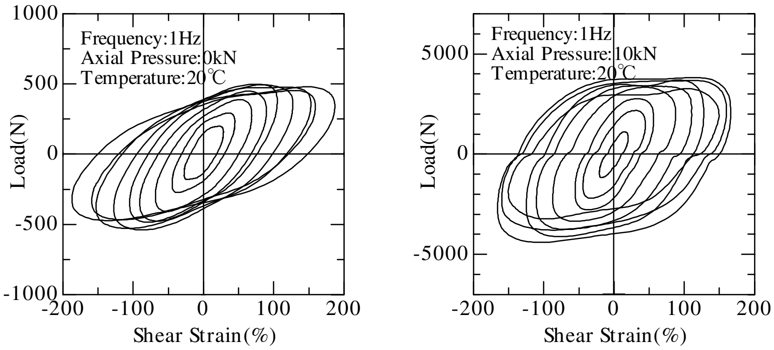


Fig.5 Histerisis loop

Frequency, shear strain dependency

The relationship between storage modulus (*G'*) and frequency, loss modulus (*G"*) and frequency are shown in Fig.6. From Fig.6, it is confirmed *G'* and *G"* increase as same as the increase in frequency, and decrease with the increase in shear strain. Equivalent damping factor (h_{eq}) is not influenced by frequency and shear strain.

Temperature dependency

The relationship between storage modulus (*G'*) and temperature, loss modulus (*G"*) and temperature are shown in Fig.7. *G'* and *G"* are influenced by temperature. Ones for 0 deg. increase as 1.5 times for 20 deg. and ones for 40 deg. decrease as 0.6 times. These values are not so large compared to ordinary viscoelastic material. In addition, equivalent damping factor (h_{eq}) show almost constant value in spite of temperature change.

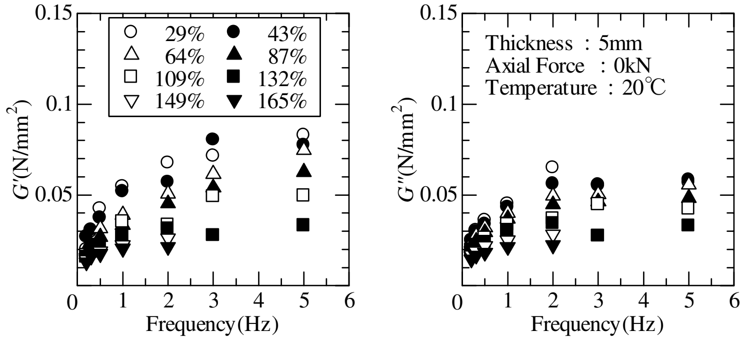


Fig.6 Frequency, shear strain dependency

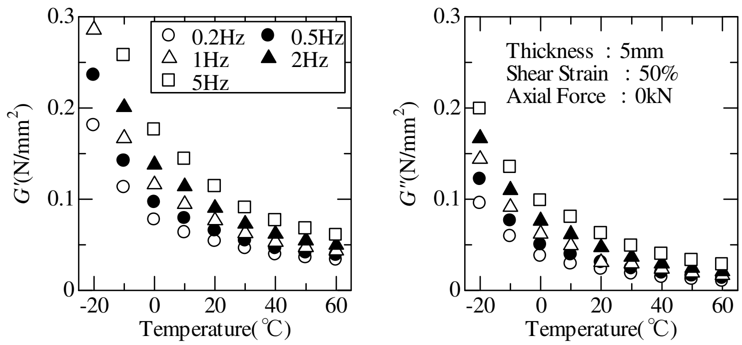


Fig.7 Temperature dependency

Thickness dependency

Resistance force of viscoelastic material is in proportional to shape factor (A_s/d). For each thickness PUR, the relationship between storage modulus (*G'*) and frequency, loss modulus (*G"*) and frequency are shown in Fig.8. Each thickness PUR show almost same value. Similar result is obtained in case of igh axial pressure as well. Therefore, thickness dependency can be estimated by shape factor.

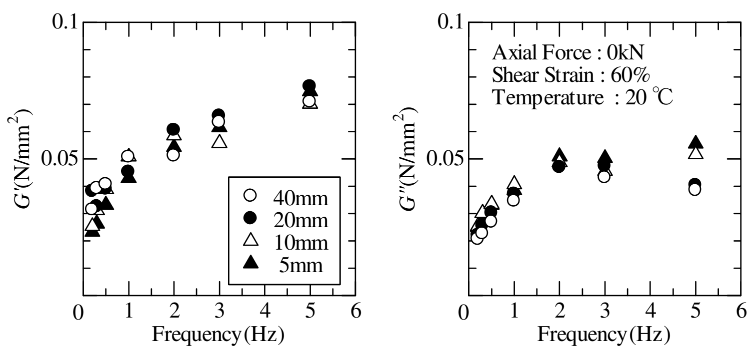


Fig.8 Thickness dependency

Axial pressure dependency

The relationship between storage modulus (*G'*) and axial pressure, loss modulus (*G"*) and axial pressure are shown in Fig.9. From Fig.9, it is confirmed that *G'* and *G"* increase as axial pressure also increases. Equivalent damping factor (h_{eq}) is not influenced by axial pressure.

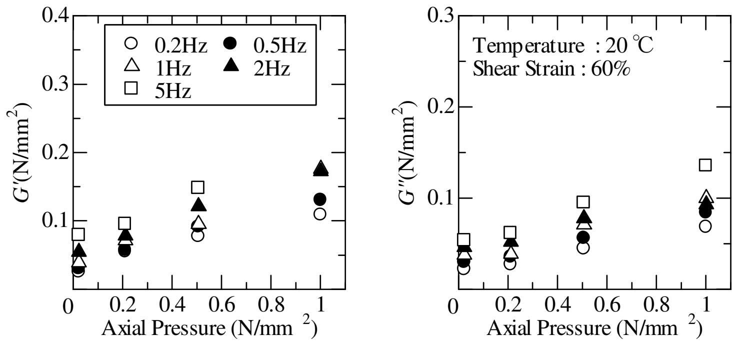


Fig.9 Axial pressure dependency

MODELING

Method of Modeling

It has been reported in the previous studies that each dependency (frequency, share strain, and temperature) of viscoelastic material can be treated independently. So, storage modulus(G'_{ref}) and loss modulus(G''_{ref}) is estimated based on the test results for shear stain of 60%, axial pressure of 0 N/mm^2, and temperature of 20 deg. Celsius. Each dependenciy is introduced as shift factor. Therefore, storage modulus (*G'*) and loss modulus (*G"*) are show in Eq.(1) and Eq.(2). Kelvin-Voigt model is used to represent constitutive law of PUR defined by G' and G''.

$$G'(f,\gamma,T,\sigma) = G'_{ref}\,(f)\cdot\rho_{G',\gamma}(\gamma)\cdot\lambda_{G',T}(T)\cdot\kappa_{G',\sigma}(\sigma) \quad (1)$$

$$G''(f,\gamma,T,\sigma) = G''_{ref}\,(f)\cdot\rho_{G'',\gamma}(\gamma)\cdot\lambda_{G'',T}(T)\cdot\kappa_{G'',\sigma}(\sigma) \quad (2)$$

ρ : shift factor for shear strain dependency
λ : shift factor for temperature dependency
κ : shift factor for axial pressure dependency

In addition, time moment frequency (f_t) is derived from Eq.(3) [1]. Therefore, time history response analysis by equivalent stiffness (K_{eq}) and equivalent damping coefficient (C_{eq}) can be carried out.

$$f_t = \frac{1}{2\pi}\sqrt{\sum_{j=1}^{n}\left|v_t^2 - v_{t-j\Delta t}^2\right| \Big/ \sum_{j=1}^{n}\left|x_{t-j\Delta t}^2 - x_t^2\right|} \quad (3)$$

v_t , x_t : velocity and displacement in time moment of *t*.

Determination of Shift Factors

Fig.10 shows the relationships between frequency and storage modulus (*G'*) for the loading case of shear strain of 60% as the base of the modeling. Indicated formula is obtained by least-square method. Fig.11 shows shift factor of each dependency. Shift factors are decided according to regression analysis by least-squares method. Although there is a little variation, each dependency can be expressed by indicated formulas. The same estimation is carried out for loss modulus (*G"*). Therefore, model of storage modulus (*G'*) and loss modulus (*G"*) considering each dependency of PUR are shown in Eq.(4) and Eq.(5).

$$G' = 0.0578 f^{\,0.411}\cdot e^{-0.590\gamma}\cdot(0.628+2.53\sqrt{\sigma})\cdot\left(\frac{65.6}{45.9+T}\right)^{1.46} \quad (4)$$

$$G'' = 0.0513 f^{0.252} \cdot e^{-0.486\gamma} \cdot (0.631 + 2.45\sqrt{\sigma}) \cdot \left(\frac{101}{81.7 + T}\right)^{2.80} \quad (5)$$

f : frequency(Hz), γ : share strain(%), σ : axial pressure(N/mm^2), T : temperature(degree)

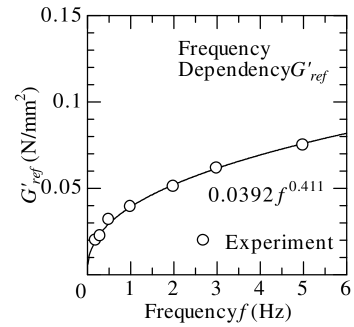


Fig.10 Base storage modulus (G')

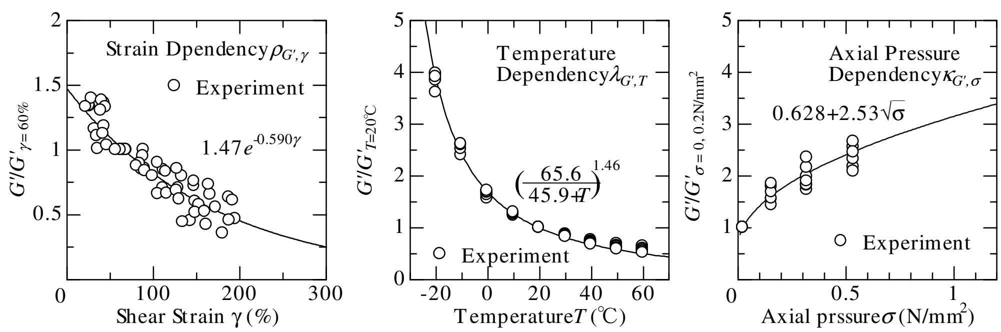


Fig.11 Shift factor of each dependency

Adaptability of Model

Comparisons between test results and model are shown in Fig.12. Modeled histerisis loops show a good agreement with test results. Fig.13 shows comparison between result of randomly dynamic loading response test and analytical result using proposed model. The response analysis is carried out using single-mass model in which the upper part of structure is assumed to be rigid body. The based-isolation layer is represented by proposed Kelvin-Voigt model. The analysis is done by direct integration using Newmark β method. Input wave is time history data which is acceleration obtained by vibration table in the response test Result of experiment and analysis show a good correspondence.

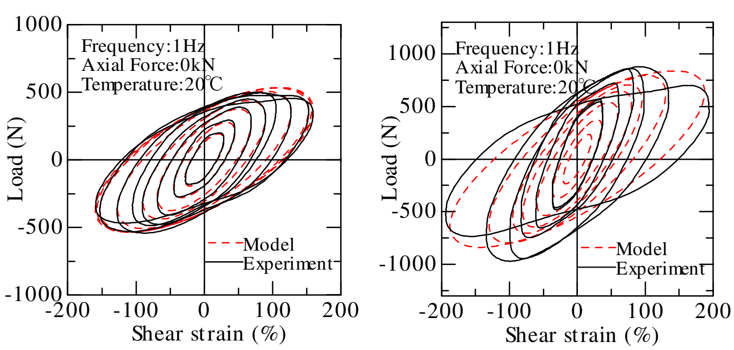


Fig.12 Comparing Histerisis loop

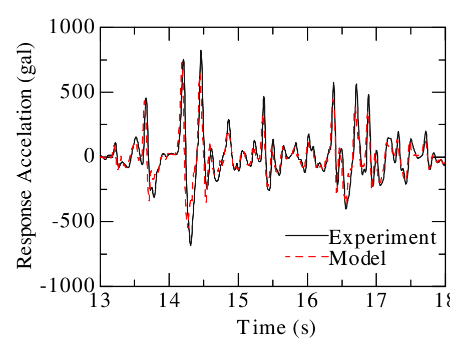


Fig.13 Comparing response

LAMINATED PUR BEARING

Outline of Experiment

From the results of vibration test, mechanical characteristics of PUR are strongly influenced by axial pressure. Considering PUR as isolated devices, it is important that equivalent stiffness should be controlled at low level in spite of the increment of axial pressure. The shape factor decreases as much as PUR becomes thick. And this leads the decrement of the stiffness of PUR. For the purpose of proposing low stiffness bearing device, laminated PUR bearing is proposed. Because thin PUR has small influence of axial pressure, laminated PUR can keep suitable shape factor and low stiffness even if axial pressure exists. In this study, vibration test for the laminated PUR bearing is conducted to compare with mechanical characteristics of PUR.

Test pieces are laminated PUR (section: 50*50mm, thickness: 9mm for 1 layer) and steel plate (diameter: 50mm, thickness: 1mm) with 4 layers. It is covered with rubber tube (thickness: 2mm, inner diameter: 49mm, width: 40mm). The test pieces are shown in Fig.14. Experimental equipment is the same as the case of sin wave vibration tests of PUR. Parameters of input sin wave are frequency (0.2, 0.5, 1.0, 2.0, 5.0 Hz), shear strain, and axial force (0, 2, 5, 10kN).

Test piece Inside of the test piece

Fig.14 Laminated PUR

Test Results

Fig.15 shows histerisis loop obtained by loading test. Fig.16 and Fig.17 show equivalent stiffness and equivalent damping factor. The results of 40mm PUR are compared with laminated PUR. Equivalent stiffness of laminated PUR is sufficiently small comparing with 40mm PUR. And laminated PUR has high damping as same as 40mm PUR.

Modeling

From the result of loading test, differences in mechanical characteristics of laminated PUR and 40mm

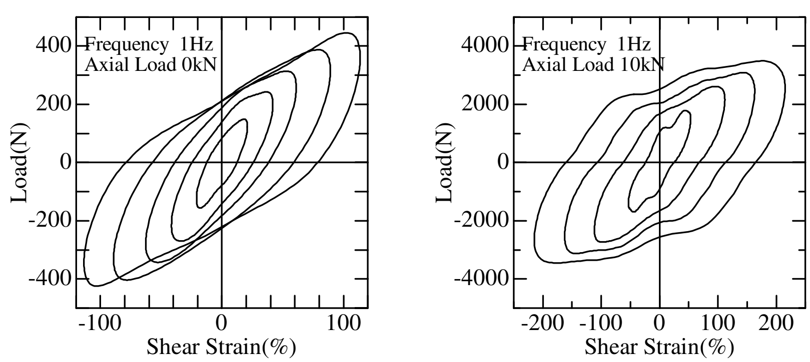


Fig.15 Histerisis loop of laminated PUR

PUR are depended on shape factor. Therefore, model for laminated PUR is expressed as same as model of PUR. Fig.18 shows comparisons between test results and model's value. Since model's value can represent experiment value well. So, the same model can be used for laminated PUR bearing.

SEISMIC RESPONSE ANALYSIS

Method of Analysis

A target structure for seismic response analysis is the two-story wooden house which weight is 35tf. Laminated PUR bearings (section: 100*100mm) are set between the base and ground sill. The number of bearings is assumed to 35. Analysis variavle is number of laminating. Analysis model is single-mass model in which the upper part of structure is assumed to be rigid body. The based-isolation layer is represented using proposed Kelvin-Voigt model. Response analysis is time history response analysis by direct integration using Newmark β method. Input waves are simulated wave of Building Center of Japan (Bcj-L1, Bcj-L2) and El Centro NS.

Result of Analysis

Maximum responses by Bcj-L2 and El Centro NS are shown in Fig.19. Effect of based-isolation can be expected that maximum response acceleration decreases. When the number of laminating is 30, response acceleration decreases 1/2 – 1/3 time in comparison with non-isolated houses. In addition, shear strain of laminated bearing is restrained within 100%. Therefore, it is considered that the most suitable number of laminating is about 30 layers.

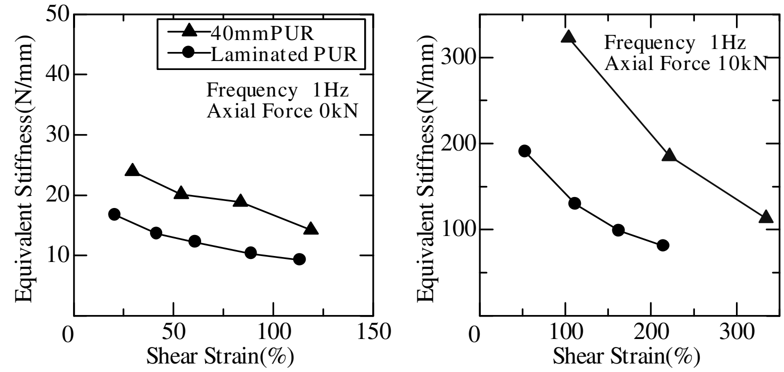


Fig.16 Equivalent stiffness

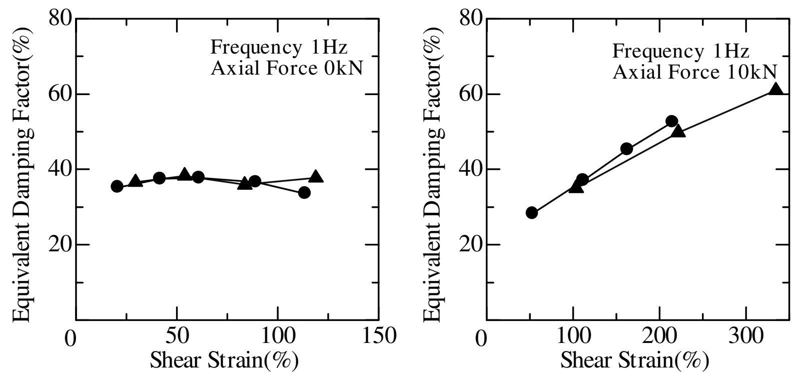


Fig.17 Equivalent Damping Factor

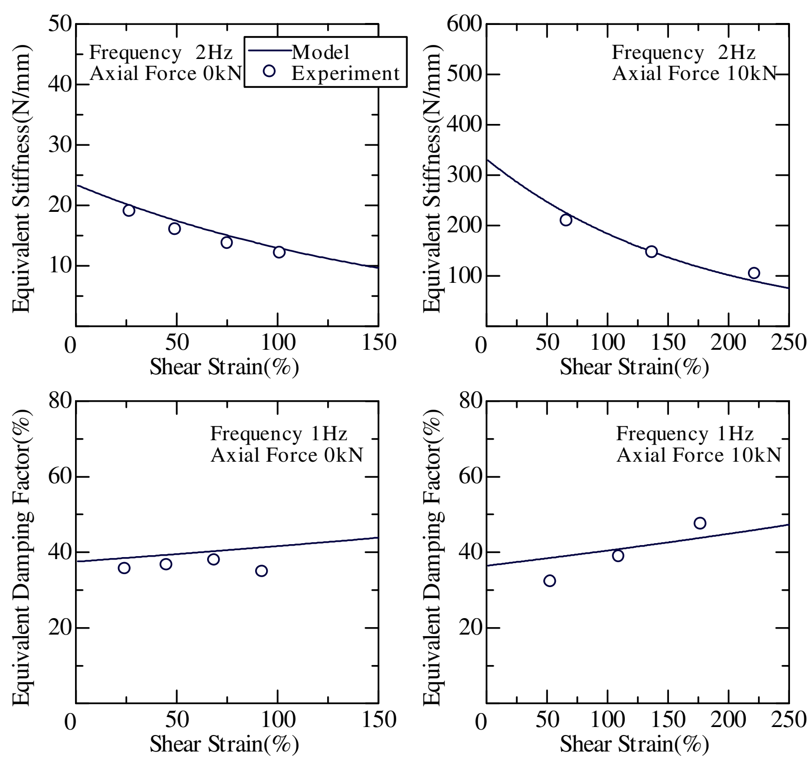


Fig.18 Comparison between test results and model's value

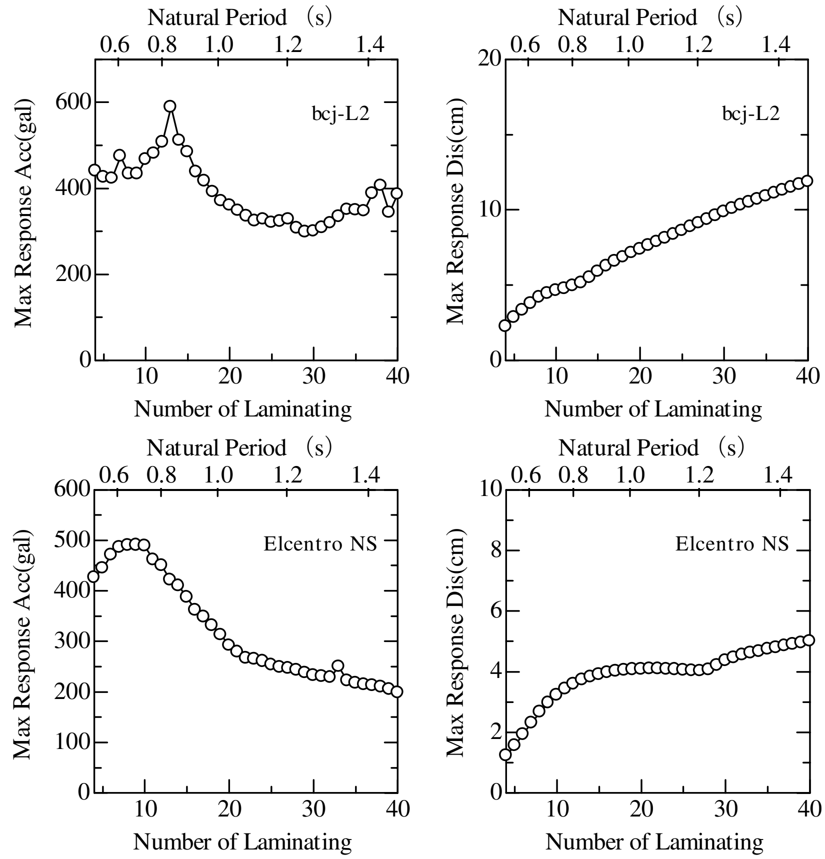


Fig.19 Maximum response

CONCLUSIONS

Vibration test and seismic response analysis which is conducted to investigate the fundamental mechanical characteristic of PUR and effectiveness for based-isolated structures are carried out. The followings are concluded.

1. PUR has frequency dependency, strain dependency, temperature dependency, and axial pressure dependency. Especially, axial pressure dependency is bigger. The equivalent stiffness increases as axial pressure also increases.
2. Equivalent stiffness of laminated PUR is sufficiently small comparing with 40mm PUR. Laminated PUR has high damping as same as 40mm PUR.
3. Mechanical characteristic of PUR can be expressed by shift factors which involve each dependency. Characteristics of laminated PUR is also represented by same model of PUR
4. From the seismic response analysis of laminated PUR bearing, laminated PUR bearings are effective for based-isolated structures.
5. It is considered that the most suitable number of laminating is about 30 layers.

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