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Experimental study on the compressive stress dependency of full scale low hardness lead rubber bearing

Hong-Pyo Lee[*1], Myung-Sug Cho[1a], Sunyong Kim[1b], Jin-Young Park[2c] and Kwang-Seok Jang[2d]

[1]*Plant Const. & Eng. Lab., KHNP Central Research Institute, Yuseong, Daejeon 305-343, Korea*
[2]*R&D Center, UNISON eTech Co. Ltd., Cheoan, Soosin 330-882, Korea*

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Abstract. According to experimental studies made so far, design formula of shear characteristics suggested by ISO 22762 and JEAG 4614, representative design code for Lead Rubber Bearing(LRB) shows dependence caused by changes in compressive stress. Especially, in the case of atypical special structure, such as a nuclear power structure, placement of seismic isolation bearing is more limited compared to that of existing structures and design compressive stress is various in sizes. As a result, there is a difference between design factor and real behavior with regards to shear characteristics of base isolation device, depending on compressive stress. In this study, a full-scale low hardness device of LRB, representative base isolation device was manufactured, analyzed, and then evaluated through an experiment on shear characteristics related to various compressive stresses. With design compressive stress of the full-scale LRB (13MPa) being a basis, changes in shear characteristics were analyzed for compressive stress of 5 MPa, 10 MPa, 13 MPa, 15 MPa, and 20 MPa based on characteristics test specified by ISO 22762:2010 and based on the test result, a regression analysis was made to offer an empirical formula. With application of proposed design formula which reflected the existing design formula and empirical formula, trend of horizontal characteristics was analyzed.

Keywords: lead rubber bearing; compressive stress dependency; low hardness rubber; shear stiffness; equivalent damping ratio; nuclear power plants

1. Introduction

Base isolation system is widely applied home and abroad as being the most positive technology to mitigate earthquake damage on a structure. Because the base isolation system provides a relatively high level of efficiency and economic feasibility, studies related to the system are actively carried out and the system is actively applied (Chang *et al.* 2002). South Korea has been thought to be safe from earthquake as being far away from border of seismically active plate.

*Corresponding author, Senior Researcher, E-mail: hplee@khnp.co.kr
[a]Principal Researcher, E-mail: concrete@khnp.co.kr
[b]Senior Researcher, E-mail: sunyongkim@khnp.co.kr
[c]Senior Researcher, E-mail: parkjy@uet.co.kr
[d]Associate Researcher, E-mail: ksjang@uet.co.kr

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However, as showing an upward trend in the frequency of annual occurrence of earthquake, it's not safe to say that South Korea is safe from earthquake.

From the aspect of structure stability and increasing usability, the system is being widely applied home and abroad in order to minimize earthquake damage on structures, such as a bridge, building, LNG storage tank and nuclear power plant. Thanks to development and improvement of various technologies about the base isolation device, the system is being used for a nuclear power structure in advanced countries which requires a high level of stability, in addition to bridges and buildings in high seismicity regions.

Domestically, in bridge sector, from the year of 2005, the seismically isolated bridge design regulation was newly established in seismic design of Highway Bridge Design Code and since then, seismic isolator has been widely used for a considerable number of bridges. And, in construction sector, the seismic isolator was used not only for office building, such as Technology Institute of UnisonEtech and Busan LG CNS data center but also for residential building such as Kimpo Apt. Laminated rubber bearing with proven safety is being used for most base isolation devices currently being applied and relevant studies have been conducted consistently.

Due to the large-scale Tsunami and earthquake in Tohoku of Japan and accident in the nuclear power plant of Fukushima, range of target structures has been expanded and there have been active studies to apply the device to nuclear power structures which requires a high level of safety (Lee *et al.* 2013). In order for improving seismic performance of nuclear power structure, review on application of various base isolation devices for the nuclear power structures is being made (Park *et al.* 2012).

The base isolation device installed between base and upper part of a structure puts flexibility on a structure in the case of earthquake, thus increasing its proper period and reducing the size of seismic force brought out on the superstructure (Jang *et al.* 2012). But, the base isolation device should be equipped with high damping capacity to reduce relative displacement at the time of earthquake. Currently, Lead Rubber Bearing (LRB) is regarded as a representative device thanks to longer proper period of a structure based on rubber flexibility, high damping capacity and good record in application. LRB has restoring force supported by the laminated rubber, re-crystallization ability, high damping ratio of cylindrical lead core inserted inside, high seismic isolation effect resulted from difference in post and prior-yield stiffness and stability against aftershock.

In the case of shear characteristics for current base isolation device of laminated rubber type, effective stiffness can be easily calculated based on normal equation once shear elastic modulus, primary shear factor and secondary shear factor of rubber are decided. However, the behavior of base isolation device will witness changes in stiffness depending on design compressive stress and displacement. The shear characteristics of base isolation device based on foreign technology and standard previously suggested does not consider impacts from compressive stress dependency. Therefore, it's required to develop design technique of base isolation system which considers characteristic changes depending on compressive stress.

For civil engineering structure, rubber with a hardness of 50 (IRHD) is applied and for laminated rubber bearing for seismic isolation used for a building, low-hardness rubber with a hardness below 50 (IRHD) is applied in order to ensure long period and maximum damping effect (Chung *et al.* 2002). The low-hardness rubber is resulted from adjusting mixing quantity of stiffening member (carbon black, etc) out of various chemicals mixed with rubber materials. In general, the low-hardness rubber is mainly used for LRB or rubber bearing for a building. Reduced height of bearing and improved shear strain, it can provide excellent ultimate shear strain capability. In Japan, shear elastic modulus of rubber included into the seismic isolation member

Fig. 1 30MN LRB testing machine

certification list is marked with G4, which is equal to 0.392MPa of shear elastic modulus ($G_{r=100\%}$) and more than 90% of related products have this level.

This study intends to manufacture and make an experiment with a full-scale device which applies the low-hardness rubber to LRB, representative base isolation device to analyze changes in stiffness and damping characteristics depending on compressive stress and suggest an shear characteristics equation which considers design compressive stress after reviewing foreign technologies and standards previously offered.

2. Test overview

2.1 Overview

Mechanical characteristics of laminated rubber bearing for seismic isolation can include lateral stiffness, damping ratio, vertical stiffness and Max. strain.

In the case of lateral stiffness, the number of seismic isolation bearing is decided when design vertical load is determined according to mass of the superstructure to be installed on the upper part of laminated rubber bearing and accordingly, lateral stiffness for each laminated rubber base isolation device is determined. In general, for the base isolation device of laminated rubber type, overturning moment imposed on device at the time of shear displacement occurrence increases as compressive stress increases and in consequence, the shear stiffness having resistance to it decreases (Chung *et al.* 2002). On the other hand, in the case of equivalent damping ratio, it is known that the higher compressive stress, the higher equivalent damping ratio. Thereby, it’s necessary to consider the compressive stress when deciding design value of shear stiffness and equivalent damping ratio (Demin *et al.* 2002). If the values of shear stiffness and equivalent damping ratio based on design equation are different from characteristics values of real behaviors, reliability of device will fall down and furthermore, there will be difference with structure’s behavior that a designer has intended. In this study, regarding the representative base isolation device of LRB, a full-scale device with the application of low-hardness rubber was used to test and analyze changes in stiffness and damping characteristics according to compressive stress and basic characteristics. And design technologies and standard previously offered were reviewed and shear characteristics equation considering the design compressive stress was offered.

Table 1 Specification of 30,000 kN Compression-Shear Testing Machine

	Max load	Max. displacement	Max. rate
Vertical capacity	±30,000 kN	±100 mm	400 kN/sec
Lateral capacity	±5,000 kN	±1,000 mm	20 mm/sec
Moment	±500 kN	±100 mm	20 mm/sec
Dimension available for test		2,000×2,000×800 (mm)	

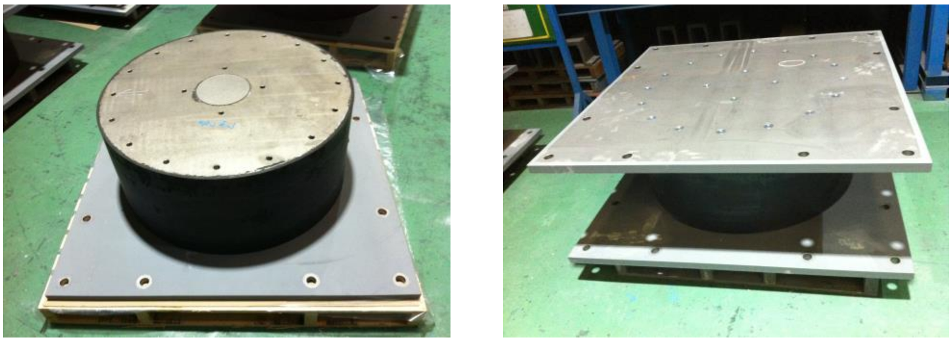


Fig. 2 Photo of the specimen

2.2 Testing machine specification

As seen in Table 1 and Fig. 1, the testing machine used during characteristics test of LRB specimen is compression-shear testing machine with Max. vertical load of 30,000 kN and Max. lateral load of 500 kN. And its Max. lateral loading rate and Max. displacement in a lateral direction are 20 mm/sec and ±1,000 mm, respectively.

In the test, double shear testing method which is a part of compression-shear testing method suggested by ISO 22762-1 was applied. The double shear test can minimize impact from frictional force of testing machine which occurs in single shear test.

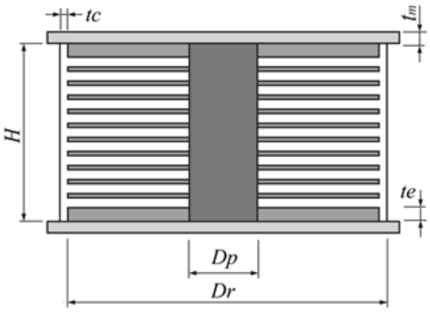
3. Specimen design

3.1 Specimen specification

For conducting a characteristics test of LRB, two full-scale LRBs were designed and manufactured as seen in Fig. 2. Specification specimen designed reflected target period based on seismic isolation technology at a nuclear power plant (JEAG 4614-2000). With regards to characteristics of materials used in the full-scale LRB, the rubber used had shear elastic modulus *G* value of 0.4 MPa under shear strain of 100% and compressive stress of 13 MPa and the lead shear yield strength amounted to 8.34 MPa. As seen in Table 2, the specimen manufactured and tested had an external diameter of 1,120 mm (external diameter of laminated rubber: 1,100 mm, thickness of covered rubber: 20 mm) and a lead core of 240mm. The primary shear and secondary shear factors of specimen were 39.3 and 4.9, respectively which are similar to those used in laminated rubber bearing for normal building. Generally, the primary shear factor related to vertical and bending stiffness of LRB is between 20 and 35 and the secondary shear factor related

Table 2 LRB Specification

	Symbol	Unit	Value
External diameter	D	mm	1,120
Internal reinforcing steel plate diameter	D_s	mm	1,100
Lead core diameter	D_p	mm	240
Rubber layer Number	n	-	32
Rubber 1st layer thickness	t_i	mm	7
Rubber layer total thickness	T_r	mm	224
Internal reinforcing steel plate thickness	t_s	mm	4.5
Rubber sectional area	A	mm^2	905,093
Primary shear factor	S_1^{*}	-	39.3
Secondary shear factor	S_2^{**}	-	4.9



$$*\,S_1 = \frac{D_s - D_h}{4 \cdot t_i}$$

$$**S_2 = \frac{D_s}{n \cdot t_i}$$

Table 3 Test results on rubber material characteristics

Item		Based on ISO 22762-1 (G0.4)	Characteristics value
Hardness	IRHD	35±5	39.20
Tensile strength(MPa)	KS M 6518	14	23.27
Elongation (%)	KS M 6518	600	635.80
Adhesive strength(kN/m)	90°Peel Method	6	8.6
Permanent compression set (%/ 70℃, 24hr)		-	14.37

to buckling of LRB is over 5 (JIS K 6410-1 2011). Therefore, the two specimens are thought to have large resistance to bending deflection of laminated rubber and to be less likely to show stiffness degradation or buckling caused by shear strain.

3.2 Rubber material characteristics

A characteristics test was conducted for the rubber materials applied to specimen in order to examine required material property specified by ISO 22762-1. As a result of test, the minimum required material property specified by ISO 22762-1 was satisfied as seen in Table 3.

3.3 Specimen design

The specimen design calculated characteristics values based on the following equation. Characteristics of lead and rubber based on 20℃ showed design results as seen in Table 4.

Table 4 LRB design characteristics

Design characteristics value (20℃, γ=100%)	
Item	Design value
Vertical stiffness (K_v)	5,475,801 N/mm
Primary stiffness (K_1)	21,836 N/mm
Secondary stiffness (K_2)	1,680 N/mm
Fragment stiffness (Q_d)	306,636 N
Equivalent stiffness (K_{eq})	3,290 N/mm
Equivalent damping factor (H_{eq})	0.287

The vertical stiffness was calculated as seen in Eq. (1). And the volumetric modulus (E_b) of 1,960 MPa and modulus of longitudinal elasticity (E_0) of 1.44 MPa were used.

$$K_v = \alpha_v \cdot \frac{\alpha}{T_r} \cdot \frac{E_0(1+2kS_1^{\ 2})E_b}{E_0(1+2kS_1^{\ 2})+E_b} \tag{1}$$

Design of lateral characteristics was based on Eq. (2)~(5) and stiffness and equivalent damping constant were calculated for shear strain of 100 %. For comparison with lateral characteristics test results specified by ISO22762, value at the 3rd cycle or mean value of from 2nd to 11th cycles was referred.

Base isolation device's secondary stiffness after shear yielding of lead is calculated as seen in Eq. (2) and increase in post-yield stiffness (K_p) of lead core and shear stiffness (K_r) of rubber are reflected.

$$K_2 = CKd(K_r + K_p)$$

$$(K_r = G_r \frac{A_r}{T_r}, K_p = \alpha \frac{A_p}{T_r}) \tag{2}$$

Equivalent stiffness is expressed as seen in Eq. (3). It is calculated by the application of shear strain (γ, T_r) to characteristic stiffness and secondary stiffness calculated in Eq. (2).

$$K_{eq} = \frac{Q_d}{\gamma \cdot T_r} + K_d \tag{3}$$

Characteristic stiffness is calculated based on Eq. (4) where shear strain-dependent correction factor for yield load of lead core is applied. Equivalent damping factor is calculated as seen in Eq. (5) composed of stiffness before and after lead core yielding

$$Q_d = CQd \cdot \sigma_{pb} \cdot A \cdot Q_d \tag{4}$$

$$H_{eq} = \frac{2}{\pi} \cdot \frac{Q_d \cdot (\gamma \cdot t_r - \frac{Q_d}{(\beta\text{-}1)K_d})}{K_{eq} \cdot (\gamma \cdot t_r)^2} + K_d \tag{5}$$

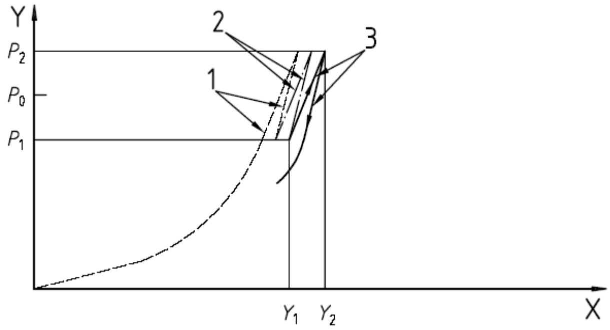


Fig. 3 Compression loading curve

4. Characteristics test

4.1 Test items

The characteristics test was divided into a basic characteristics test and compressive stress dependency test. The basic characteristics test to examine characteristic value of seismic isolation bearing was carried out with an aim to evaluate whether device is appropriate or not based on review of test results prior to mass production. First, compressive characteristics and shear characteristics tests were conducted so as to investigate basic characteristics at the time of bearing design, such as compressive stiffness, shear stiffness and damping ratio. The basic characteristic values obtained from the compressive characteristics and shear characteristics experiments were compared with design values obtained from design equation in ISO 22762-2 to check whether or not to be within the margin of error. In this case, the margin of error of ±30 % was used for compressive stiffness. The shear property's margin of error was at ±15 %, S-A grade criteria (ISO 22762-1 2010).

In the compressive stress dependency test, lateral displacement was repetitively loaded three times at a loading rate of 0.005 Hz for ±224 mm-shear displacement equivalent to shear strain of 100%. The compressive stress applied to the test includes 5 MPa, 10 MPa, 13 MPa (design compressive stress), 15 MPa and 20 MPa that applied vertical load of 4,525 kN, 9,051 kN, 11,766 kN, 13,576 kN, and 18,102 kN, respectively.

4.2 Basic compressive characteristics test

The testing method specified by ISO22762 was used to measure compression and compressive-shear characteristics of specimen. In order for examining the compressive characteristics, ISO22762-1's method 2 was applied and loading pattern is seen in Fig. 3. With ±30 % load of compressive force (P_0) corresponding to design compressive design being set as P_1, and P_2, compression loading was repeated with three rounds of cycles. As seen in Eq. (6), the vertical stiffness can be calculated based on graph slope.

$$K_v = \frac{P_2 - P_1}{Y_2 - Y_1} \tag{6}$$

Table 5 Compressive characteristics results

Item	Unit	Value
Design value of compressive stiffness	kN/mm	5,476±30 %
Experimental value of compressive stiffness	kN/mm	6616.438
Error rate	%	20.8

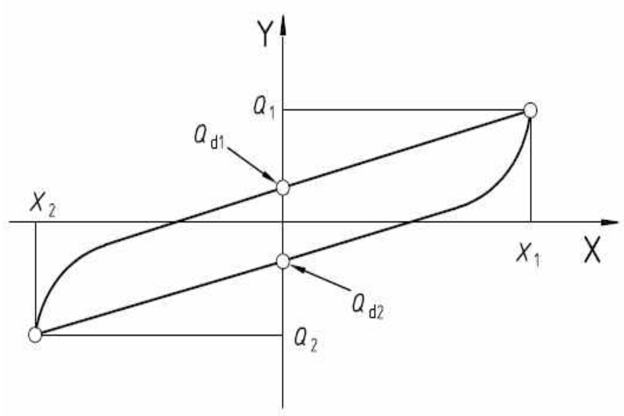


Fig. 4 Compressive-shear loading curve

As a result of the compressive characteristics test, the maximum and minimum loads at the 3rd cycle were 15,293 kN and 8,218 kN and at this time the relevant displacements were 2.729 mm and 1.660 mm, respectively. As a result of reflecting these values into Eq. (6), the compressive stiffness obtained was 6616.438 kN/mm as seen in Table 5. Design value of compressive stiffness was calculated based on Eq. (1) to check whether the experimental value meets requirements or not. After the comparison with the experimental value of compressive stiffness, the margin of error of was found to be at +20.8% which was within the permissible limits of error of ±30%, indicating that it complied with the standard. Results of calculating experimental value and deign value of compressive stiffness were summarized in Table 5.

4.3 Basic shear characteristics test

In the case of LRB shear characteristics, while maintain consistently level of compressive load, history curve at the 3rd cycle was analyzed with placing design shear strain of γ_0=100% on specimen in the shear direction. The characteristic values obtained from the shear characteristics test, such as shear stiffness of K_h, equivalent damping ratio of h_{eq}, post-yield stiffness of K_d, and characteristics strength of Q_d, are calculated by Eq. (7)~Eq. (10).

The characteristic stiffness of Q_{d1}, and Q_{d2} refer to intersection between curve and shear force axis in the positive and negative direction, respectively and ΔW refers to energy dissipation area surrounded by the history curve

$$K_h = \frac{Q_1 - Q_2}{X_1 - X_2} \tag{7}$$

$$Q_d = \frac{1}{2}(Q_{d1} - Q_{d2}) \tag{8}$$

$$H_{eq} = \frac{2\Delta W}{\pi K_h \cdot (X_1 \cdot X_{2r})^2} \tag{9}$$

$$K_d = \frac{1}{2}\left(\frac{Q_1 - Q_{d1}}{X_1} + \frac{Q_2 - Q_{d2}}{X_2}\right) \tag{10}$$

In the characteristics test, lateral stiffness characteristics were evaluated regarding displacement of lateral displacement ±100 % and design compressive stress of 13 MPa. As a result of calculating experimental data based on the above, shear stiffness was found to be at 3.10 kN/mm and equivalent damping ratio at 26.5 %. Meanwhile, design values of equivalent damping ratio and shear stiffness were calculated at 28.7 % and 3.29 kN/mm, respectively based on Table 2, Eq. (2), and Eq. (5).

Comparison of experimental values and design values displayed the shear stiffness and the equivalent damping ratio with margins of errors of −5.8 % and −7.7 %, respectively. Therefore, considering that the standard margin of error of ±10 %, the LRB used for this study is believed to be appropriate in design

According to ISO 22762-3, at the time of analysis, LRB's behaviors should be expressed with a bi-linear model to calculate initial stiffness and post-yield stiffness (Kelly *et al.* 2011, ISO 22762-3 2010). As a result of comparing calculation results based on the standard and the history graph obtained from an experiment as seen in Fig. 5, it was found that initial stiffness and post-yield stiffness all showed similar results.

Table 6 Shear characteristics results

Item	K_h (kN/mm)	h_{eq} (%)
Design value	3.29	28.7
Test value	3.1	26.5
Margin of error (%)	5.8	7.7

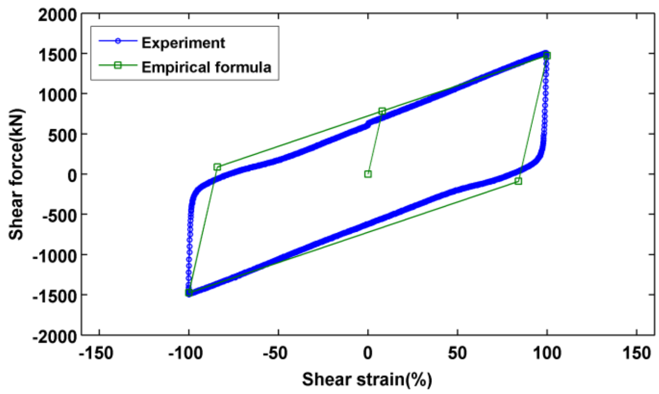


Fig. 5 History curve comparison

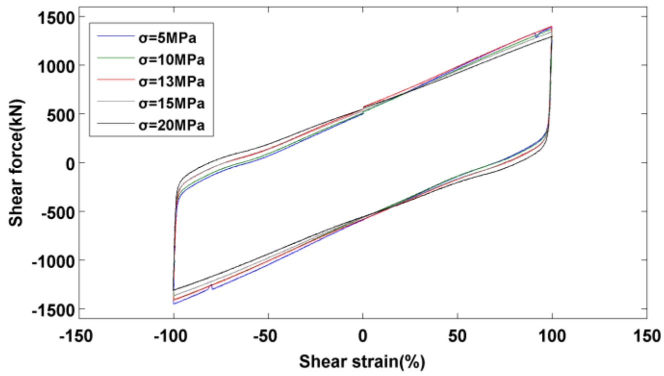


Fig. 6 Compressive-shear history curve for each compressive stress

4.3 compressive stress dependency test of shear characteristics

With an aim to investigate dependence of shear stiffness, post-yield stiffness, characteristic stiffness, and equivalent damping ratio according to vertical compressive stress of LRB, the compressive-shear experiment was conducted for various compressive stresses. While placing consistently vertical load so as to maintain relevant design compressive stress at room temperature, the characteristics test evaluated lateral stiffness characteristics by inducing displacement of ±224mm equivalent to design shear displacement of ±100 % and analyzed characteristic changes based on comparison with experiment results at design compressive stress of 13 MPa. The experiment was carried out at vertical load corresponding to a total of five compressive stresses including 5 MPa, 10 MPa, 13 MPa, 15 MPa, and 20 MPa.

A history graph about lateral characteristics for each compressive stress is shown in Fig. 6. And shear stiffness and post-yield stiffness tend to decrease overall as compressive stress increases, which was resulted from reflecting characteristics of rubber layers contributing to vertical stiffness. Value of characteristics strength that determines property of lead in charge of dissipating energy of LRB showed almost no changes according to the increase of vertical compressive stress.

As a result of experiment, based on design compressive stress of 13 MPa, changes in shear stiffness, post-yield stiffness, characteristic stiffness, and equivalent damping ratio were calculated to show results in Table 7. The shear stiffness tended to decrease as compressive stress increased and it changed within the range from −5.8 % to +1.6 %, indicating relatively small compressive stress dependency.

The post-yield stiffness referring to rubber characteristics tended to decrease as compressive stress increased and it changed within the range from 3.6 % to 9.8 %, indicating relatively large compressive stress dependency.

As previously mentioned, the characteristic stiffness changed within the range from −4.2 % to 2.9 % according to change in compressive stress and showed little dependency. The equivalent damping ratio tended to increase as compressive stress increased and it changed within the range from −4.3 % to 4.6 %, indicating relatively large compressive stress dependency.

Therefore, considering that the margin of error of shear characteristics is within ±10 % at the time of shear characteristics experiment, it is thought that design compressive stress needs to be considered when deciding design values of post-yield stiffness and equivalent damping ratio.

Table 7 Compressive stress dependency test results

Item	Characteristics value	5 MPa	10 MPa	13 MPa	15 MPa	20 MPa
Test result	K_d (kN/mm)	1.872	1.845	1.807	1.749	1.630
	K_{eq} (kN/mm)	3.109	3.098	3.059	2.990	2.884
	Q_d (kN/mm)	276.855	271.729	276.563	277.832	279.762
	h_{eq}	0.253	0.254	0.265	0.264	0.277
Dependency evaluation	$K_d(\sigma)/K_d(\sigma_{13})$	1.036	1.021	1.000	0.968	0.902
	$K_{eq}(\sigma)/K_{eq}(\sigma_{13})$	1.016	1.013	1.000	0.978	0.943
	$Q_d(\sigma)/Q_d(\sigma_{13})$	0.958	0.940	1.000	0.961	0.971
	$h_{eq}(\sigma)/h_{eq}(\sigma_{13})$	0.957	0.960	1.000	1.000	1.046

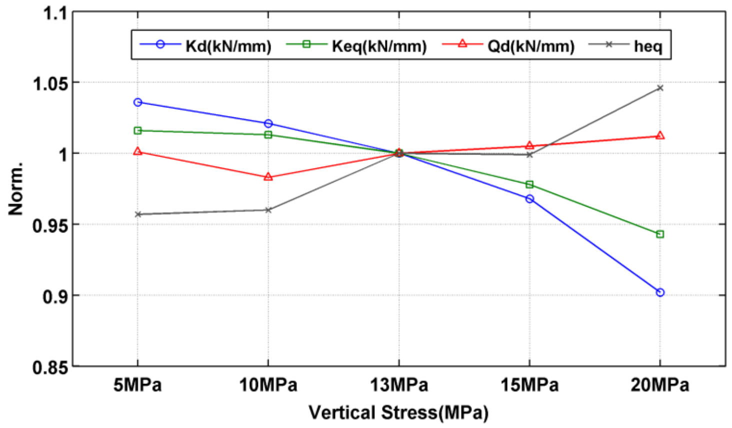


Fig. 7 Shear characteristics strain depending on compressive stress

5. Compressive stress dependency review

The design equation of shear characteristics specified by ISO 22762 (2010) and JEAG 4614-2000 which is a representative design rule of LRB has not considered the compressive stress dependency. Thus, in the case of limited arrangement of seismic isolation bearing due to structural property or a special structure (nuclear power plant, etc), variability of design compressive stress is considered depending on arrangement of device. Therefore, it is believed that there is likely to be difference between design and actual behavior of shear characteristics of base isolation device.

Based on the full-scale compressive stress dependency test results, an empirical formula was suggested through a regression analysis of shear stiffness and equivalent damping which considered the compressive stress dependency.

Based on the experimental result, an empirical formula of shear elastic modulus $G_r(\sigma)$ which considered the compressive stress dependency for shear strain of 100% was calculated at R^2=99.5% through the regression analysis as seen in regression equation Eq. (11) and value obtained the empirical formula was compared to experimental value seen in Fig. 9. Herein, the shear elastic modulus $G_r(\sigma)$ has the unit of MPa.

$$G_r(\sigma) = 0.4591 - 0.0002\sigma^2 + 0.0022\sigma \tag{11}$$

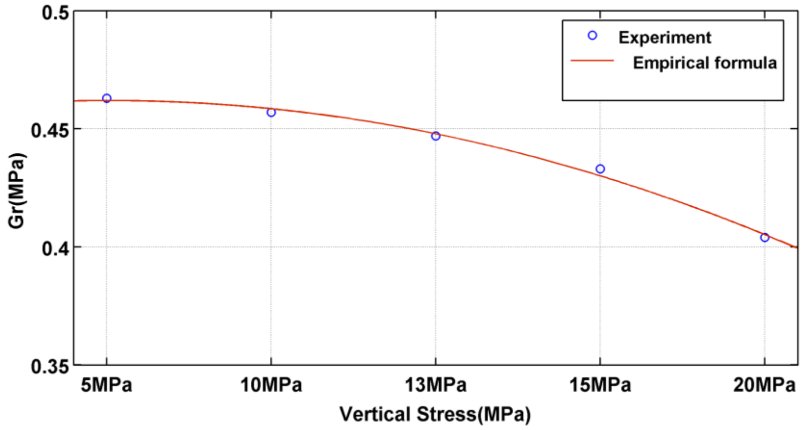


Fig. 8 Shear elastic modulus trend depending on compressive stress

Table 8 Design equation comparison depending on compressive stress change

Item	Characteristics value	5 MPa	10 MPa	13 MPa	15 MPa	20 MPa
Design value	K_{d_design}(kN/mm)	-	-	1.680	-	-
	K_{eq_design}(kN/mm)	-	-	3.290	-	-
	h_{eq_design}	-	-	0.287	-	-
Test result	K_{d_exp}(kN/mm)	1.872	1.845	1.807	1.749	1.630
	K_{eq_exp} (kN/mm)	3.109	3.098	3.059	2.990	2.884
	h_{eq_exp}	0.253	0.254	0.265	0.264	0.277
Proposed design value	K_{d_emp} (kN/mm)	1.736	1.720	1.691	1.664	1.568
	K_{eq_emp} (kN/mm)	3.346	3.330	3.301	3.274	3.178
	h_{eq_emp}	0.283	0.284	0.286	0.288	0.295

The post-yield stiffness obtained from reflecting the shear elastic modulus Eq. (11) that considers the compressive stress dependency into the existing design equation of Eq. (2) can be expressed as seen in Eq. (12).

$$K_d(\sigma) = CKd\left(G_r(\sigma)\frac{A_r}{T_r} + \alpha\frac{A_p}{T_r}\right) \tag{12}$$

Herein, $K_d(\sigma)$: Shear elastic modulus per strain considering compressive stress.

The shear stiffness and equivalent damping ratio considering compressive stress dependency can be calculated by Eq. (12) where the compressive stress-considered shear elastic modulus empirical formula is reflected.

By using characteristics design equation that reflected empirical formula, characteristics of shear stiffness, post-yield stiffness, and equivalent damping ratio were compared as seen in Table 8 and Fig. 9~11. Characteristics value calculated based on the proposed design equation shows trend similar to experimental value according to changes in compressive stress. Although shear characteristics value obtained by the experiment and design value obtained by design equation

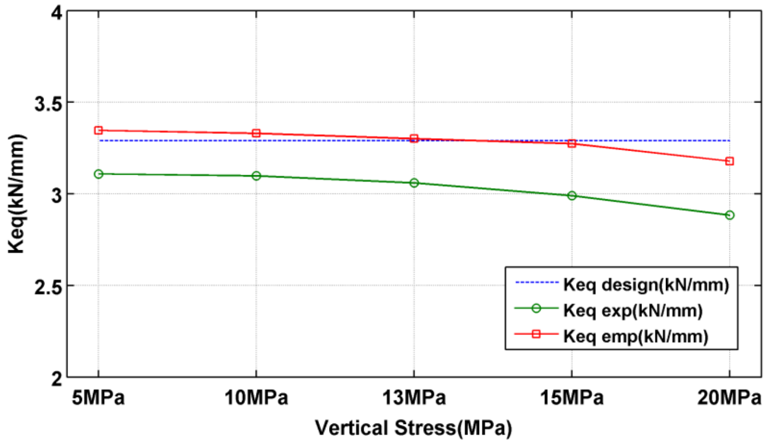


Fig. 9 Predictive design equation comparison of shear stiffness depending on compressive stress change

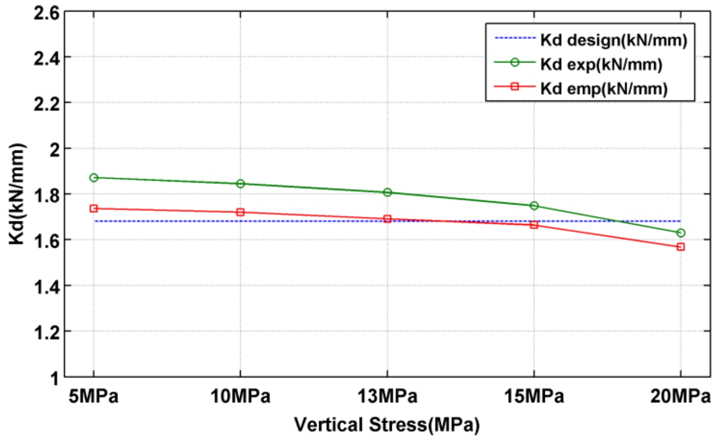


Fig. 10 Predictive design equation comparison of post-yield stiffness depending on compressive stress change

were different, those values were within the margin of error specified by the design standard. And identical variation trend for each change in compressive stress was identified. Thus, when using the design equation previously proposed, different shear characteristics could be identified in case of compressive stress smaller or bigger than design compressive stress. Therefore, without consideration of compressive stress dependency of base isolation device, it would be difficult to accurately reflect shear characteristics of base isolation device and there would be a difference between design and actual structure behaviors.

In this study where G4-level rubber materials were used, it's thought that additional test about various shear elastic modulus is necessary to generalize the improved design equation. And based on the experiment results, it seems to be possible to propose and apply the design equation where compressive stress dependency is reflected into LRB for building that is generally applied.

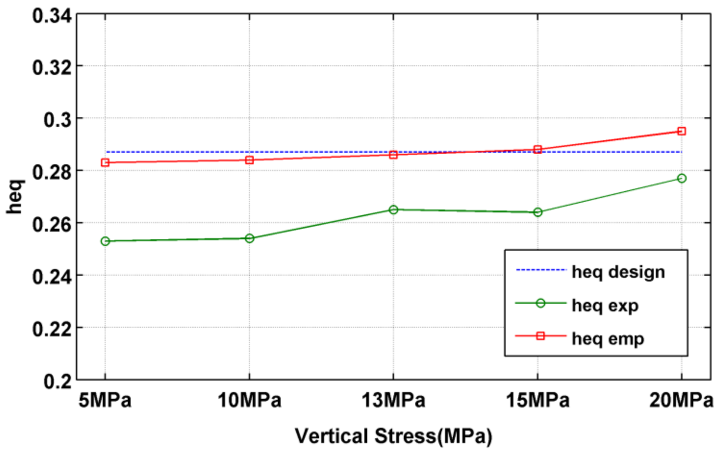


Fig. 11 Predictive design equation comparison of equivalent damping ratio depending on compressive stress change

6. Conclusions

This study analyzed through the experiment the lateral characteristics changes depending on compressive stress conditions of low-hardness full scale LRB with laminated rubber's shear elastic modulus ($G_{r=100\%}$) of 0.392 MPa. And in this study, the characteristics equation considering compressive stress dependency was proposed and compared with the design equation specified by current foreign standard.

(1) In the basic characteristics test, the shear characteristics experiment with shear strain was conducted according to displacement equivalent to 100 % rubber thickness, consequently showing design value of shear stiffness and the margin of error of −5.8 %. The margin of error is within that of ±10 % specified by ISO 22762-3, indicating that the bearing design of the full-scale LRB used for this study is appropriate when the dependency is not considered.

(2) When it comes to the shear characteristics results according to various compressive stresses, the shear stiffness showed a relatively significant level of decrease as compressive stress increased and the post-yield stiffness contributing to the shear stiffness showed the same decrease trend. For the equivalent damping ratio, it tended to increase as compressive stress increased, indicating that it's required to consider compressive stress at the time of design due to dependency of shear stiffness and equivalent damping ratio caused by compressive stress.

(3) With application of design equation specified by foreign technology standard, the margin of error of shear characteristics was found to be bigger than the range of design compressive stress in the case of lower or higher compressive stress than the design compressive stress. As a result, the empirical formula was proposed through the regression analysis of shear elastic modulus which is the rubber layer characteristics contributing the shear stiffness.

(4) With regards to the lateral characteristics calculated by the application of proposed design equation, trend of changes in characteristics which were different from the experiment value could be described after comparison with the existing design equation. And it is concluded that in order to generalize the proposed design equation, additional tests will be required later for a variety of shear elastic modulus.

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