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DEVELOPMENT OF EVALUATION METHOD FOR SEISMIC ISOLATION SYSTEMS OF NUCLEAR POWER FACILITIES -BREAK TEST OF FULL SCALE LEAD RUBBER BEARINGS FOR NUCLEAR FACILITIES, PART 4 BREAK BOUNDARY CRITERIA OF REAL-SIZE ISOLATOR SPECIMENS-

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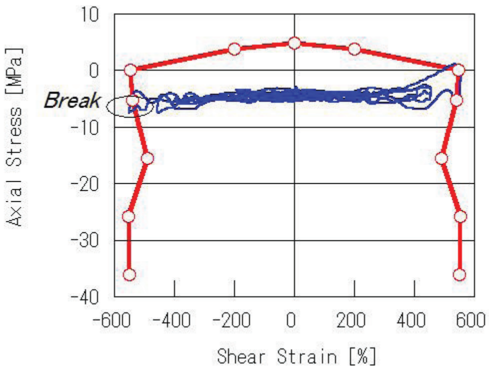
ABSTRACT

A research program for seismically isolated Nuclear Power Plants (NPPs) has been conducted since 2008 as the newest Japanese national project, whose research results are summarized as the series papers on this conference. In this project a Lead Rubber Bearing (LRB) of 1600 mm in diameter with a large lead plug is newly designed to satisfy the current Japanese design requirements for seismic isolated NPPs, and a series of break tests is also conducted by using the real-size or closely real-size of LRB specimens to evaluate ultimate seismic performance of base-isolated NPPs beyond design earthquakes. Having no previous break test of large rubber bearing for nuclear facilities; e.g. of 1600 mm in diameter, the aim herein is to evaluate the breaking strength of the real-size LRBs to avoid the difficulties considering size effect. This paper presents twenty break test results of single-lead-plug typed and multi-lead-plug typed LRBs, mainly focused on two points: one is ultimate behaviours and the broken surfaces observed from each break test, and the other is break boundary criteria in the application for evaluating residual risk of base-isolated NPPs. It should be noted that the break capabilities of the real-size LRBs are well-evaluated as expected; i.e. the breaking shear strain and tensile stress exceed the commercial reference values of 400 in percentage and 1.0MPa, respectively. A tentative break boundary criterion is also able to be conservatively evaluated for employing the risk analysis of base-isolated nuclear facilities.

INTRODUCTION

Development of evaluation methods for seismically isolated Nuclear Power Plants (NPPs) has been conducted since 2008 as the newest Japanese national project, whose research results are summarized in the series papers on this conference of the twenty-third Structural Mechanics in Reactor Technology (SMiRT23) in Manchester, UK, 2015, e.g. Imaoka, et al.(2015). In this project a Lead Rubber Bearing (LRB) of 1600 mm in diameter with a large lead plug, called single-lead-plug type in the paper, is newly designed to satisfy the current Japanese design requirements for seismic isolated NPPs, and feasibility studies have been carried out upon the seismic design for nuclear reactor buildings with the application of seismic isolation systems, Matsuoka, et al.(2013), Takeuchi, et al.(2013), Suzuki, et.al.(2014). In the project a series of break tests is also conducted by using the real-size or closely real-size of LRB



*) In the paper tensile stress and strain are taken to be positive.

Figure 1. An example of evaluation on break limit surface of rubber bearings, where the break on a shaking table test specimen occurred outside the break limit surface estimated from static loading tests, Kanazawa et al. (2012).

specimens to evaluate ultimate seismic performance of base-isolated NPPs beyond design earthquakes, whose development processes have been found in Kosugi, et al.(2014), Sato, et al.(2014), Hiraki et al.(2014). This paper discusses break limit criteria of the LRBs by using all break test results, in order to utilize for residual risk analysis of base-isolated NPPs, Nuclear Safety Commission of Japan (2006).

In the residual risk analysis of base-isolated NPPs, a breaking event of rubber bearings must be evaluated as ultimate limit state. In order to clarify breaking phenomena of rubber bearings, many break tests using unit rubber bearing specimens and shake table tests using base-isolated models have been conducted, e.g., Mazda et al.(1990), Ishida et al.(1992). Based on the results of the foregoing studies, the break events of rubber bearings can be numerically predicted by using break limit surface estimated from static break test of rubber bearings, Hirata et al.(1998), Japan Electric Association(2013). This break evaluation procedure has been confirmed in the 1/3.16 scale shake test, as shown in Figure 1, Yabana et al.(2009), Kanazawa et al.(2012). The shake test has been conducted by using the world-largest shake table E-defense, where a 600 kN rigid mass was supported on six LRBs of 505mm in diameter. During a shake test one of the LRBs was ruptured completely when the response of the LRB in shear strain-axial stress exceeded the break limit surface estimated from static unit break tests of the same typed LRBs, as denoted “*Break*”.

Thus the break limit surface, estimated from static unit break tests of LRBs, can be employed to evaluate break phenomena in the residual risk analysis. It is known, however, that the size effect of break strength cannot be neglected in rubber bearings, especially in tensile stress. Because of specification limit of loading machine, the ultimate properties have not been obtained in such large LRBs treated here. Further, few variability data has been obtained in break stress and break strain of LRB, which must be referred in Probabilistic Risk Assessment (PRA).

In the paper twenty results of break tests will be summarized in the LRBs of 1600mm in diameter with single-lead-plug and multi-lead-plug. With observing damage surfaces and starting points of break processes, break phenomena in a series of break tests can be classified into two categories, such as shear and tensile breaks. Break boundary criteria are tentatively presented on shear and tensile fractures, for employing in the PRA-based residual risk analysis.

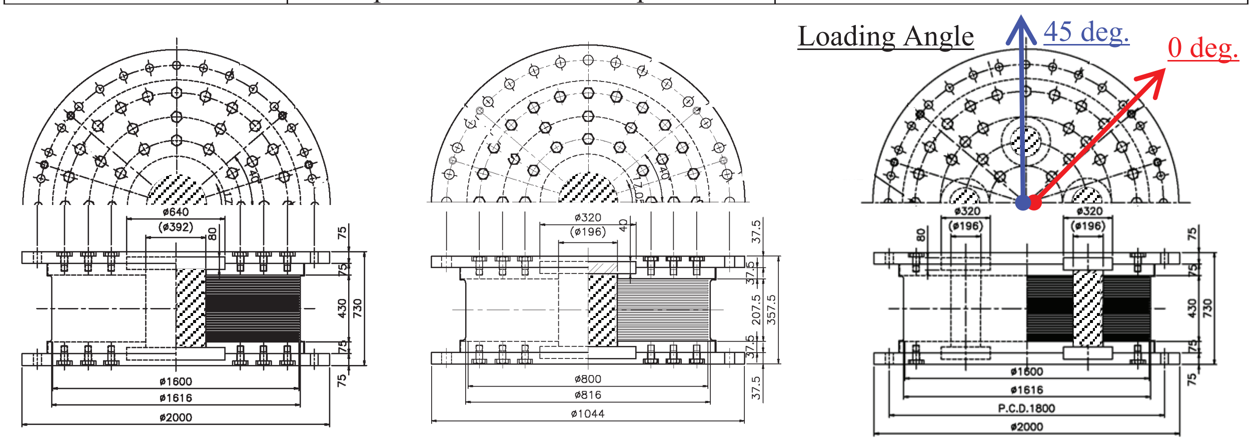
OUTLINE OF BREAK TEST

Specimens

The LRBs treated in the paper are designed and made with considering the evaluation results of both seismic response of base-isolated reactor buildings in the feasibility studies and commercial producibility

Table 1: Design specification of full scaled LRBs

Model	Single-plug Type	Multi-plug Type
Rubber diameter	1600mm	1600mm
Bearing load	9000kN	9000kN
Axial stress	4.8 MPa	4.8 MPa
Horizontal Period T_2	3.41 s	3.41 s
Yield seismic intensity β	0.121	0.121
Vertical frequency	16.3 Hz	16.3 Hz
Inner rubber	10.0mm x 26 Layers	10.0mm x 26 Layers
Inner Steel plate	6.8mm x 25 Layers	6.8mm x 25 Layers
Num. of Lead Plug	1 plug (single-plug type)	4 plugs (multi-plug type)
Lead Plug diameter	392 mm	196 mm
Aspect ratio of lead plug	1.097	2.190
Num. of specimens	14 specimens: Full scale specimen 3 specimens: Half scale specimen	3 specimens: Full scale specimen



(a)Full-scale single-plug type (b)Half-scale single-plug type (c)Full-scale multi-plug type

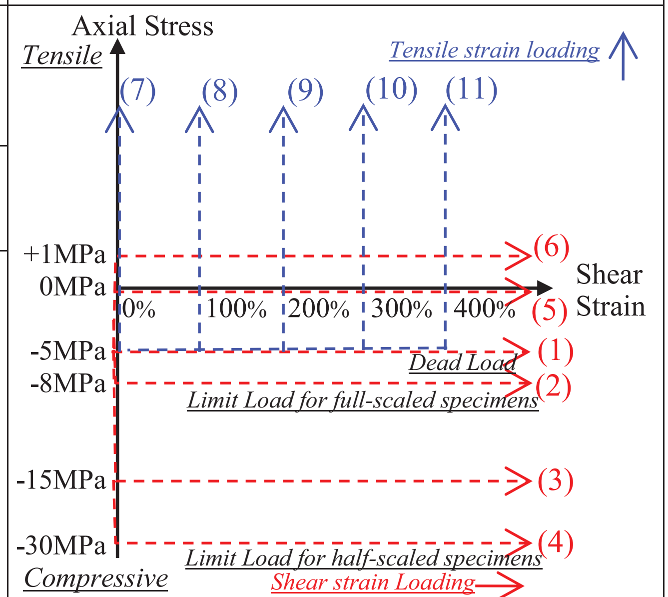
Figure 2. Specimens of the LRBs employed in the break tests

of LRBs by Japanese rubber manufacturers. The specifications of the LRBs specimens are shown in Table 1 and Figure 2. The "single-plug type" is made as reference specimen in the project, where fourteen full scale specimens and three half scale specimens are tested. The half scale specimens are employed in the shear strain loading with large compressive loads since the scale effect is not severe in compression. The thickness of the single-lead-plug of the reference specimens is larger than the one employed in the conventional studies, e.g., Hirata.et al.(1998), Yabana et al.(2009), thus three multi-plug typed specimens are also made to compare hysteresis curve in stress-strain relation and break capability.

Loading Patterns of Break Test

The loading patterns are determined by evaluating the feasibility studies for the base-isolated NPPs, such that the horizontal and vertical peak response can be covered with the range of the loading patterns. For the reference specimens of the single-plug-type, six kinds of shear break tests is conducted with constant vertical loading such as 0MPa, -5MPa, -8MPa, -15MPa and -30MPa in compressive stress, +1MPa in tensile stress; whereas five kinds of tensile break test is conducted with constant offset horizontal deformation such as 0%, 100%, 200%, 300%, and 400% in offset shear strain. To verify individual

Table 2 Loading Pattern List of all break tests

No.	Test Name Abbr.	Loading Type	Specimen Type	Loading Patterns (Loading Type)
1	1F1	(1)	Full-scale single-plug type	
2	1F2	(1)		
3	1F3	(1)		
4	2F	(2)		
5	1H	(1)	Half-scale single-plug type	
6	3H	(3)		
7	4H	(4)		
8	5F	(5)	Full-scale single-plug type	
9	6F	(6)		
10	7F	(7)		
11	8F	(8)		
12	9F1	(9)		
13	9F2	(9)		
14	10F1	(10)		
15	10F2	(10)		
16	11F1	(11)		
17	11F2	(11)		
18	1M1	(1)	Full-scale multi-plug Type	Loading angle 0deg
19	1M2	(1)		Loading angle 45deg
20	10M	(10)		Loading angle 45deg

variability in break strength, three and two times of break tests are conducted by employing different virgin specimens under shear loading with -5MPa in compressive stress, and under the tensile loadings with 200%, 300%, and 400% in offset shear strain, respectively.

For the multi-plug typed specimen, shear break tests with -5MPa in compression and a tensile break test with 300% in offset shear strain are conducted: these loading patterns are most likely to appear in residual risk analysis. To verify anisotropic stiffness of multi-plug typed specimens, two shear break tests are conducted in two different directions of 0 and 45 degrees as described in Figure 2(c).

BREAK TEST RESULTS

Shear Break test

Break shear strains and break shear stresses of the LRB specimens are experimentally evaluated from the shear stress-shear strain curves, where the break occurrence points are defined when the shear stress reaches at a peak value during breaking process. The experimental results of shear strain and shear stress are summarized in Table3, where it is also shown as controlled axial stresses and surface temperatures in the test condition, axial stresses and axial strains in the experimental results. All experimental values in shear strain are over 400% except in the Test-6F: In the Test-6F the initial axial stress is to set to tensile, as discussed in detail later. The shear strain of 400% is often treated as minimum requirement for shear breaking under the compressive dead loads in the commercial rubber bearings in Japan. Thus the shear break capability of the real-size LRBs of 1600 mm in diameters can be confirmed, at least, to be satisfied with commercial minimum requirement, and both break capabilities with two different plug types are quite similar to each other.

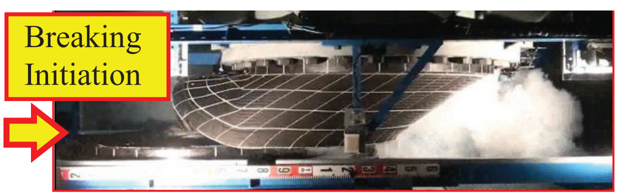
All damage surfaces were observed after the break tests. Typical break behaviour in the shear break test is shown in Figure 3. To verify manufacturable of specimens, it is important to investigate the location and the material of break initiation: where the break process started is and which the material is. As shown in Figure 3, the break initiation is located at the left-edge of the lowest rubber layer, whose material is estimated to be rubber. Within the break tests almost all of the break initiations were observed in rubber material, whose break surfaces around the initiation are not rough as shown in Figure 3(c).

Tensile Break Test

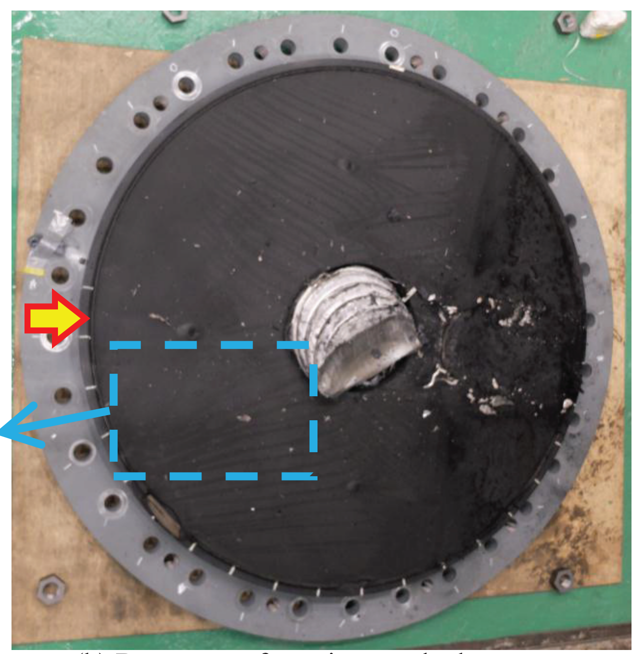
Experimental results of tensile strain and tensile stress are summarized to evaluate the tensile stress-strain curves in the same manner. The minimum value in break tensile stress is read as 1.5 MPa. By referring

Table 3 Shear break test results

No.	Test Name Abbr.	Test condition		Measured stress and strain at breaking			
		Initial Axial Stress [MPa]	Surface Temp. [Deg.]	Shear Stress [MPa]	Shear Strain [%]	Axial Stress [MPa]	Axial Strain [%]
1	1F1	-5	24.4	4.2	448.5	-4.4	-3.5
2	1F2	-5	19.9	3.8	439.4	-4.9	-4.7
3	1F3	-5	20.1	4.5	465.9	-4.9	-4.4
4	2F	-8	15.4	4.9	447.5	-7.5	-4.9
5	1H	-5	8.0	6.5	458.2	-3.1	-2.9
6	3H	-15	8.3	8.3	473.0	-13.4	-8.1
7	4H	-30	10.8	7.6	500.5	-27.2	-18.9
8	5F	0	19.1	5.1	466.4	0.3	0.5
9	6F	+1	7.9	3.4	394.1	1.1	9.3
18	1M1	-5	8.0	4.6	437.0	-4.9	-3.6
19	1M2	-5	28.8	3.4	454.1	-4.8	-4.0



(a) Broken deformation shape.



(c) Enlarged view on the damage surface. (b) Damage surface view on the lower part.

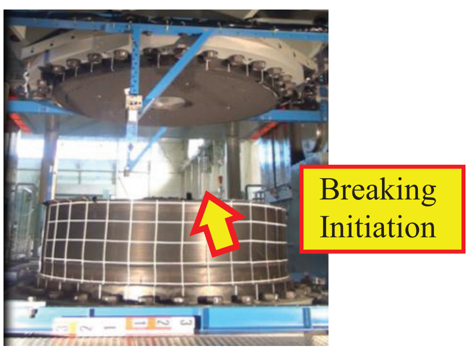
Figure 3. Typical break behaviour on the shear loading(Test-1F1).

the foregoing study, Hirata et al.(1998), the tensile linear stress limit is able to be set to 1.0MPa: the experimental values in break tensile stress measured herein are large enough to compare the conventional linear limit. Further the tensile break stresses of the real-size LRBs of 1600 mm in diameters can be confirmed, at least, to be almost the same as the one of small specimens employed in the foregoing study, and also, both break capabilities with two different plug types are quite similar to each other.

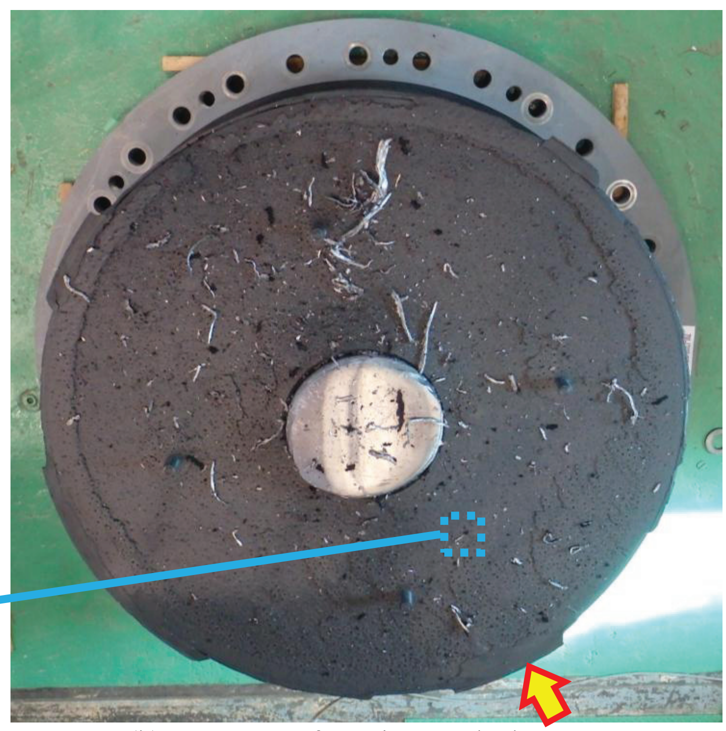
In tensile break tests almost all of the break initiations are observed in rubber material, whose surfaces are observed to be significantly rough as shown in Figure 4(c). The pattern like scattering circles shown in Figure 4(c), is clouds of voids. The observed result indicates that the rubber parts around break initiate

Table 4 Tensile break test results

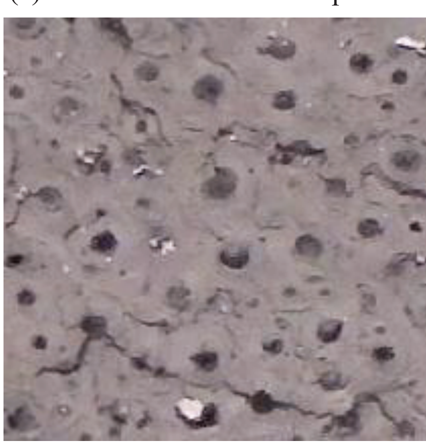
No.	Test Name Abbr.	Test condition		Measured stress and strain at breaking			
		Offset Shear Strain [%]	Surface Temp. [Deg.]	Shear Stress [MPa]	Shear Strain [%]	Axial Stress [MPa]	Axial Strain [%]
10	7F	0	19.8	0.0	0.5	3.5	291.3
11	8F	100	14.4	0.6	110.5	3.4	255.4
12	9F1	200	11.1	0.8	200.8	1.9	63.0
13	9F2	200	25.0	0.7	207.6	2.1	141.1
14	10F1	300	10.3	1.5	298.2	1.8	21.7
15	10F2	300	24.5	1.3	304.8	1.6	37.0
16	11F1	400	8.6	3.0	387.8	2.1	11.1
17	11F2	400	26.7	1.9	385.9	1.5	17.7
20	10M	300	22.9	1.3	305.9	1.8	52.1



(a) Broken deformation shape.



(b) Damage surface view on the lower part.



(c) Enlarged view on the damage surface.

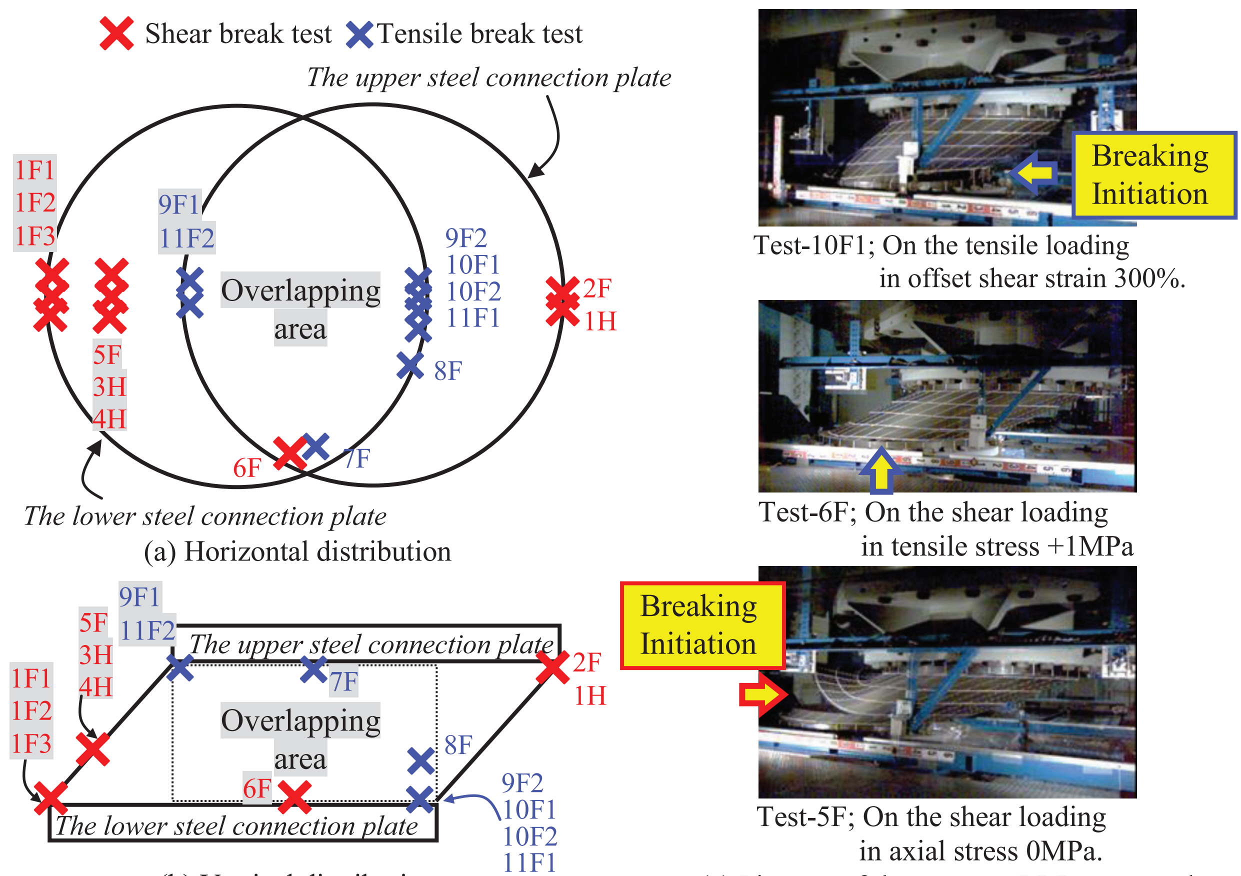
Figure 4. Typical break behaviour on the tensile loading (Test-7F).

have ultimate tensile strain before ruptured. Such rough surface including clouds of voids is also observed in the break initiation surface of the test-6F specimen. The break test under tensile-shear loading such as test-6F might be classified into tensile break phenomenon.

Classification of break type

The break phenomena of laminated rubber bearings are classified into four types, such as tensile break, shear break, buckling failure and compressive crushing, Hirata, et al.(1998), Japan Electric Association(2013). All break events observed here can be shear break or tensile break. Since a break initiation is the weakest in whole area, break type can be classified to investigate the location of a break initiate and stress distribution estimate before breaking. The distribution of break initiation is shown in Figure 5. The break initiation classified into two areas; e.g., inside or outside the overlapped area between the upper and the lower steel connection plates. Under tension-shear loading tensile stress is transmitted inside the overlapping area, thus break starts at the part of the inside overlapping area where the principal tensile stress is the largest of all. In contrast, under compression-shear loading compressive stress is transmitted inside overlapping area, thus the break starts at the outside of the overlapping area where the principal tensile stress is the largest. By utilizing the facts we can classify the break types.

Within the break tests of the reference specimens shown in Figure 5, all tensile tests and the test-6F are classified to *tensile break type*: whereas the shear break tests except for the test-6F are classified to *shear break type*. In the next section we will evaluate break boundary criteria divided into shear break type and tensile break type, utilizing two classes of the results based on the classification here.



(a) Horizontal distribution

(b) Vertical distribution

(c) Pictures of the moment LRBs ruptured

Figure 5. Distribution of break initiation points in the single-plug typed LRBs.

A TENTATIVE EVALUATION ON BREAK BOUDARY CRITERIA

Break limit in axial stress-shear strain plane

According to the concept of the Japanese design guideline for base-isolated nuclear power plants (JEAG4614-2013), break boundary criteria are tentatively evaluated from the break test data.

Regression formulas of break limit in axial stress-shear strain plane are defined as

$$x = a \qquad (y < d) \tag{1}$$

$$y = bx + c \quad (y \geq d) \tag{2}$$

where x and y are shear strain and axial stress; a, b, c and d are the coefficient of regression, respectively. Here, a and c are assumed to be stochastic variables, whereas b and d are assumed to be non-stochastic variables. Two regression formulas in Eqs. (1) and (2) are calculated from five and eight experimental data as shown in Figure 6. The results are shown that mean and standard deviation of a are 453.5% and 10.8%; b is -0.00492 MPa; mean and standard deviation of c are 3.385MPa and 0.365MPa; d is +1.15 MPa, respectively.

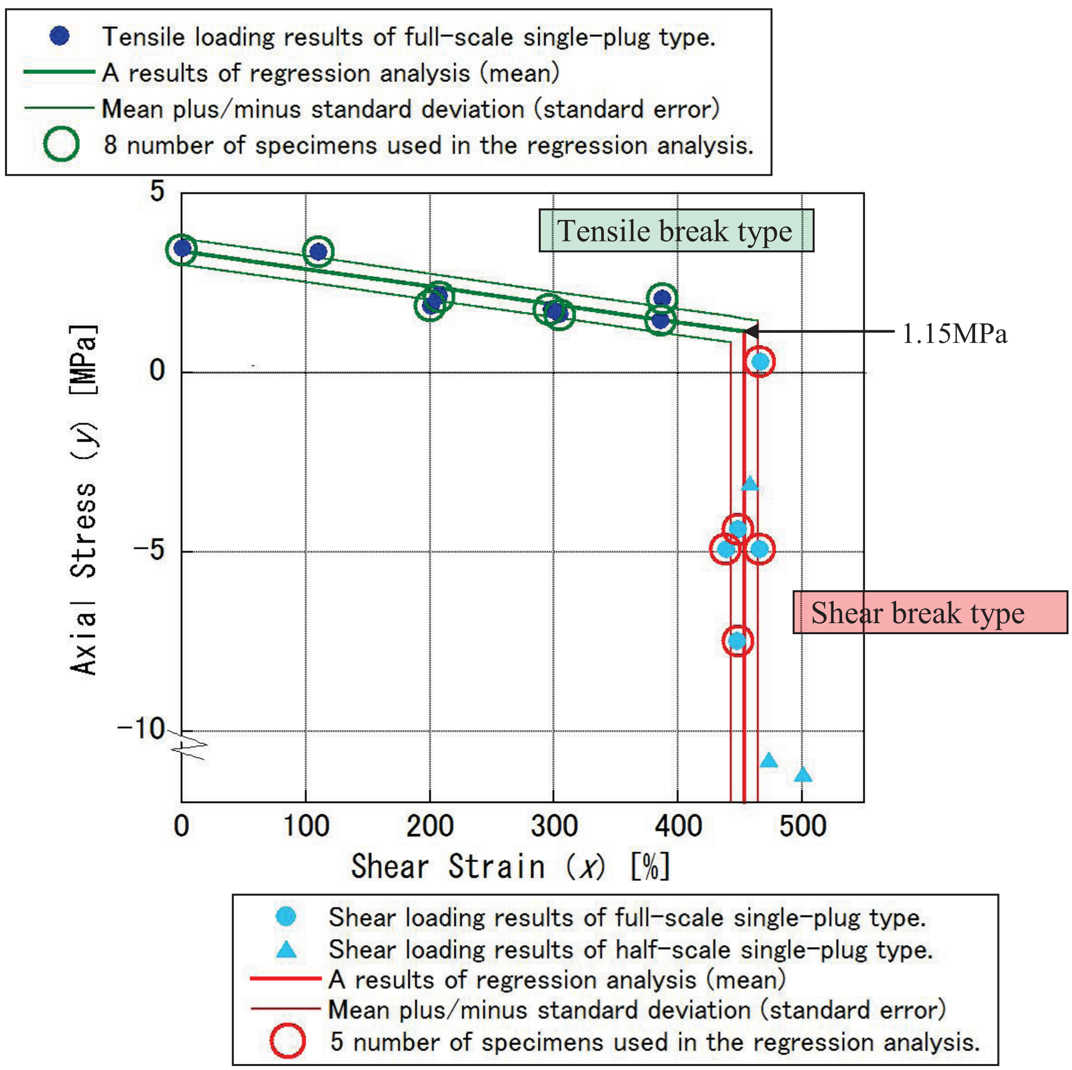
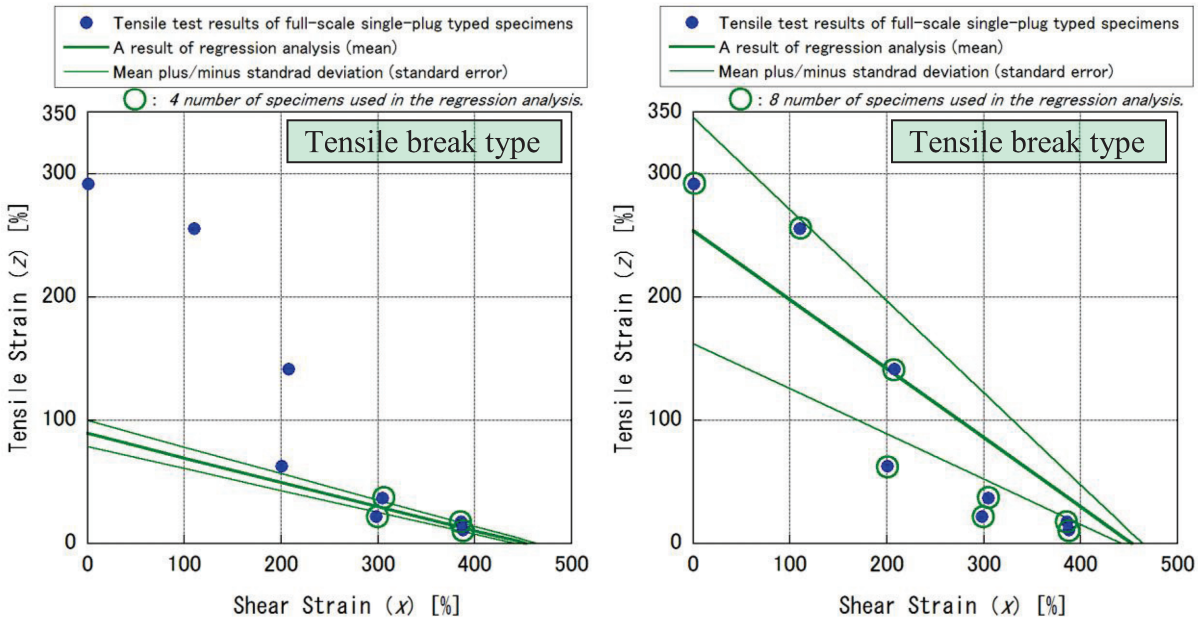


Figure 6. Break boundary criteria in the shear strain-axial stress coordinate plane.



(a) A regression result based on the tensile test only in the large offset shear strain.

(b) A regression result from all tensile tests.

Figure 7. Break boundary criteria in the shear strain-tensile strain coordinate plane.

As shown in Figure 6, the experimental data are distributed around the regression results; For the half scale break test in large compression, the regression gives conservative criteria: thus the regression model are well adequate to explain the break limit criteria.

Break limit in tensile strain-shear strain plane

Regression formula of break limit in tensile strain-shear strain plane is defined as

$$\frac{x}{a}+\frac{z}{e}=1 \qquad (z \geq 0) \tag{3}$$

where z is axial strain; e are the coefficient of regression and stochastic variable. The regression formula in Eq.(3) are calculated by a constraint condition of a given in the previous regression, i.e., in the regression of Eq.(1). Two regression results from four and eight experimental data are shown in Figure 7, where mean and standard deviation of e are 89.3% and 10.6% in the four-point regression; 253.8% and 91.6% in the eight-point regression, respectively.

The result from four-point regression gives conservative criteria in Figure 7(a); whereas the result from eight point regression gives non-conservative criteria within large shear strains, as shown in Figure 7(b). With considering that coupled horizontal and vertical responses on the base-isolated NPPs most likely appear within shear strain 300% or more in tensile behaviours, the four-point regression gives better safety result in risk residual analysis.

CONCLUSION

Break capabilities of the Lead Rubber Bearings (LRB) of 1600 mm in diameter with a large single-lead-plug are well-evaluated from a series of the full-scale break tests. It should be noted that the break shear strain and the tensile stress of the real-size LRBs exceed the commercial reference values of 400% and 1.0MPa, respectively. Especially, the experimental values in tensile break stress are almost the same as one of the small specimens employed in the foregoing study. A tentative break boundary criterion is able to be conservatively evaluated for employing the probability-based residual risk analysis.

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