EXPERIMENTAL STUDY ON STRUCTURAL CHARACTERISTICS OF FOUNDATIONS ATTACHED TO THE LAMINATED RUBBER BEARING

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Abstract

Laminated rubber bearings are generally installed between the superstructure and the foundation of a building. When such a bearing is strongly deformed in a horizontal direction, as occurs in an earthquake, this gives rise to high stresses throughout the overlapped region between the upper and lower faces of the deformed laminated rubber bearing that remain vertically opposite each other act as an effective support for the weight of the building. This situation must be considered when deciding the locations of the bearings and their installation method. This is one of the reasons for the upper limit of 15MPa on the design compressive pressure for laminated rubber bearings. The stress distribution inside laminated rubber bearings has been studied using the finite element method (FEM), but the effect of the high stresses acting in the portion of a deformed laminated rubber bearing on the foundation itself has not been examined.

This paper describes an experiment to measure the internal stresses in a reinforced concrete (RC) foundation below a laminated rubber bearing.

Keywords: Seismic isolation, Laminated rubber bearing, Reinforced concrete foundation, Confining effect

1. INTRODUCTION

Laminated rubber bearings are generally installed between the superstructure and the foundation of a building. When such a bearing is strongly deformed in a horizontal direction, as occurs in an earthquake, this gives rise to high stresses throughout the overlapped region between the upper and lower faces of the deformed laminated rubber bearing that remain vertically opposite each other act as an effective support for the weight of the building. This situation must be considered when deciding the locations of the bearings and their installation method. This is one of the reasons for the upper limit of 15MPa on the design compressive pressure for laminated rubber bearings. The stress distribution inside laminated rubber bearings has been studied using the finite element method (FEM), but the effect of the high stresses acting in the portion of a deformed laminated rubber bearing on the foundation itself has not been examined. This paper describes an experiment to measure the internal stresses in a reinforced concrete (RC) foundation below a laminated rubber bearing.

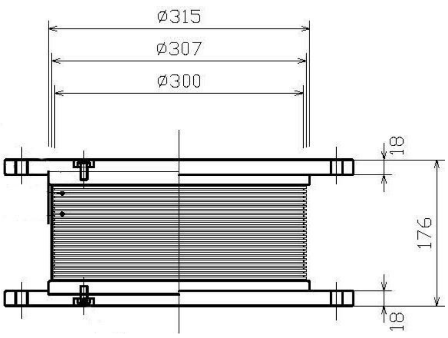
2. SPECIMENS

2.1 Laminated rubber bearings

The bearings employed in this test were 3 natural rubber bearings (NRBs) 300 mm in diameter. Fig.1 is a diagram of the NRBs and Table 1 provides their stiffness properties.

2.2 Reinforced concrete foundation specimen (RC specimen)

Table 2 presents the specifications of the RC specimen and the combinations with laminated rubber bearings and Fig.2 shows how the rebar, strain gauges and mold strain gauges were positioned in the RC specimen. The foundation consisted of the upper foundation, to which the bearing was fixed, and the lower foundation beneath it. A base plate was embedded in the top of the upper foundation, just as how a bearing is used in an actual seismically isolated structure. The rebar the foundation was SD295. A concrete mix with a design strength of Fc=30MPa was used in the lower foundation, and 2 mixes were used for the upper foundation, with design strengths of Fc=13.5MPa and 30MPa. The 4-week measured strengths of these were 18MPa for the Fc=13.5MPa mix and 23MPa for the Fc=30MPa mix. The strain in the upper foundation was measured using strain gauges (FLK-2-11-5LT, TML) attached to the shear reinforcement and 13 mold strain gauges (PMFL-50-5LT, TML) embedded in the concrete (M1 to M13). In addition to the shear reinforcement placed to surround the upper portion of the upper foundation of RC specimen No.2 (1st layer of reinforcements, H1a to H1d), this specimen also contained a 2nd layer of reinforcements (H21a to H21d) placed to surround the flange plate for the laminated rubber bearing, near the portion directly below the bearing.



Diameter of rubber: 300mm
Thickness of a rubber: 2.25mm
Number of rubber: 26
Total thickness of rubber: 58.5mm
Primary shape factor S_1:33
Secondary shape factor S_2:5.1

Fig.1 – Natural Rubber Bearing (unit: mm)

Table 1 – Stiffness of Rubber Bearings

Rubber Bearing	Compressive Stiffness (kN/mm)	Horizontal Stiffness(kN/mm)
NRB1	1387	0.48
NRB2	1295	0.50
NRB3	1341	0.47

Table 2 – Reinforced concrete foundation specimen

RC foundation specimen (Laminated rubber bearing)		No.1 (NRB1)	No.2 (NRB2)	No.3 (NRB3)
Upper foundation	Size	600×600×150mm		
	Main reinforcement	5-D4		5-D10
	Shearing reinforcement	2-D4 (H1a-H1d)	2-D4 (H1a-H1d) 2-D4 (H21a-H21d)	2-D4 (H1a-H1d)
	Concrete strength	Fc=13.5MPa		Fc=30MPa
Lower foundation	Size	1000×700×300mm		
	Concrete strength	Fc=30MPa		

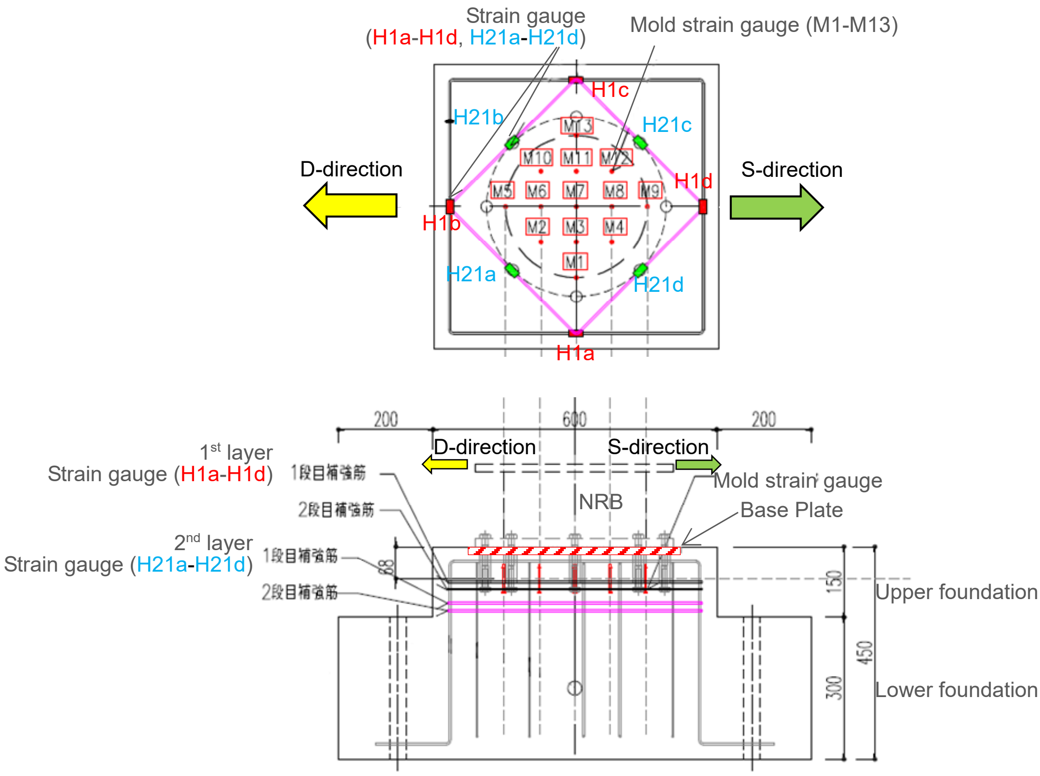


Fig.2 – Reinforced concrete foundation specimen No.2 (unit: mm)

3. RESULTS

3.1 Ordinary amplitude test

In order to examine the fundamental characteristics, the specimens were deformed to a shear strain $\gamma \approx 260\%$ while under compressive pressures of up to 25MPa.

3.1.1 Test overview

The test was performed on the compressive shearing test machine shown in Fig.3. This is a 2-axis test machine which exerts a compressive load with a jack and a shearing load with an actuator. The direction in which the actuator acts on the specimen in traction is defined as the “D-direction”. Fig.4 shows a laminated rubber bearing under compressive loading and deformed 150mm in the horizontal direction.

As the horizontal deformation is getting larger, the effective support area decreases and the pressure of the effective supporting portion becomes larger. (see Fig.17) The bearing was subjected to a specified horizontal deformation (offset) which was then held constant, and progressive compressive loads were exerted on the specimen to perform the shear-compression tests. The compressive loads were limited to the range causing no more than 2000μ maximum strain on the mold strain gauges. The system was unstable while applying a horizontal deformation if no compressive load was simultaneously applied, so horizontal deformation was performed under compressive loads of 100kN (1.4MPa). Table 3 shows the basic loading pattern. Forces (1) to (31) were applied in ascending order. The horizontal deformation was kept to a shear strain $\gamma \approx 260\%$ due to the limitations of the loading frame.

3.1.2 Load-deformation curve for laminated rubber bearing

Fig.5 shows how the Compressive load and shearing load varied with deformations. The compressive and horizontal stiffnesses both match well with the values for all of the bearings given in Table 1. The points on the shearing load-deformation curve that show load fluctuation represent times at which the horizontal deformation was fixed and the compressive load was increased. Some fluctuations in the shearing load are also visible with changing compressive load.

Fig.3 – Compressive shearing test machine 1

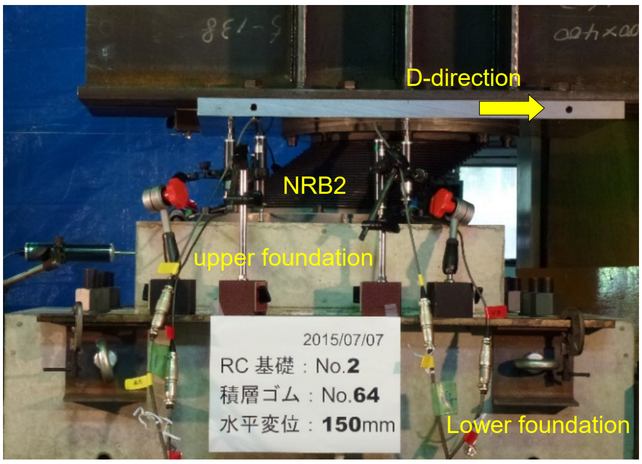


Fig.4 – RC specimen No.2 (NRB deformed 150mm)

Table 3 – Basic loading pattern (D-direction)

Compressive pressure (MPa)	Compressive load (kN)	Horizontal deformation (Shear strain γ)					
		0mm (0%)	30mm (51%)	60mm (103%)	90mm (154%)	120mm (205%)	150mm (256%)
0	0	(1)					
1.4	100		(7)	(13)	(19)	(24)	(28)
5	353	(2)	(8)	(14)	(20)	(25)	(29)
10	707	(3)	(9)	(15)	(21)	(26)	(30)
15	1060	(4)	(10)	(16)	(22)	(27)	(31)
20	1414	(5)	(11)	(17)	(23)		
25	1767	(6)	(12)	(18)			

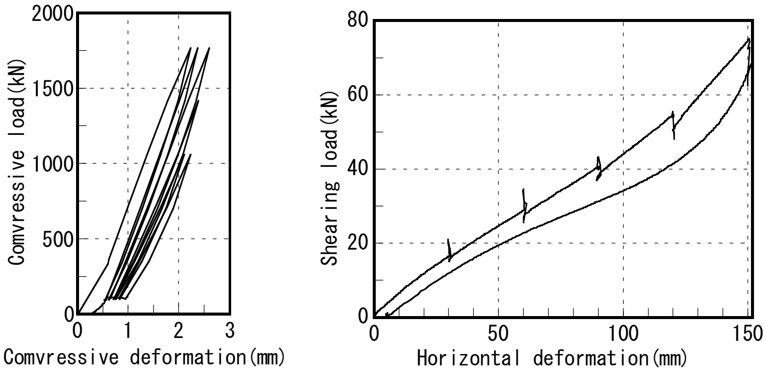


Fig.5 – Hysteresis loops of NRB1

3.1.3 Variation in compressive load with strain for shear reinforcement

Fig.6 to Fig.8 show how the compressive load varied with the strain in the shear reinforcement in the upper foundation. The measurements were performed at the strain gauge positions indicated in Fig.2. Fig.6 shows the strain in the shear reinforcement placed to surround the flanges for the laminated rubber bearing (2nd layer of reinforcements: strain gauges H21a to H21d). There was almost no change in the strain; it remained below 50μ.

Fig.7 and Fig.8 present the strains in the shear reinforcement placed to surround the upper foundation (1st layer of reinforcements: strain gauges H1a to H1d). Strain gauge H1b, which was oriented perpendicular to the direction of force application, measured a high tensile strain. The effective supporting portion approached this strain gauge as it deformed toward a horizontal shape, so this gauge showed a higher value than H1d did. The strain values in the shear reinforcement in Specimen No.2, with a concrete strength of the upper foundation of Fc=13.5MPa, and in Specimen No.3, with Fc=30MPa, were almost indistinguishable.

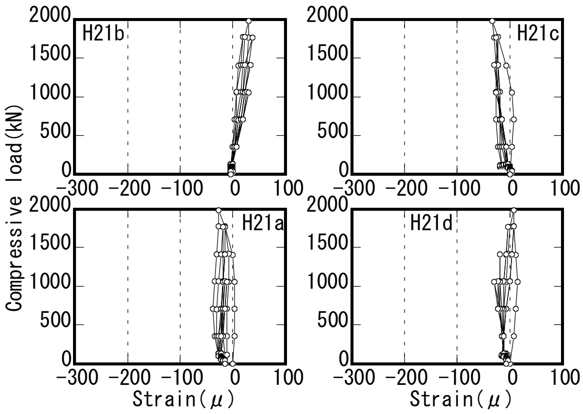


Fig.6 – Strain of shear reinforcement (Strain gauge: H21a - H21d, RC specimen: No.2)

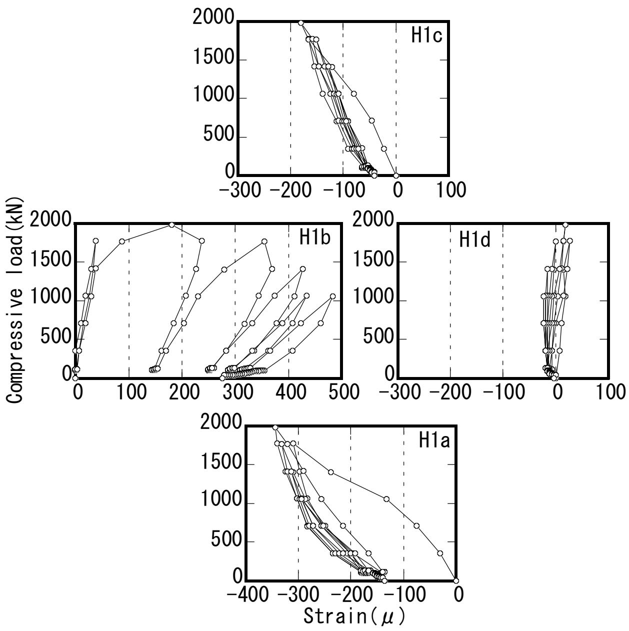


Fig.7–Strain gauge H1a - H1d of shear reinforcement

(RC specimen: No.2, Fc=13.5MPa)

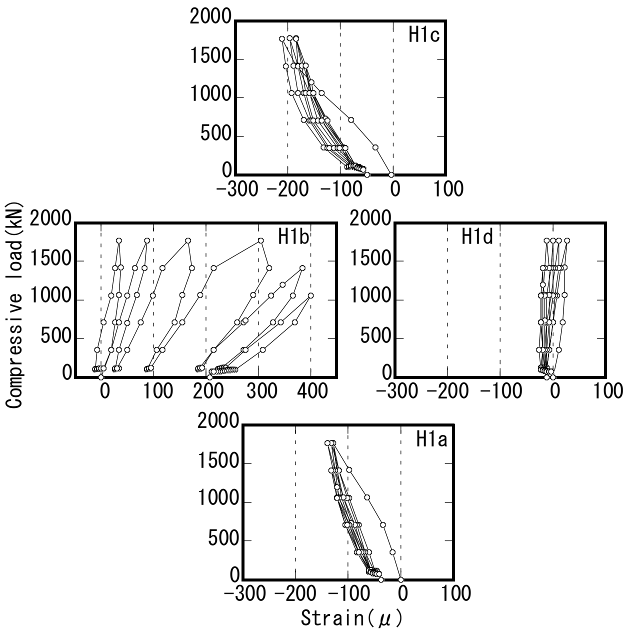


Fig.8– Strain gauge H1a - H1d of shear reinforcement

(RC specimen: No.3, Fc=30MPa)

3.1.4 Variation in compressive load with concrete strain

Fig.9 and Fig.10 show how the compressive load varied with the compressive strain in the concrete, as measured by the mold strain gauges at the positions shown in Fig.2. The compressive strain increased with compressive load. The compressive strain for Specimen No.3 (Fc=30MPa) was 15% to 30% lower than that for Specimen No.1 (Fc=13.5MPa). We next consider the compressive strain at mold strain gauges M5 to M9, oriented in the loading direction in the center of the bearing. M9 was located in a portion of the bearing which shifted away from the effective supporting portion; the compressive strain here did not increase much throughout the test. In contrast, M5, which approached the effective supporting portion, showed increasing compressive strain with the compressive load during the same horizontal deformation. The compressive strain also increased with the horizontal deformation. Since the effective supporting portion decreased during increasing horizontal deformation, the compressive pressure acting on the foundation increased; this may have caused the increase in compressive strain.

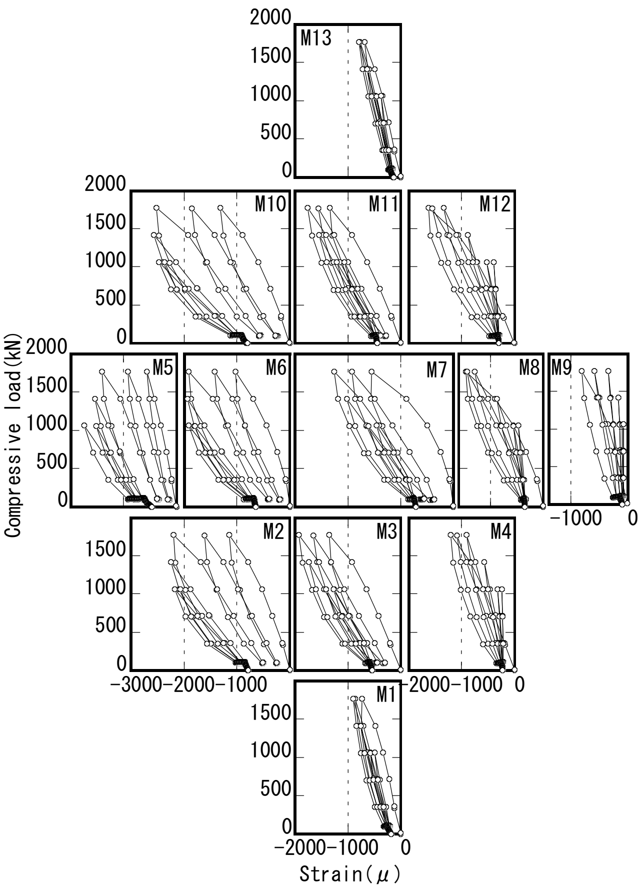


Fig.9 – Mold strain gauge M1 - M13

(RC specimen: No.1, Fc=13.5MPa)

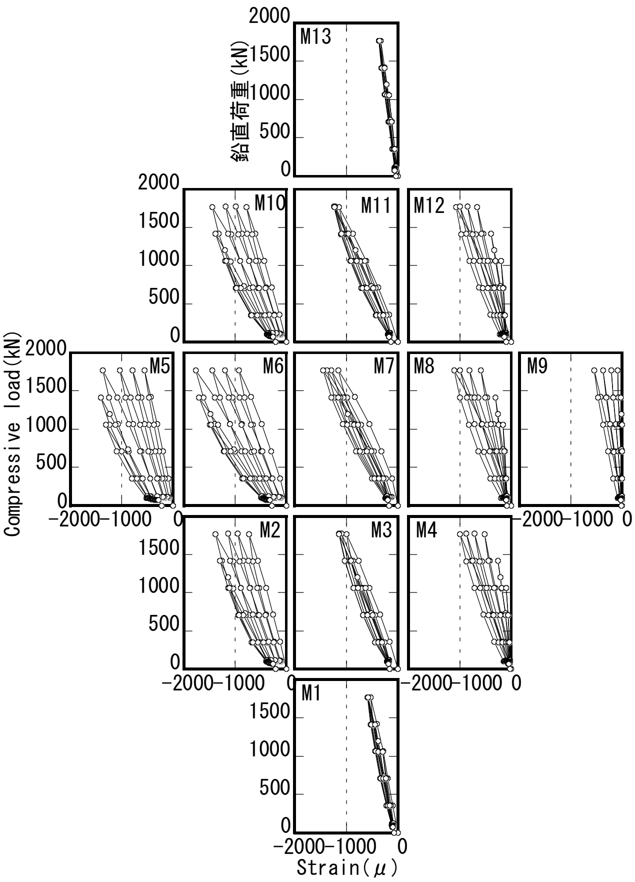


Fig.10 – Mold strain gauge M1 - M13

(RC specimen: No.3, Fc=30MPa)

3.1.5 Stress in RC foundation

It is well known from previous research that the compressive strength and ductility of constrained concrete members vary with the degree of constraint. Generally, stresses are higher under triaxial loading than under uniaxial loading. We made a simple model on the basis of Reference 1) and analyzed it using the FEM to estimate the compressive pressure acting on the concrete directly below the laminated rubber bearing. On the basis of that result, the strength of the concrete under triaxial stress was estimated to have increased by a factor of 3 to 4. The numerical results for strain obtained in the test imply that the concrete reached its peak strength. However, it is possible that a specimen under triaxial stress does not actually reach peak strength, due to the confining effect.

3.2 Large amplitude test

The test apparatus was replaced with another apparatus, and specimens were deformed to shear strains in the range $\gamma \approx 260\%$ to 400% while under compressive pressures of up to 30MPa.

3.2.1 Test overview

The test was conducted on the compressive shearing test machine shown in Fig.11. Fig.12 is a photograph of a test in progress. The mechanism applied a shear deformation to a laminated rubber bearing placed between the RC foundation specimen and the test machine by making the upper flange of a laminated rubber bearing move in a horizontal direction. The apparatus loaded the bearing specimens as follows: A specified horizontal deformation (offset) was applied to the bearing, followed by loading in compression; once the specified maximum loading had been applied at the given shear deformation value, the load was released and the next offset was applied for the next sequence of compressive loads. The directions of force application were those marked D-direction and S-direction as shown in Fig.12. Forces (1) to (16) in Table 4 were applied in ascending order in the D-direction. Next, forces (17) to (34) were applied in ascending order in the S-direction.

Fig.11 – Compressive shearing test machine 2

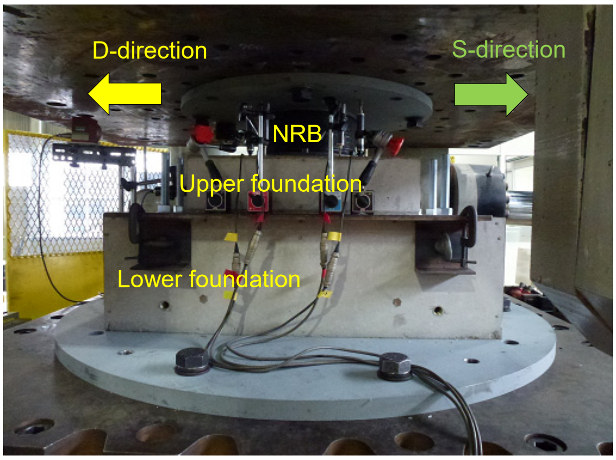


Fig.12 – NRB and RC specimen

Table 3 – Basic loading pattern

Compressive pressure (MPa)	Compressive load (kN)	Horizontal deformation (Shear strain γ)			
		150mm (256%)	180mm (308%)	210mm (359%)	235mm (402%)
0	0	(1) (17)			
1.41	100		(5)	(9) (21)	(13) (28)
5	353	(2) (18)	(6)	(10) (22)	(14) (29)
10	707	(3) (19)	(7)	(11) (23)	(15) (30)
15	1060	(4) (20)	(8)	(12) (24)	(16) (31)
20	1414			(25)	(32)
25	1767			(26)	(33)
30	2121			(27)	(34)

*Black is D-direction, Red is S-direction

3.2.2 Variation in compressive load with strain in shear reinforcement

Fig.13 presents the strain for RC specimen No.3, where the shear reinforcement was placed to surround the upper foundation. The results for forces in the D-direction are shown in black and those for the S-directed forces are in red. Compressive strain appeared while the shear reinforcement was apart from the edge of the effective supporting portion. Tensile strains increased markedly when the edge of the effective supporting portion approached the shear reinforcement due to the horizontal deformation.

Fig.14 shows the highest strain occurring in the shear reinforcement in RC specimens No.1 and No.2, at H1d in both specimens. In comparison with the results for RC specimen No.3 shown in Fig.13, RC specimen No.1 exhibited about twice the amount of strain. Part of the shear reinforcement in No.2 exhibited a strain of 10,000μ. Since the other measured strains (H1a to H1c) were about the same as for RC specimen No.1, it is possible that the strain gauges malfunctioned.

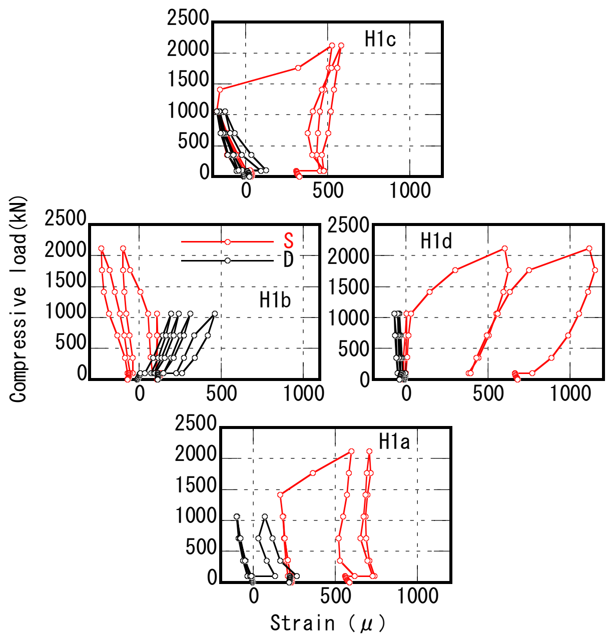


Fig.13 – Strain gauge H1a - H1d of shear reinforcement (RC specimen: No.3, Fc=30MPa)

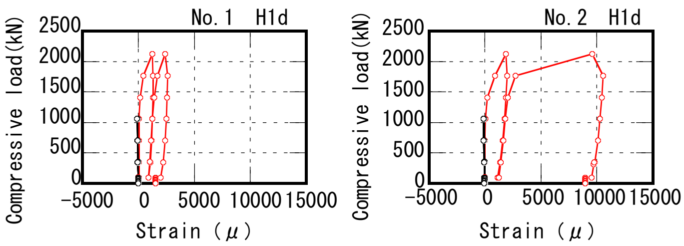


Fig.14 – Strain gauge H1d of shear reinforcement

(RC specimen: No.1 and No.2, Fc=13.5MPa)

3.2.3 Variation in compressive load with concrete strain

Fig.15 shows how the compressive load varied with the strain in the concrete as indicated by the mold strain gauges for RC specimen No.3, for the positions shown in Fig.2. The compressive load and compressive strain increased together. The compressive strain reached its maximum at M5 when the force was in the D direction and at M9 when the force was in the S direction as the edge of the effective supporting portion approached the respective gauges.

Fig.16 provides the strains found at M9 for RC specimens No.1 and No.2. The maximum strain was about 15,000μ, which is almost three times that for RC specimen No.3 in Fig.15.

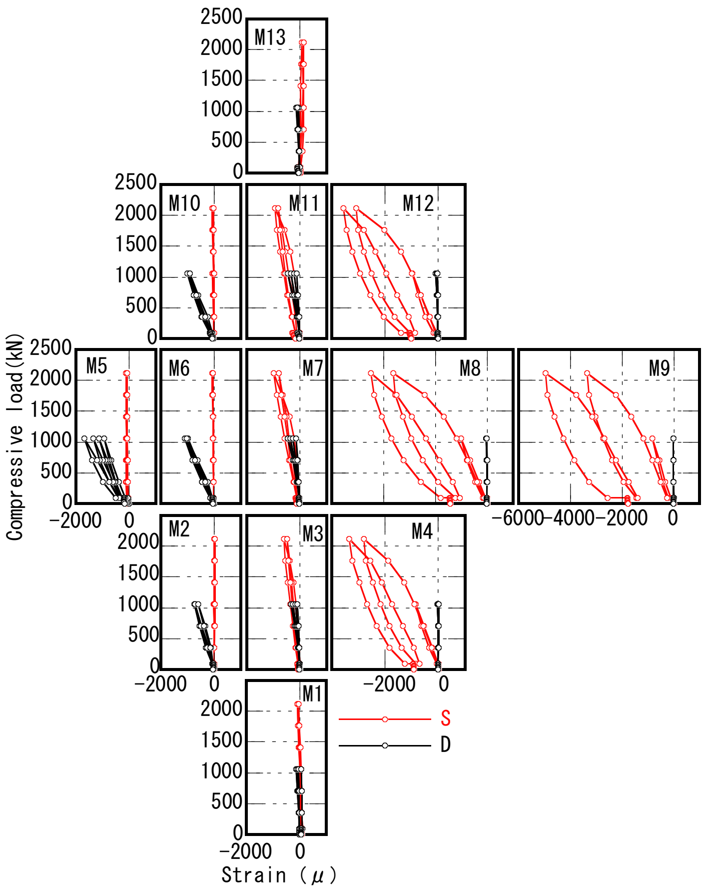


Fig.15 – Mold strain gauge M1 - M13 (RC specimen: No.3, Fc=30MPa)

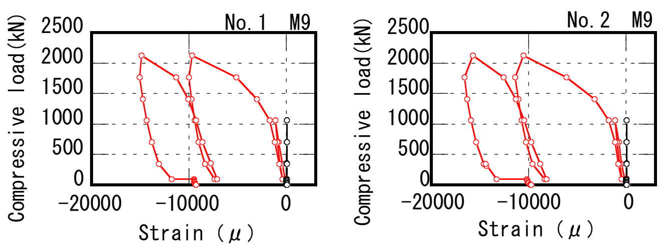


Fig.16 – Mold strain gauge M9 (RC specimen: No.1 and No.2, Fc=13.5MPa)

3.3 Strain distribution in concrete in upper foundation

The mold strain gauge measurements indicated that the compressive strain tended to be lower in concrete with higher strength. This suggests that the concrete strength must be correctly selected when designing foundations in which laminated rubber bearings will be used under high compressive pressures.

Fig.17 provides the distribution of strain in the concrete during low-amplitude excitation under a compressive pressure of 15MPa and a horizontal deformation of 150mm. The actual measured strains are shown at the locations given in Fig.2, and the strains at locations between these were estimated by linear interpolation. It can be seen that the compressive strain was high at M2, M6 and M10, directly below the effective supporting portion.

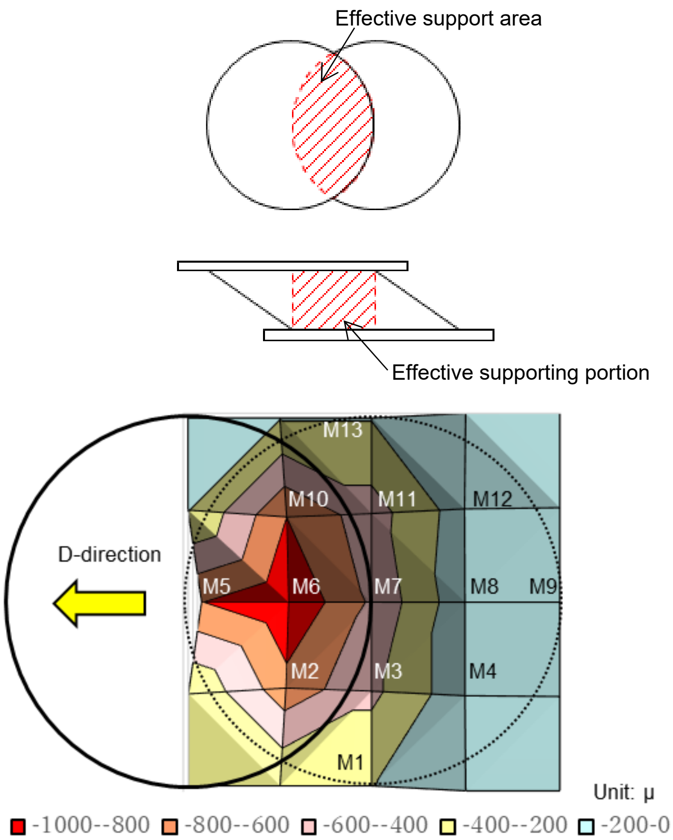


Fig.17 – Strain distribution of upper foundation

(RC specimen: No.3, Fc=30MPa, Compressive pressure: 15MPa, Deformation: 150mm)

3.4 Subsidence of base plate

After the test, the laminated rubber bearing was removed and the amount of subsidence of the base plate was measured. Fig.18 shows the amount of subsidence along radial lines from the center of a circle in the directions of the applied forces. Under a compressive pressure of 30MPa, there was greater subsidence from forces in the S-direction than in the D-direction. Subsidence diminished with increasing concrete strength; no influence of the main reinforcement could be discerned. No significant cracking was found in the RC foundation specimen.

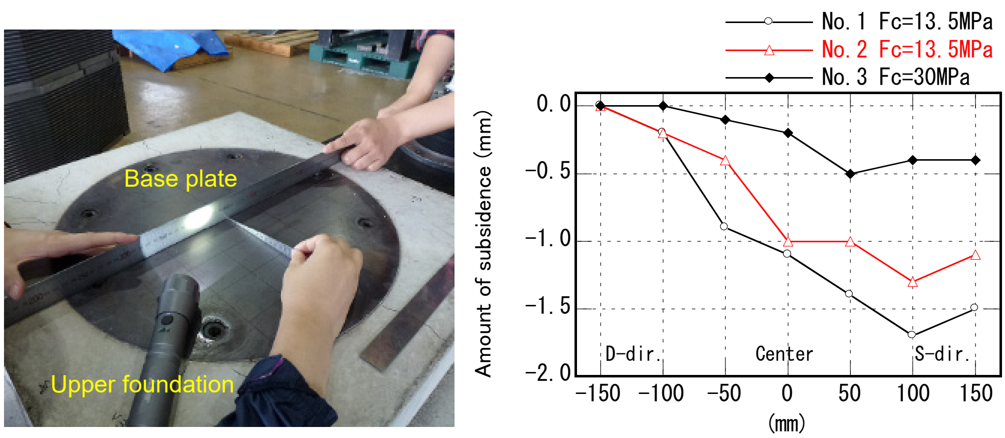


Fig.18 – Amount of subsidence of base plate

4. SUMMARY

A test was performed with a RC foundation specimen and a laminated rubber bearing, deforming the rubber at up to 400% shear under a compressive pressure of up to 30MPa, in order to examine the stress exerted on the RC foundation by the bearing. The test showed that the compressive strain in the RC foundation supporting a bearing tends to be lower when the concrete strength was high. In terms of the out-of-plane deformation of the base plate beneath a bearing, subsidence decreased when the concrete strength was high, and is a maximum immediately beneath the effective supporting portion.

5. ACKNOWLEDGEMENT

We thank the cooperation of Kurashiki Company which allowed to use the testing machine when we carried out the large deformation test.

6. REFERENCES

[1] Naganuma K (1995): Stress-strain relationship for concrete under triaxial compression. *Journal of Structural and Construction Engineering, Transactions of AIJ,* (474), 163-170. (in Japanese)

