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OBSERVATION RECORDS OF BASE-ISOLATED BUILDINGS IN STRONG MOTION AREA DURING THE 2011 OFF THE PACIFIC COAST OF TOHOKU EARTHQUAKE

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ABSTRACT: Many buildings in the area of Tohoku and Kanto suffered structural damage by the 2011 off the Pacific coast of Tohoku earthquake occurred on March 11th. Although few base-isolated buildings which have suffered structural damage are reported, there are some reports that nonstructural elements, such as expansion joints, in base-isolated buildings have suffered damage.

In this paper, strong motion observation records of base-isolated buildings in Miyagi (BLD.A) and Chiba prefectures (BLD.B) are shown. Isolation systems used in both of these buildings are high damping rubber bearings. The acceleration reduction effect by the base-isolation system is confirmed in both of these buildings. The first floor/basement acceleration is 200/381 cm/s^2 in BLD.A, and is 98/219 cm/s^2 in BLD.B. No structural damage in either building is reported. The maximum relative displacement of the isolated layer is 18 cm in BLD.A and is 5 cm in BLD.B. The cumulated relative displacement of the isolated layer is 14.6m in BLD.A and is 8.5m in BLD.B, which is larger than one in an ordinary earthquake because of long duration time of the earthquake. Natural period of the building varied along with the time course on the earthquake due to characteristics of high damping rubber bearings, which become softened in proportion to horizontal displacement.

Based on the analysis of the observation data, it is shown that 1) load-history dependency of base isolation systems has been observed, 2) high damping rubber bearings have remained softened after maximum relative displacement of isolation layer and 3) it has taken about a month until the stiffness of the isolation layer has been back to the initial stiffness.

Key Words: long-period ground motion, base-isolated building, high damping rubber bearings, load-history dependency

INTRODUCTION

After the 1995 Hyogoken-Nanbu earthquake, the number of base-isolated buildings has increased. The total number of constructed base-isolated buildings in Japan has been about 2,900 in 2009 (Tanaka 2011). Acceleration reduction effects in base-isolated buildings have been proved by strong motion records. These records have contributed to spread the base-isolated system. In contrast, there are few strong motion records in base-isolated buildings during long-period ground motions. The duration time of the 2011 off the Pacific coast of Tohoku earthquake (i.e. the Tohoku earthquake) occurred on March 11th is much longer than ones of ever observed earthquakes. High damping rubber bearing, representative one of base-isolated systems, have load-history dependency. There are few reports about dynamic characteristics of base-isolated buildings using high damping rubber bearings during long-period ground motions.

This paper shows strong motion records in two base-isolated buildings using high damping rubber bearings during the Tohoku earthquake. The load-history dependency of high damping rubber bearings is confirmed by the variation of the dynamic characteristics obtained through the analysis of the records.

BASE-ISOLATED BUILDING

BLD.A is a six story base-isolated building, 74.6 m long and 37.0 m wide, in Miyagi prefecture. BLD.B is an eight story base-isolated building, 30.0m long and 47.6m wide, in Chiba prefecture. Both of them are office buildings. The superstructure of BLD.A is a moment resisting steel frame structure and that of BLD.B is moment resisting frame structure consisted of steel encased reinforced concrete column and steel beam. The elevation plans and accelerometers locations of these buildings are shown in Fig. 1. Isolation systems used in both of these buildings are high damping rubber bearings. The accelerometers are located at the basement, the floor above the isolated layer and the top floor in both buildings. Two accelerometers of NS direction are located at each floor in BLD.A.

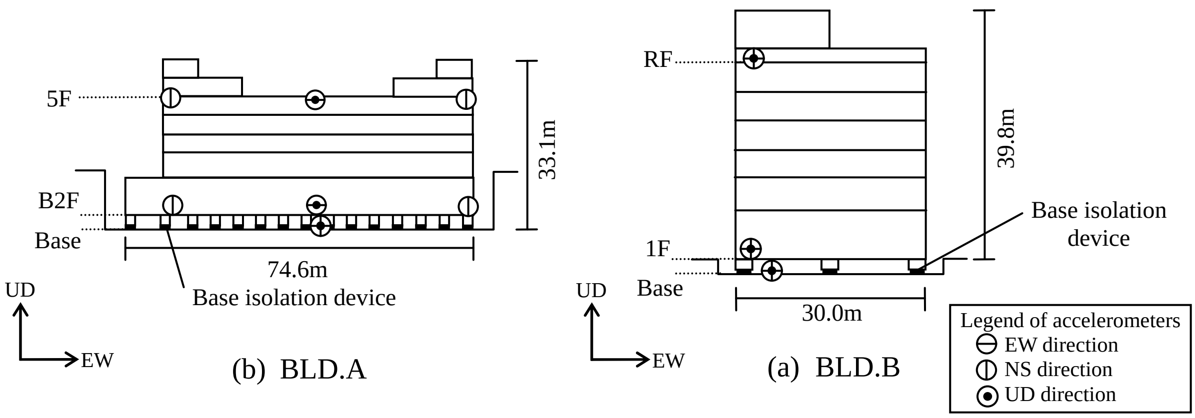


Fig. 1 Elevation plans and accelerometers locations of the base-isolated buildings

BASE ISOLATION SYSTEM

The base-isolation systems in both buildings consist of only high damping rubber bearings. The number of bearings is 64 in BLD.A and 35 in BLD.B. The specifications of the base isolation bearings in BLD.A and BLD.B are shown in Table 1 and Table2. The designed deformation limit of both base isolation systems is 40 cm. Total rubber layer thickness of base isolation bearings is 150 - 203 mm in BLD.A and 198 – 215 mm in BLD.B.

Table 1 Specification of the base isolation bearings in BLD.A

Number of bearings	Diameter	Rubber layer	Steel plate layer	1st shape factor	2nd shape factor
10	1,000mm	8.0mm, 25layers	3.1mm, 24layers	30.1	5.0
20	850mm	7.0mm, 29layers	2.2mm, 28layers	30.4	4.2
20	800mm	6.5mm, 31layers	2.2mm, 30layers	30.8	4.0
14	600mm	5.0mm, 30layers	2.2mm, 29layers	30.0	4.0

Table 2 Specification of the base isolation bearings in BLD.B

Number of bearings	Diameter	Rubber layer	Steel plate layer	1st shape factor	2nd shape factor
5	1,180mm	9.5mm, 21layers	3.1mm, 20layers	31.1	5.9
18	1,000mm	8.0mm, 25layers	3.1mm, 24layers	31.3	5.0
8	800mm	6.5mm, 31layers	2.2mm, 30layers	30.8	4.0
4	700mm	6.0mm, 33layers	2.2mm, 32layers	29.2	3.5

OBSERVATION RECORDS

The maximum accelerations in two buildings are shown in Table 3 and Table 4. Distribution of the maximum accelerations at each story in EW direction is shown in Fig. 2. Acceleration reduction effects by the base-isolation systems are confirmed in both of the buildings, as shown in Fig. 2. The maximum acceleration at the floor above the isolated layer is 41 - 83 % of the basement. Acceleration records at the basement and the floor above in EW direction are shown in Fig. 3. The first 200 s of the accelerations and displacements are shown in Fig. 3 and Fig. 4. The duration time of the acceleration data is 205 s in BLD.A and 713 s in BLD.B during the earthquake. As shown in Fig. 3, the periods of acceleration wave at the floor above the isolated layer are longer than the one at the basement in both buildings. The acceleration reduction effects in almost all the duration time are confirmed through comparison of the acceleration amplitudes. Observation data of the first 80 s were missed in BLD.A, as overwritten by the aftershocks observation data. Therefore, although two principal shocks were observed in Miyagi prefecture, only later principal shock was recorded in BLD.A, as shown in Fig. 3(a).

Relative displacements of the isolated layer in EW direction are shown in Fig. 4. The displacements are calculated via double integration of the acceleration record filtered out the component lower than 0.1 Hz. Maximum relative story displacements of the isolated layer in two buildings are shown in Fig. 5. The maximum relative story displacement in horizontal direction is 19.9 cm in BLD.A, 6.0 cm in BLD.B. These displacements correspond to shear strain 133 % of the thinnest base-isolation bearing in BLD.A and 30 % in BLD.B.

Cumulative Relative story displacements in horizontal direction of the isolated layers are shown in Fig.6. The cumulated relative story displacement of the isolated layer is 14.6m in BLD.A and is 8.5m in BLD.B. The displacement is much larger than one in ordinary earthquakes because of long duration time of the earthquake. For example, in the case that maximum acceleration was observed at basement of BLD.B during an earthquake before the Tohoku earthquake, the cumulated relative story displacement of the isolated layer is 0.67m.

Table 3 Maximum acceleration in BLD.A (cm/s^2)

	NS	EW	UD
Base	277	381	213
B2F	163, 214	200	185
5F	240, 231	209	424

Table 4 Maximum acceleration in BLD.B (cm/s^2)

	NS	EW	UD
Base	174	219	128
1F	71.7	97.5	129
RF	128	129	295

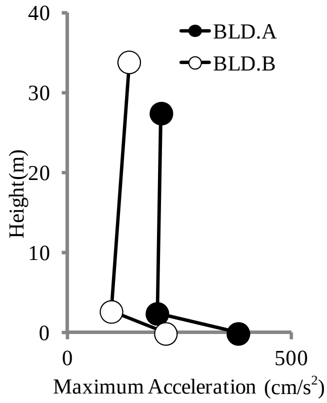
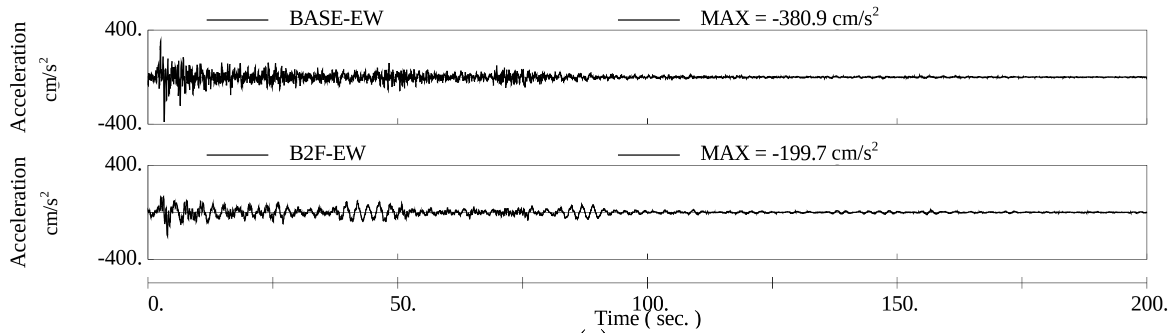
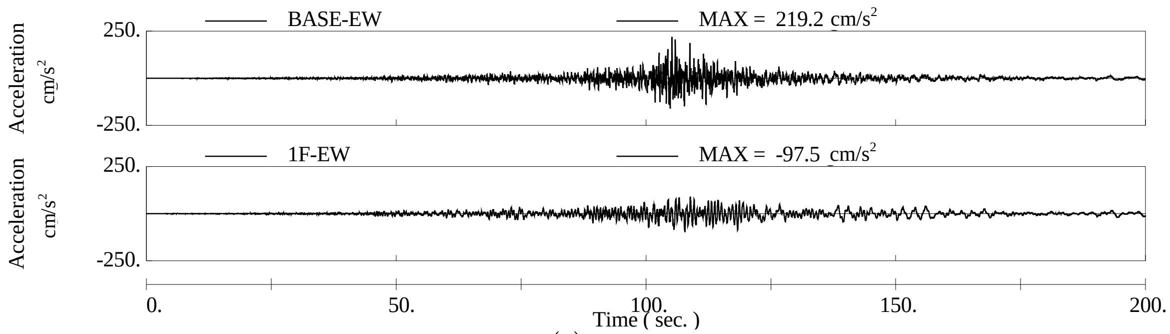


Fig. 2 Distribution of maximum accelerations in base-isolated buildings (EW)

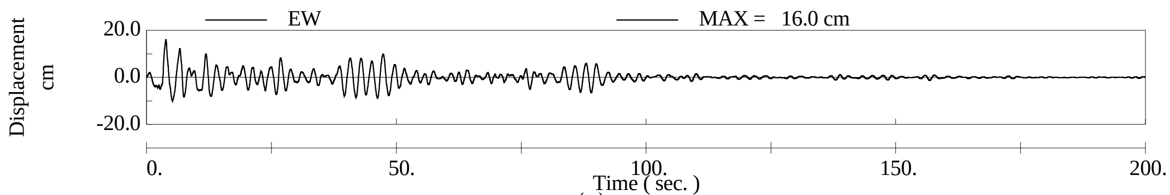


(a) BLD.A

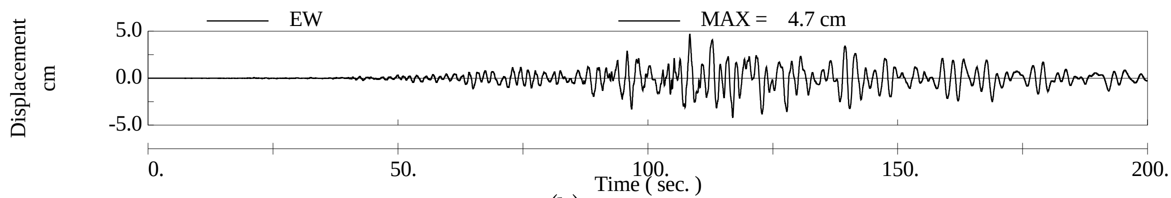


(b) BLD.B

Fig. 3 Acceleration records



(a) BLD.A



(b) BLD.B

Fig. 4 Relative story displacement records of the isolated layer (EW)

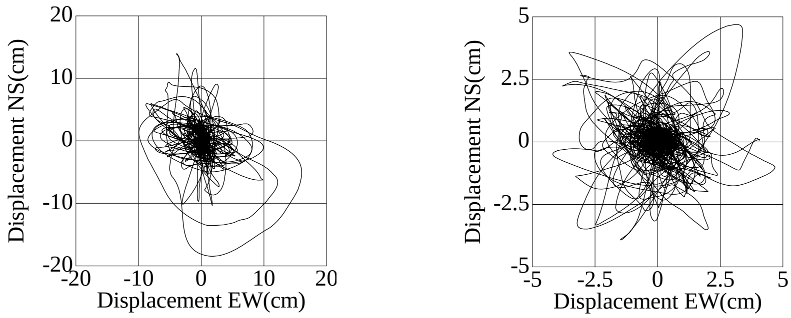


Fig. 5 Relative story displacements of the isolated layers (Left: BLD.A, Right: BLD.B)

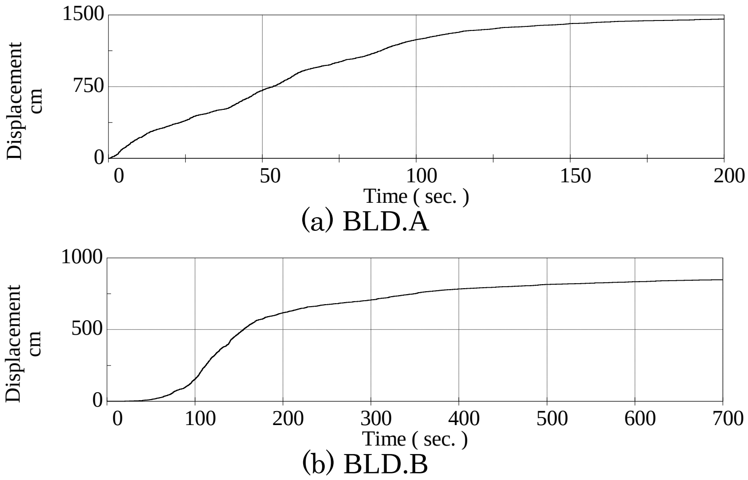


Fig. 6 Cumulative Relative story displacements of the isolated layers

IDENTIFICATION OF DYNAMIC CHARACTERISTICS

Transfer function of 1st floor/basement and roof floor/basement are identified by ERA (Eigensystem Realization Algorithm, Juang 1985) in BLD.B during the earthquake. Dynamic characteristics are obtained through the identified transfer function. The identified natural period and damping factor are shown in Table 5. For reference, designed primary natural period in BLD.B is shown in Table 6. In this table, “small amplitude” corresponds to shear strain ratio smaller than 10% and displacement 10 cm in “Level 1” corresponds to shear strain ratio about 56 %. Identified natural period at 1st mode is slight larger than designed one in the case of “Small amplitude”, as shown in Table 5 and Table 6. Maximum shear strain ratio in BLD.B is 30 %. As the observed natural period and the maximum shear strain ratio are in between the designed value of “Small amplitude” and “Level 1”, the observed dynamic characteristics approximately agree with the designed one. Comparison of observed and identified transfer function at 1st floor/basement is shown in Fig. 7. It is considered that damping factors are well estimated, judging from the identified amplitude and phase being same as observed one.

Table 5 Identified dynamic characteristics in BLD.B

	NS		EW	
Mode	Natural period(s)	Damping factor(%)	Natural period(s)	Damping factor(%)
1	1.99	15.7	1.98	16.0
2	0.63	10.2	0.65	12.3
3	0.31	4.65	0.27	3.54

Table 6 Designed primary natural period in BLD.B

	NS	EW
Small amplitude	1.81	1.78
Level 1 displacement :10cm	2.50	2.48
Level 2 displacement :20cm	2.99	2.97

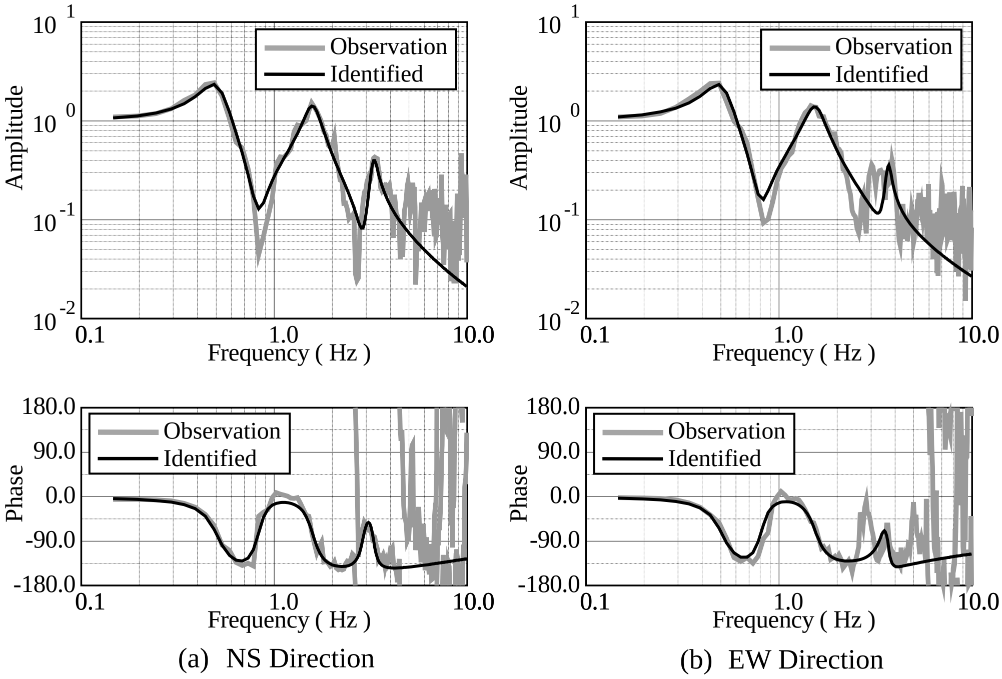


Fig. 7 Comparison of observed and identified transfer function at 1st floor/basement in BLD.B

DYNAMIC CHARACTERISTICS VARYING ALONG WITH THE TIME COURSE

In BLD.B, the variation of hysteresis characteristics in every 20 s during the earthquake in EW direction is shown in Fig. 8. Gray line, which connects maximum and minimum loads, shows approximate stiffness of the isolated layer. The story shear force of the base-isolated layer in Fig. 8 is estimated from the 1st floor acceleration, which is filtered out the component higher than 1 Hz, multiplied by the building mass. As shown from 40 s to 160 s in Fig. 8, the approximate stiffness becomes low along with the increase in the relative displacement of the isolated layer. It shows that the base-isolated system has been softened from the initial condition. After 160 s, although relative displacements of the isolated layer decrease from the maximum displacement, the base-isolated layer stiffness remains lower than the initial stiffness. It is due to load-history dependency of base isolation systems of high damping rubber bearings (Torii 1999 and AIJ 2001). Estimated natural period and damping factor through ARX model (autoregressive model with exogenous input) are shown in Fig. 9. The estimation was done in every 1 s with the prior 10 s observed data. As shown in Fig. 9, the natural period increases from the initial period 1.2 s to 2.2 s in around 120 s when the largest relative displacement was observed. After the largest displacement, although the natural period decreases gradually to 1.4 s in the end of observation, the natural period remains longer by 0.2 s than the initial period. It shows that in the end of observation, the base-isolated layer stiffness remains lower than the initial stiffness. Damping factor also increases to 23 - 30 % from the initial damping factor in around 120 s. After the largest displacement, damping factor, though varying widely, decreases gradually.

The relation of the identified natural period and maximum relative displacements of the isolated layers in every 10 s is shown in Fig. 10. In the displacement larger than 1 cm, the natural period after the maximum relative displacement is about 0.2 s longer. The time course of the natural period in BLD.B is shown in Fig. 11. It is evaluated from the first 10 s of observation data during each earthquake, which has occurred from about a month before to a month after the Tohoku earthquake. The time course is smoothed with a 10-point moving average and is shown in gray line. It has taken about a month until the stiffness of the isolation layers has been back to the initial stiffness.

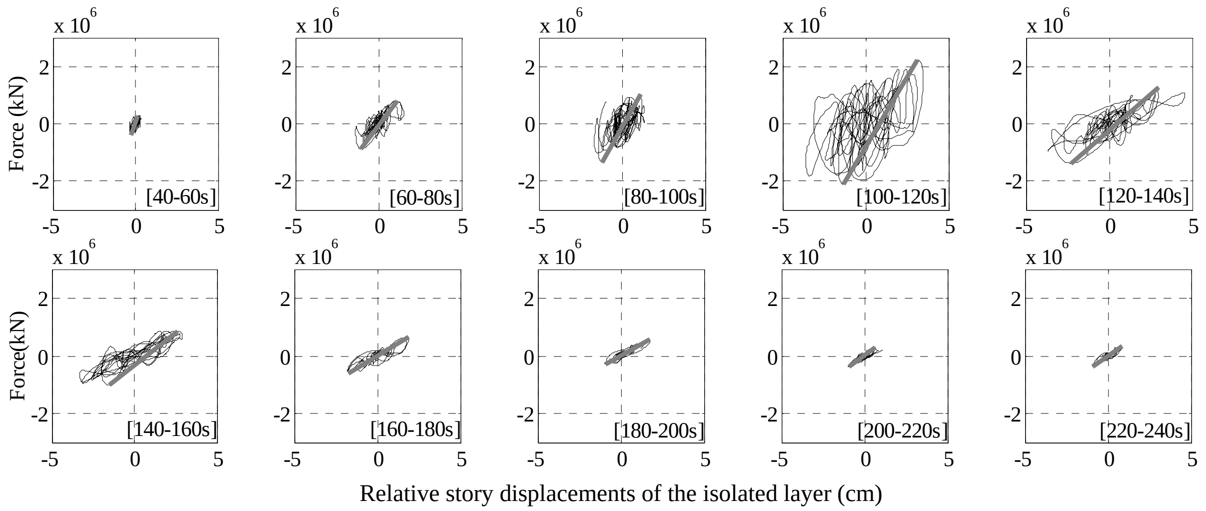


Fig. 8 Variation of hysteresis characteristics in EW direction along with the time course in BLD.B

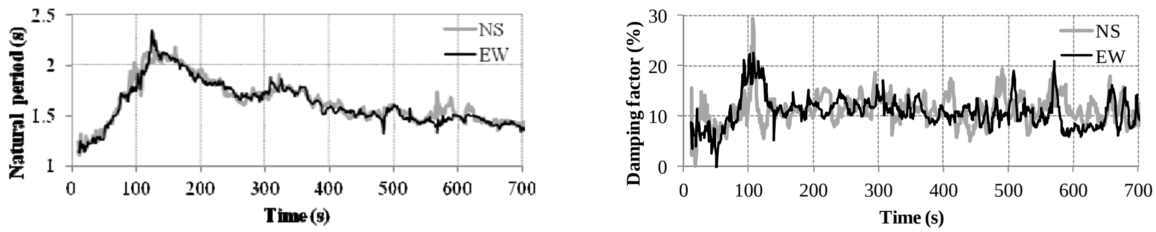


Fig. 9 Variation of identified period and damping factor along with the time course in BLD.B

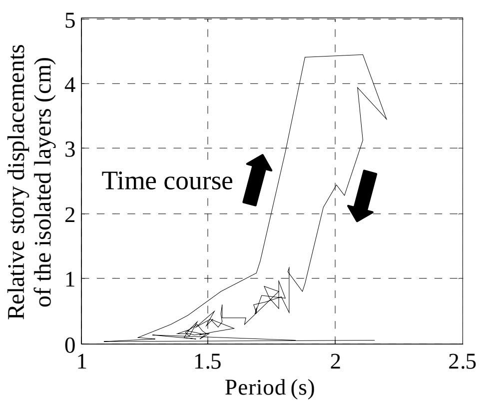


Fig. 10 Relation of identified natural period and maximum relative story displacements of the isolated layer in EW direction in every10 s in BLD.B

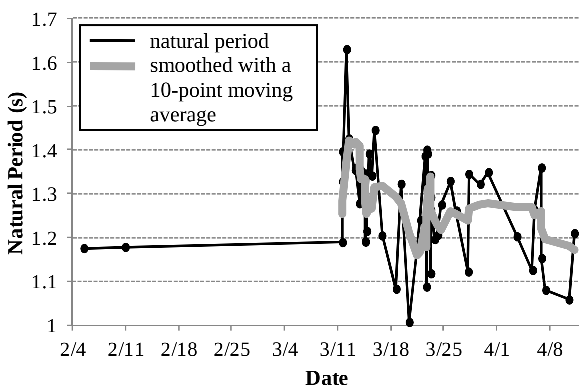


Fig. 11 Time course of the natural period in BLD.B evaluated from the the first 10 s of observation data

CONCLUSIONS

In this paper, the observation records of base-isolated buildings using high damping rubber bearings in Miyagi and Chiba Prefectures during the Tohoku earthquake have been reported. Dynamics characteristics obtained from the records in these two base-isolated buildings have been described.
The analyses on the observation records are shown below.
1) The acceleration reduction effects by the base-isolation system are confirmed in both of the buildings.
2) Load-history dependency of base isolation systems using high damping rubber bearings has been observed.
3) High damping rubber bearings have remained softened after maximum relative displacement during the earthquake.
4) It has taken about a month until the stiffness of the base isolation layer has been back to the initial stiffness.

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