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MID-STORY SEISMIC ISOLATION FOR STRENGTHENING OF A MULTI-STORY BUILDING

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SUMMARY

The seismic strengthening in Japan has been accelerated and extended to official, public, memorial and residential buildings with large scale and great height. For such kind of building, however, only using the conventional strengthening measures is difficult to meet the seismic requirements and service requirements, because they have many problems needed to be solved, and usually requires that strengthening works should not affect their normal service and continuing occupation. . Therefore, some new seismic isolation and vibration control technologies have been developed. This paper presents a case study for strengthening a 9-story RC/SRC mixed structure, which locates in the suburb of Tokyo. The structure has a weak story at the 4-th story. The upper stories (above the 4-th story) and lower stories are for residential and business uses, respectively. Retrofitting work is not allowed for the upper stories because of the requirement of concurrent occupation of the residential stories. In this case applying mid-story seismic isolation (at the weak story) is conceived and studied. The new method is compared with other strengthening methods, such as the framed K-shape steel bracing, the externally cladding SRC-frame bracing, the energy absorbing vibration damping, and the base isolation. Following the careful analysis and comparison, it was found that the mid-story seismic isolation can fully meet the seismic requirements and is able to ensure the concurrent occupation during retrofitting work. It also results in a lower retrofitting cost. The seismic isolation system combines laminated rubber bearing (of natural rubber) with energy-absorbing dampers together. To confirm the effectiveness of the system and to ensure the pre-set design aim, the time history nonlinear analysis is carried out by inputting a simulated field wave and some typical seismic waves. The analytical results show that after the installation of the isolation system, the building needs no structural strengthening to the upper stories (above the isolated 4-th story), only minor strengthening required for the lower stories.

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INTRODUCTION

In the Hyogoken-Nanbu earthquake 1995 in Japan, although 240,000 buildings collapsed or were severely damaged, two seismic isolated buildings within the epicenter zone survived without any damage. This showed that the isolated buildings maintain extraordinary earthquake resistant. capability. As a result, the base isolated techniques has been tremendously applied into the construction of new buildings since then. Over the whole decade before the earthquake, the total number of isolated buildings evaluated by the Building Center of Japan was only 82. Only within one year following the earthquake, however, over 200 buildings were evaluated as isolated buildings and the number is kept around 140 in every following year.

In the meantime, with the implementation of "The Act of Building Seismic Improvement Promotion" by the Japanese Government in December 1995, a great progress has been made in the seismic diagnosis and strengthening. From 1997 to 2001, 25,000 public buildings, most of which are school buildings, were evaluated by the Assessment Committees,. In recent years, seismic diagnosis and strengthening has been accelerated and extended to official, public, memorial and residential buildings with large scale and great height. However, only using applying g the conventional strengthening measures into such buildings is hard to meet the seismic requirements and service requirements, because such buildings, either high-rise or mid-rise buildings, have many problems need to be solved, and usually require the continuing occupation during strengthening works. Therefore, some new seismic isolation and vibration control technologies have been developed.

This paper introduces isolation proposal and discuss its utilization into a mid-story of a public building near Tokyo on basis of the nonlinear time-dependent analysis.

DESCRIPTION OF THE BUILDING

This building to be seismic strengthened is located near Tokyo. It was constructed in 1972 consisting of A & B blocks both of nine stories. Its 1st to 4th stories are of steel reinforced concrete (SRC) structure, and 5th to 9th stories of reinforced concrete (RC) structure. Its total built-up area is 9632 m^2. The normal concrete with a design strength of 21 N/mm^2 was used for 1st to 4th stories. The light-weight aggregate

Fig.1 The Building

concrete with a design strength of 18 N/mm^2 was used for 5th to 9th story,. The 1st to 3rd stories of the building are used as government offices, and its 5th to 9th stories as normal residential apartments. The 4th story is a transitional story, which is built with connecting corridors and shared space for the residents of upper stories. No earthquake resisting wall was built on this story and the story is a pure frame structure (refer to Fig.1). The foundation of the building sits on a clayed rocks layer with a bearing strength of 2000 kN/mm^2. It is an independent footing foundation. The predominant period of the building is 0.25~0.30 seconds.

As the residential stories and offices stories have been occupied, the occupation of building must not be disturbed while seismic strengthening works go on.

SEISMIC DIAGNOSIS RESULTS

The seismic diagnosis was carried out according to the Third level Evaluation Method, as prescribed by the "Standard for Evaluation of Seismic Capacity of Existing Reinforced Concrete Buildings" by the Japan Building Disaster Prevention Association[1] and "Technical Manual for Seismic Diagnosis and Seismic Retrofitting Design of Existing Reinforced Concrete Buildings" by Japan Association for Building Research Promotion[2]. The evaluation results are listed in Table 1. After taking account of the region effect factoring, the seismic indices of the structure should meet the following requirements: Is $\geqq$ 0.66, $C_TS_D \geqq 0.3$. Table 1 indicated that all stories in the longitudinal direction and 3rd & 4th story in the span direction of both A and B blocks do not meet these requirements. Thus they may be damaged during earthquakes, and consequently strengthening needs to be implemented.

Table 1 Seismic Diagnosis Results (The Third level Evaluation Method)

Stories	Block A in Long. Direction		Block A in Span Direction		Block B in Long. Direction		Block B in Span Direction	
	Is	C_TS_D	Is	C_TS_D	Is	C_TS_D	Is	C_TS_D
9F	0.53	0.20	0.72	0.74	0.44	0.16	0.47	0.50
8F	0.30	0.24	0.86	0.89	0.46	0.24	1.39	1.49
7F	0.58	0.19	0.79	0.82	0.61	0.22	1.15	1.24
6F	0.57	0.19	0.75	0.78	0.64	0.22	1.03	1.10
5F	0.31	0.32	0.72	0.74	0.37	0.13	0.95	1.02
4F	0.48	0.39	0.44	0.36	0.31	0.26	0.33	0.27
3F	0.45	0.46	0.42	0.34	0.61	0.51	0.52	0.44
2F	0.45	0.46	0.75	0.61	0.47	0.40	0.64	0.54
M2F					0.40	0.43	0.57	0.48
1F	0.53	0.55	0.70	0.57	0.63	0.53	0.66	0.56

Is: structural seismic index; C_T: ultimate strength index at the maximum ductility; S_D: shape parameter of structure

COMPARISON OF DIFFERENT STRENGTHENING PROPOSALS

The 5th to 9th residential stories and 1st to 3rd government office stories all fall into the specific building groups according to "The Act of Building Seismic Improvement Promotion". The evaluation results show that the earthquake resisting capability of the building does not meet the requirements, and certain strengthening measures must be taken. Various strengthening methods are analyzed and compared with respect to the particular conditions of the building. Typically only the Block A of the building is used for the comparison of the strengthening methods.

Strengthening with the Steel Framed Braces

Method 1

The residential stories will not be strengthened. Strengthening will only be applied to the 1st to 4th stories. After strengthened, the Expected Structural Seismic Index is taken as Iso = 0.66. Without consideration of the service conditions, the results calculated from the earthquake resisting capacity show that even if 70 sets of steel framed braces were provided, the structure is still not able to meet the seismic requirements. In addition, such strengthening methods do not meet the requirement of continuing occupation.

Method 2

Residential stories and office stories will be strengthened. After strengthened, the Expected Structural Seismic index is Iso=0.66 x 1.25=0.83. Calculations of the earthquake resisting capacity show that even if 105 sets of steel framed braces are provided, the structure is still not able to meet the seismic requirements. In addition, such strengthening methods do not meet the requirement of continuing occupation either.

Strengthening with the External Cladding SRC-Frame Braces

To meet the requirement of continuing occupation, the residential stories will not be strengthened, and only the 1st to 4th stories will be strengthened externally with the cladding SRC-frame bracings. After Strengthened, the Expected Structural Seismic Index is taken as Iso=0.66. With the internal strengthening works being minimized, even 40 sets of the external cladding SRC-frame bracing are not enough to for the structure to meet the seismic requirements. Calculations show that the external cladding SRC-frame bracing presents no greater structural seismic capacity than conventional strengthening methods (Steel framed Braces). .

Energy-Consuming Seismic Reduction Proposal

This proposal is to install viscous dampers into the external steel framed bracing system, so as to strengthen the structure by absorbing the seismic energy. This proposal requires the structurally weak story, the 4th story, to be reinforced at all its columns. Also, to meet the structural displacement requirements under seismic conditions, all side-walls and columns on the residential floors must be separated with grooves. The seismic design objective is to ensure that the maximum story displacement would not exceed 1/200 under the action of the most severe earthquake, and to maintain the member stresses within the ultimate strength. Analysis of the seismic response shows that at least 76 dampers are to be installed so as to meet the seismic requirements. However, it is difficult to satisfy the demand of continuing occupation while the structure is being reinforced. In addition, the cost of the strengthening works is relatively high.

Base Isolation Method

This method is to provide seismic isolation layer below the foundation, to isolate the upper structures and prevent the ground motion from acting on the structure, which consequently change the dynamic properties and reactions of the structure. The seismic response of the building will be reduced with the increased flexibility of the overall structure. Calculations show that 26 sets of seismic rubber isolation bearings are required. This method can meet the requirement of continuing occupation. However, it is required to install the isolation layer and its foundations below the existing foundation of the building, and that needs relatively long construction period cost too much.

Mid-Story Seismic Isolation Method

This method is to install a seismic isolation layer into the structural weak story, the 4th story, so that the earthquake resisting capacity will be increased by completely isolating the office stories and the residential stories. Calculations show that 24 rubber bearings and several dampers are required. This method meets the requirement of continuing occupation. As the elevator shaft will also be separated into upper and lower sections at this story, new elevators will need to be constructed.

Integrated Comparison

Table 2 below compares the costs, construction durations of the above methods.

Table 2 Costs and Construction Durations Required for Each Method

No	Proposals	Strengthening Story	Cost ($x10^8$ Yen)			Duration (Months	Seismic Capacity	Cost
			Block A	Block B	Sum			
1	Steel Framed Bracings 1	1～4	5.73	3.65	9.38	5	×	◎
2	Steel Framed Bracings 2	1～9	8.53	5.25	13.78	7	△	△
3	External SRC Framed Bracings	1～4	4.65	4.75	9.40	8	×	◎
4	Seismic Reduction	1～5	9.66	7.15	16.81	7	○	×
5	Base Isolation	Below Foundation	8.52	4.08	12.60	14	◎	△
6	Mid-Story Isolation	4	7.83	2.38	10.21	9	◎	○

It is decided to provide the seismic isolation layer to the mid-story, the pure-frame 4th story, after comparing the above proposed systems: steel framed bracings, external cladding SRC-frame bracing, energy-consuming seismic reduction, base isolation, and mid-story isolation.

DESCRIPTION OF THE SEISMIC ISOLATION SYSTEM

Normally 3 types of rubber seismic bearings are used in seismic isolation structures: 1) laminated natural rubber bearings, 2) laminated high damping rubber bearings, 3) laminated lead rubber bearings. After analysis and comparison, it is decided that the laminated natural rubber bearing is to be adopted for this building.

Fig.2 shows the restoring force curve of the natural rubber bearings under 14.7 MPa compressive stress, which indicates that the rubber bearing is excellent in linear spring characteristics.

The Isolation System will be installed into all the SRC columns of the 4th story one by one. After one column was cut off at its mid-level, the rubber bearing will be installed instantly between its two cuts, before another column was cut off. The energy-consuming dampers will be installed in both longitudinal and span directions of the building. Block A requires 24 sets of laminated natural rubber bearings (G4.0), and 4 sets of dampers in each of the longitudinal and span directions.

This project uses 600mm diameter laminated natural rubber bearings. Their elastic shear modulus is 0.39 MPa, first shape factor 33.0, second shape factor 5.1, horizontal rigidity 9.50 kN/cm, and vertical rigidity 28500 kN/cm. Maximum allowable long-term compressive stress is 15.0 Mpa, and maximum allowable

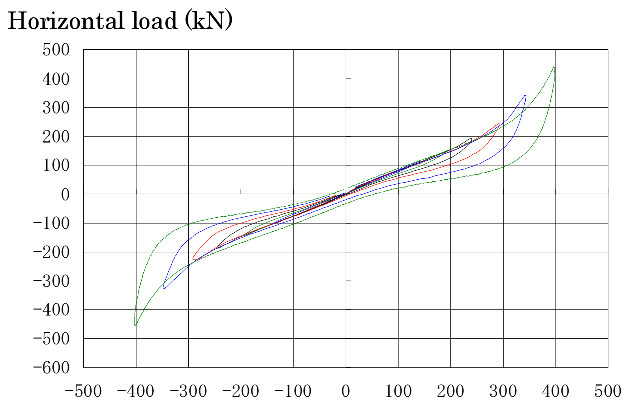

Fig.2 Restoring Force Curve of the Rubber Bearings (G4.0 Φ600)

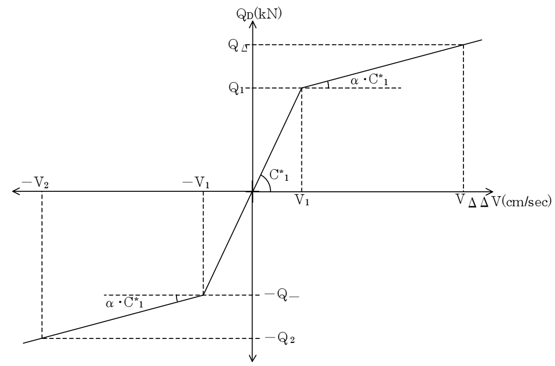

Fig.3 Restoring Force Curve of Dampers (500KN)

C^*_1 = 12.25 KN·sec/cm/set
α = 0.068
Q_1 = 400KN $\quad$ Q_2 = 500KN
V_1 = 32 cm/sec $\quad$ V_2 = 150 cm/sec

short-term compressive stress is 30.0 MPa; no tensile stress is allowed. Maximum horizontal displacement is 350mm. Calculations show that actual compressive stress of the rubber bearings under long-term loading is 0.6 Mpa, which is well below the maximum allowable compressive strength of 15.0 MPa.

The hysteric curve of the dampers is as shown in Fig.3.

MODELING AND SEISMIC DESIGN OBJECTIVES

The objective of the seismic strengthening the building structure is to ensure that its main structural members will not generate excessive displacement or suffer from damages if it suffered from intensive earthquake. Hence, the non-linear time-dependent analysis were carried out by inputting the earthquake waves , to examine if the objectives can be met and safety of the building can be assured.

Modeling

This building has one story underground and 9 stories above ground. The 4th story is structurally weak as it has no shear walls and is of pure frame structure with large open space. For the seismic isolation strengthening concept, it is to install laminated natural rubber bearing into the columns and viscous dampers to form a mid-story seismic isolation structure. The overall structure is idealized as a stick with 10 mass points for analysis. Each story of the building is simplified as a mass point with a lateral spring, the well-adopted response analysis model for building structure. Isolation model adopts horizontal shear spring one to simulate the shear viscous loop of natural rubber.

The damping ratio of the building is taken as 2% (initial rigidity proportionally descending). Damping ratio of the isolation story is taken as zero.

Seismic Waves Used for Design

The seismic waves used in the analysis include the conventionally used waves: EL CENTRO NS and TAFT EW, the long period waves: HACHINOHE NS and YOKOROCK, and the synthetic wave from the scenario Kanto earthquake. The published wave (refer to as Kokuji wave) simulated by fitting the acceleration spectra published by the government. The phase characteristics of the published wave were taken from the records of Hachinohe, JMA Kobe, and a random phase, respectively. Totally 8 waves were used.

Seismic Design Standard

Seismic Design Standard 1: the main structural members shall be in elastic state due to the earthquake that the building may experience once or more times within its lifetime (refer to as level 1).
Seismic Design Standard 2: the stress in each structural member shall be less than the member's ultimate strength due to the strongest earthquake that the building may experience within its lifetime in the region (refer to as level 2).

The seismic waves used in time history analysis are modified based on the peak velocity of the wave. Namely, for the standards 1 and 2, the wave will be modified so that the peak velocity of the wave will be 25 and 50 cm/sec, respectively;.

Design Objectives of Structure above Isolation Story

For the structure above isolation story, the seismic design objectives for the standard 1 are: after experiencing level 1 earthquakes, the structure will be in good service condition without large-scale remedial works, and the member stresses do not exceed the respective allowable stress limits; for the standard 2: during level 2 earthquakes, the member stresses do not exceed the respective ultimate strength; for Design Standard of Seismic Safety Evaluation: the member stresses are within the respective ultimate strength.

Design Objectives of the Isolation System

For the isolation structure, in order to maintain safety of itself, the seismic design objectives for the standard 1: during level 1 earthquakes, the displacement of the bearing is within the stable displacement range (234mm); for the standard 2: displacement of the bearing is within the performance guarantee displacement range (350mm), and no tensile stress shall occur; for Design Standard of Seismic Safety Evaluation: displacement of the bearing is within the displacement range (350mm), and inter-story displacement shall not exceed the standard displacement of the isolation story (450mm).

Design Objectives of the Structure below the Isolation Story

For the structure below the isolation story and the foundation, the seismic design objectives for the standard 1 are: during level 1 earthquakes, the member stresses do not exceed the respective allowable stress limits; for the standard 2: during level 2 earthquakes, the member stresses do not exceed the respective ultimate strength.

ANALYSIS RESULTS

Analysis Method

Time history analysis adopts direct integration. The hysteresis model of the upper structure uses equivalent shear model, isolation layer uses horizontal shear model. The sustain periods are around 50 to 120 seconds for various earthquake waves were adopted in the time history analysis. Ambient temperature of isolation devices is 20 ℃, and the stiffness variation in analysis is between +28%～－14% by considering the aging effects of natural rubber laminates and the allowable construction error. The computer program used for the time history analysis is CANNY.

Analysis of characteristic parameters

The natural periods of existing structure and after isolation were calculated respectively. Results of building A is shown in table 3, the first period of current structure is around 0.4~0.5 second, and is changed as 2.7 seconds after isolation.

Table 3 Natural Periods of Building A

Classification	Modes	Longitudinal direction（sec）	Span direction（sec）
Existing structure	1	0.540	0.440
	2	0.210	0.164
	3	0.143	0.116
After isolation	1	2.687	2.674
	2	0.235	0.185
	3	0.180	0.149

Time history analysis

Table 4 summarize the analytical results of level 2 earthquakes (maximum 50 cm/sec). It can be seen in the table that the maximum shear factor for stories above isolation layer is around 0.17~0.23, maximum story displacement is 2.6mm (leaning angle 1/1000). Based on the analysis results, the upper structure satisfied the targets for seismic design. It's also shown in the table that maximum shear factor for stories under isolation layer is around 0.24~0.36. In comparison with the structure strength, the lower structure needs to be reinforced in some parts. It's also shown in the table that the displacement of isolation layer reaches maximum under yokorock wave, which is about 225.4mm, but still less than target value of 350mm.

Table 4 Maximum Response of Building A（Level 2 earthquake）

Story No.	Longitudinal Direction				Span Direction			
	Shear（ton）	Inter-story Displacement (mm)	Shear Factor	Input Wave	Shear（ton）	Inter-story Displacement (mm)	Shear Factor	Input Wave
9	78.94	0.8	0.226	Yokorock	74.6	0.5	0.190	Yokorock
8	204.9	1.1	0.204	Yokorock	196.4	0.5	0.180	Yokorock
7	323.7	1.8	0.186	Yokorock	314.7	0.6	0.180	Yokorock
6	436.5	2.3	0.177	Yokorock	431.2	0.7	0.180	Yokorock
5	546.4	2.6	0.173	Yokorock	548.1	0.7	0.180	Yokorock
4	536.8	225.0	0.171	Yokorock	538.1	225.4	0.170	Yokorock
3	878.3	1.4	0.234	Yokorock	903.0	1.7	0.240	TaftEW
2	1262.7	1.5	0.316	Yokorock	1293.7	1.5	0.320	TaftEW
1	1718.4	2.1	0.352	Yokorock	1713.3	1.5	0.360	TaftEW
B1	2197.7	1.26	0.345	Yokorock	2220.5	2.08	0.360	TaftEW

SEISMIC STRENGTHENING OF THE STRUCTURE BELOW THE ISOLATION STORY

Analysis and calculations are carried out according to the “Standard for Seismic Diagnosis and Seismic Retrofitting Design of Existing Government Buildings”[5]. The importance factor of the building is taken as 1.25. The calculations show that the structure below the isolation story needs to be strengthened to a certain degree to meet the seismic requirements; RC walls will be provided in the longitudinal direction of the building, 2 to the basement, 2 to the first story, and 1 to the second story.

CONCLUSIONS

This building has a middle transition story, which is structurally weak; and the upper and lower stories are of different structural types. The mid-story isolation technology for strengthening can meet the structural seismic requirements and service requirements of continuing occupation at relatively low cost. It is the most suitable strengthening method for this building. Mid-story isolation method has very good prospects among the existing mid to high-rise buildings which normally has many problems and difficulties for strengthening. Mid-story seismic isolation is to install an isolation layer, which is similar to the base isolation system, to a certain story of a building. It can be regarded as general form of seismic isolation. The mechanical properties of the structure above the isolation story are similar to that of a base-isolated structure, and its earthquake resisting capacity is achieved in a similar way. For the structure below the isolation story, the analysis results showing that seismic forces acting on the structure have been significantly reduced and the expected strengthening effects have been achieved. This method is particularly suitable for high-intensity seismic areas, and mid to high-rise buildings of higher level design objectives. It can be expected that as the demand of seismic diagnosis and strengthening increases, the mid-story isolation method will be implemented to more and more buildings.

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