Comparative Study of Seismic Isolation as Retrofit Method for Historical Constructions

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***Abstract*—**Seismic isolation can be used as a retrofit method for historical buildings with the advantage that minimum intervention on super-structure is required. However, selection of isolation devices depends on weight and stiffness of upper structure. In this study, two buildings are considered for analyses to evaluate the applicability of this retrofitting methodology. Both buildings are located at Akita prefecture in the north part of Japan. One building is a wooden structure that corresponds to the old council meeting hall of Noshiro city. The second building is a brick masonry structure that was used as house of a foreign mining engineer and it is located at Ani town. Ambient vibration measurements were performed on both buildings to estimate their dynamic characteristics. Then, target period of vibration of isolated systems is selected as 3 seconds is selected to estimate required stiffness of isolation devices. For wooden structure, which is a light construction, it was found that natural rubber isolators in combination with friction bearings are suitable for seismic isolation. In case of masonry building elastomeric isolator can be used for its seismic isolation. Lumped mass systems are used for seismic response analysis and it is verified in both cases that seismic isolation can be used as retrofitting method of historical construction. However, in the case of the light building, most of the weight corresponds to the reinforced concrete slab that is required to install isolation devices.

***Keywords*—**Historical building, finite element method, masonry structure, seismic isolation, wooden structure.

I. Introduction

THE seismic isolation structure has been proved to be effective for protection of buildings against earthquake action. This has been verified by observing the behavior of isolated structures during past earthquakes and confirmed by analytical studies [1]. Furthermore, seismic isolation technology is still in the development stage, and a great development of advanced isolation devices and technologies is expected in the future. In recent years, cases of using seismic isolation devices to protect existing buildings, in special buildings that represent historical, cultural and social values, have been increasing [2]. Such repair is called seismic isolation retrofit (hereinafter referred to as seismic isolation repair). This method is a method that does not impair the usability of the building after renovation, and it is characterized that the seismic isolation device can be attached while using the building. However, it is necessary to fully study the mechanical properties such as stiffness and damping force of the entire seismic isolation layer, and the material of the upper structure at the time of seismic isolation repair.

In this study, two representative historical constructions are selected to investigate their seismic isolation repair. The first one is a wooden historical building, and the second one is a brick masonry building. Both are existing buildings located at Akita Prefecture in the northern part of Japan. They have similar size however have different mass and stiffness. Once the isolated layer is designed for each building, non-linear time history response analysis using multiple seismic waves with different frequency contents was performed. Seismic response and seismic isolation effect were examined and compared for both buildings.

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II. Target Structures

Target buildings were Noshiro City Assembly Hall in Noshiro City as a wooden building, and Ani House in Kita Akita City as a brick building. Both buildings are located at Akita Prefecture, Japan.

The Noshiro City Assembly Hall was constructed in 1950 as a part of the city hall complex which was designed by the famous Japanese architect and structural engineer Kiyoshi Muto [3]. At present, this city council building of Noshiro city has been declared as a building heritage in risk. The structure corresponds to a two-story frame wooden structure however, to harmonize with the administrative building, which is a reinforced concrete construction, the finishing was made of cement mortar. Fig. 1 shows elevation views and the general plan view of the building. Dimensions of the building are approximately 20 m in front by 29 m in transverse direction. Fig. 2(a) shows the main entrance of the target building situated at west side. It can be observed large windows arranged in the entrance porch and sides parts with a western style design. Fig. 2(b) also shows a view of the interior of the assembly hall located at first floor.

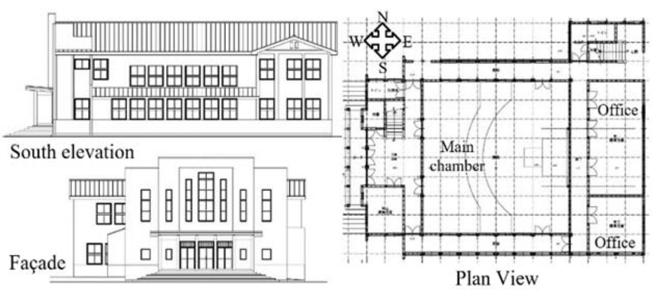


Fig. 1 Elevation views and general plan view of Noshiro Assembly Hall

(a) Façade

(b) Assembly Hall

Fig. 2 Details of Façade and interior of Noshiro Assembly Hall

The second building in this study is a brick masonry building in Ani Village, Akita Prefecture, which was built in 1879. It was built to host Adolf Mecker, a German engineer who came to Japan to work in mining industry of the Akita region. The main characteristics of this building described in [4] and [5] are presented in following paragraphs.

Fig. 3 shows the main structure consisting of a brick wall and a fence containing wooden elements around the building. The architecture corresponds to a Gothic Renaissance style with several arches on the doors and windows. The masonry bricks were manufactured with zone clay and burned in a factory built for this specific purpose. The direction of the design and construction of the house was done by Mecker himself. After finishing his employment contract, Mr. Mecker returned to his country, and the house was first used as an agency and as a social club for miners. The building was affected by several earthquakes, and the most recent was the 1982 Mori Yoshiyama earthquake. This earthquake was a near source earthquake and destroyed partially the structure. The prefecture government has rebuilt a two-story triangular gable wall replaced with light material instead of clay brick masonry. Then, only the first floor walls remain with the original clay bricks joined with cement mortar. This building was designated as a prefecture's cultural heritage in 1956, and in 1990 it was designated as a Japanese national cultural heritage.

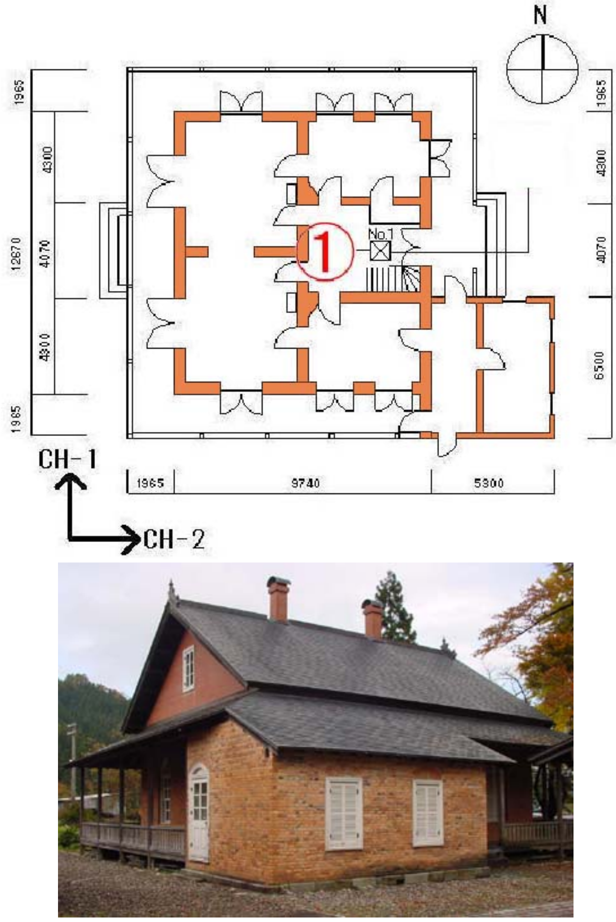


Fig. 3 Plan view and photograph of Ani House

Characteristics of target buildings are compared as shown in Table I. Both buildings have similar dimensions; however, the Ani House has a weight that is approximately ten times the weight of Noshiro Assembly Hall.

TABLE I
CHARACTERISTICS OF TARGET BUILDINGS

Characteristic	Assembly Hall	Ani House
Location	Noshiro city	Kita Akita city
Structure	Wooden frame	Brick masonry
Height	7.7 m	7 m
Width	18 m	17 m
Large	24 m	18 m

III. MODELS FOR SEISMIC ISOLATION REPAIR

The target structures are modeled by a two degree of freedom model as is shown in Fig. 4. The mass M of the upper structure for each building is obtained from direct measurement of structure dimensions and available drawings and documents. The mass of Noshiro assembly hall is 50000 kg or 50 t, and the mass of Ani house is 570000 kg or 570 t. As can be observed, the mass of the masonry structure is ten times the mass of the wooden structure.

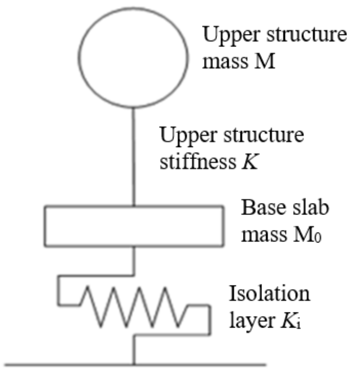


Fig. 4 Two degree of freedom model

In the previous studies, vibration characteristics of both buildings were obtained from ambient vibration measurements [3], [4]. The predominant periods are 0.25 s for Noshiro hall and 0.14 s for Ani house. Then, the stiffness of each building is obtained by using the following equation for period calculation

$$T = 2\pi\sqrt{\frac{M}{K}} \tag{1}$$

where: T = Period of vibration (s), M = Mass of the structure (kg), K = Lateral stiffness of building (N/m)

From (1), the stiffness of each building is given by the following expression.

$$K = \frac{4\pi^2 M}{T^2} \tag{2}$$

The mass of the concrete base slab (M_0) which is necessary to install isolation devices is calculated according to the in-plan area of the building and considering the specific weight of plain concrete. Table II summarize the characteristics of mass and stiffness of original target buildings

TABLE II
MASS AND STIFFNESS OF TARGET BUILDINGS

Property	Assembly Hall	Ani House
Mass M (t)	50	570
Stiffness K (kN/cm)	316	11500
Base Mass M_0 (t)	320	210

The stiffness of the isolation layer is obtained considering that target period of isolated system is set up approximately at 3.0 s. Then the following equation for period of vibration is used.

$$T_i = 2\pi\sqrt{\frac{M_i}{K_i}} \tag{3}$$

where: T_i = Period of vibration of isolated system (s), M_i = M+M_0 = Total mass of the isolated system (kg), K_i = Lateral stiffness of isolation layer (N/m)

The lateral stiffness of isolation layer corresponds to 100 % of deformation of the isolation devices. Using the stiffness K_i obtained from (3), the target period is obtained for each building as 3.032 s and 3.034 s for Noshiro hall and Ani house, respectively. Table III summarizes the parameters of isolated systems.

TABLE III
PARAMETERS FOR ISOLATED SYSTEMS

Property	Assembly Hall	Ani House
Stiffness K_i (kN/cm)	16.20	34.20
Period T_i (s)	3.032	3.034

IV. SEISMIC RESPONSE ANALYSIS

Using the two degree of freedom model defined previously, a seismic response analysis is performed to investigate the behavior of the target buildings. Five input motions are used for the analysis. These input motions are shown in Table IV. All signals are standardized to have 50 cm/s as maximum velocity. The Hachinoje signals correspond to a long duration earthquake. Fig. 5 shows the response spectrum of input these motions.

TABLE IV
INPUT MOTIONS FOR SEISMIC RESPONSE ANALYSIS

Symbol	Earthquake name, year (record place)	Max. Acc. cm/s^2	Duration (s)
ELC-NS	Imperial Valley, 1940 (El Centro)	510.84	53.76
Taft-EW	Kern County, 1952 (Taft)	496.60	54.38
Kobj-NS	Kobe, 1995 (Kobe JMA)	423.87	50.00
Hach-NS	Hachinoje, 1968 (Hachinoje)	335.46	234.00
Hach-EW	Hachinoje, 1968 (Hachinoje)	239.75	234.00

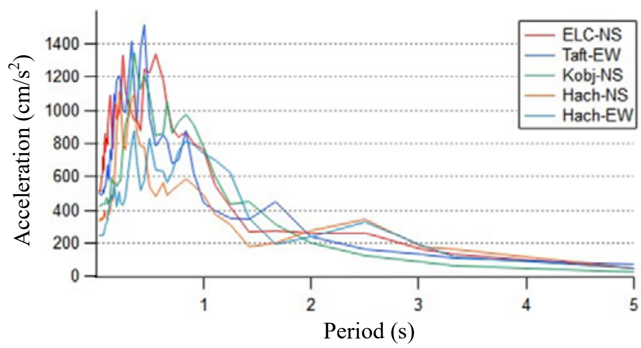


Fig. 5 Response spectrum of input motions

The response analysis is performed considering non-linear behavior of the isolation device. As illustrative example of in-elastic behavior of isolation, layer responses of isolation devices during El Centro input motion are shown in Fig. 6.

The maximum acceleration responses of Noshiro assembly hall are shown in Table V. It is observed that the maximum input acceleration is attenuated by the isolation layer, and the maximum accelerations at base level and at top are reduced. These reduction ratios are also shown is this table, and it is observed that, for long duration earthquake (which has also long period content), the level or reduction reaches approximately 40%, while for other earthquake the acceleration is reduced until 20%. In general, the reduction factor ranges approximately from 20% to 40%.

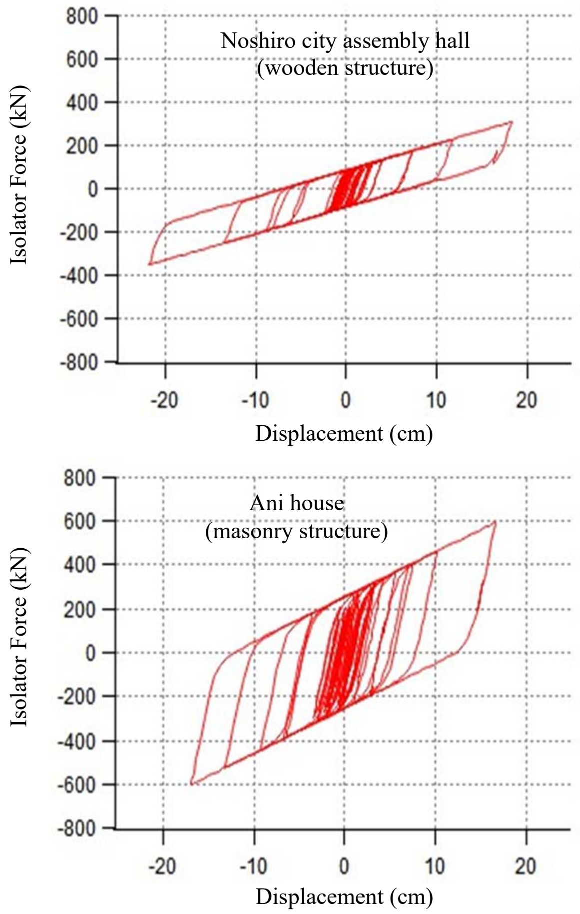


Fig. 6 Isolator responses for ELC-NS input motion

TABLE V
MAXIMUM ACCELERATION AND REDUCTION FOR NOSHIRO HALL

Input motion	Maximum Acc. (cm/s^2)			Reduction ratio	
	Input	Base	Upper floor	Base	Upper floor
ELC-NC	510.84	95.38	106.44	0.19	0.21
Taft-EW	496.60	89.09	94.18	0.18	0.19
Kobj-NS	423.87	69.85	79.77	0.17	0.19
Hach-NS	335.46	88.28	91.49	0.26	0.27
Hach-EW	239.75	92.36	98.02	0.39	0.41

Fig. 7 shows the maximum acceleration responses for Noshiro assembly hall.

Results of maximum accelerations for Ani house are shown in Table VI and Fig. 8. In this case, the reduction factor ranges approximately from 15% to 30%

TABLE VI
MAXIMUM ACCELERATION AND REDUCTION FOR ANI HOUSE

Input motion	Maximum Acc. (cm/s^2)			Reduction ratio	
	Input	Base	Upper floor	Base	Upper floor
ELC-NC	510.84	77.43	77.51	0.15	0.15
Taft-EW	496.60	85.94	86.36	0.17	0.17
Kobj-NS	423.87	67.30	67.59	0.16	0.16
Hach-NS	335.46	75.35	75.28	0.23	0.22
Hach-EW	239.75	77.02	77.16	0.32	0.32

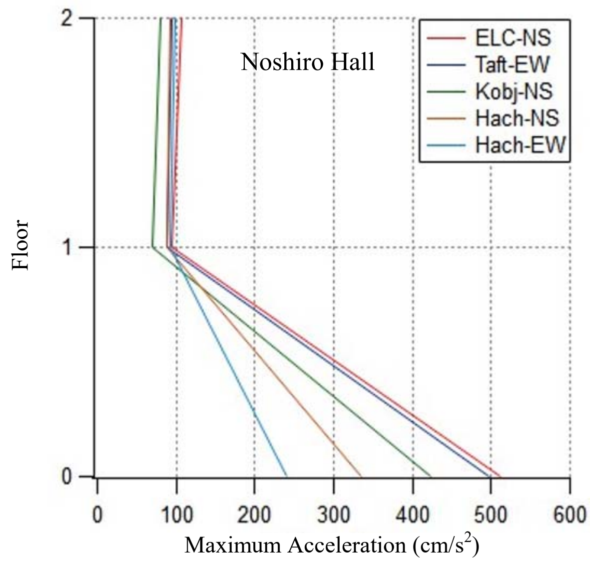


Fig. 7 Acceleration responses of Noshiro assembly hall

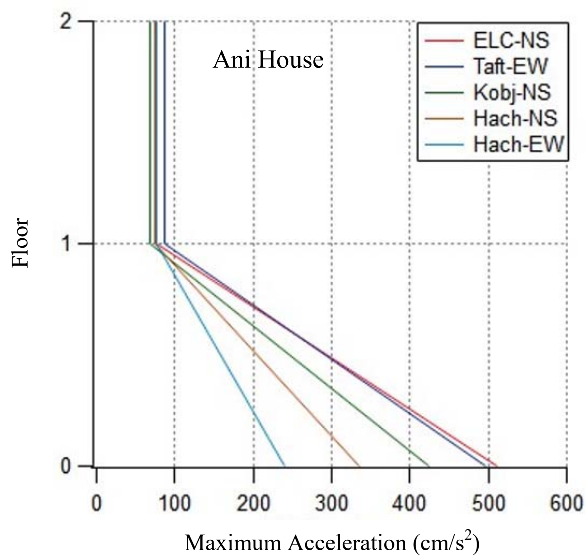
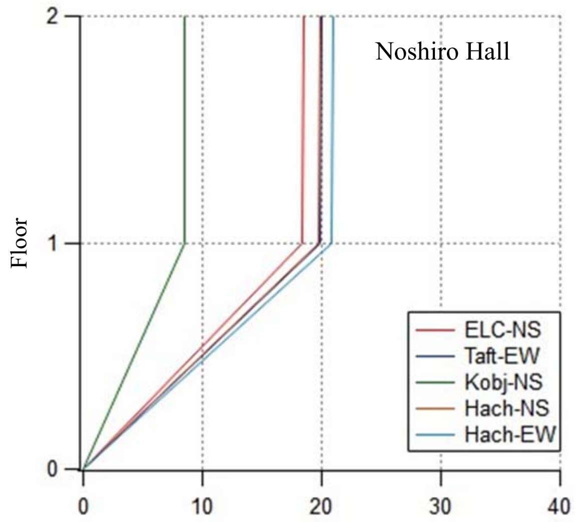


Fig. 8 Acceleration responses of Ani house

TABLE VII
MAXIMUM DISPLACEMENT RESPONSES

Input motion	Noshiro Hall displacement (cm)		Ani House displacement (cm)	
	Base	Upper floor	Base	Upper floor
ELC-NC	18.29	18.43	16.63	16.67
Taft-EW	19.83	19.97	19.87	19.91
Kobj-NS	8.44	8.51	7.89	7.92
Hach-NS	19.70	19.85	14.82	14.85
Hach-EW	20.82	20.98	17.15	17.19

Maximum displacement responses for both buildings are summarized in Table VII and shown graphically in Fig. 9. In this case, Noshiro hall presents larger displacements in comparison of those of Ani house. This could be due to the small stiffness of isolation layer that is required to support the light wooden structure. In this case, natural rubber isolator with low stiffness is used. For Ani house, which is a masonry structure, laminated rubber isolator is considered. Then, this heavy masonry structure has an isolation layer with large stiffness.



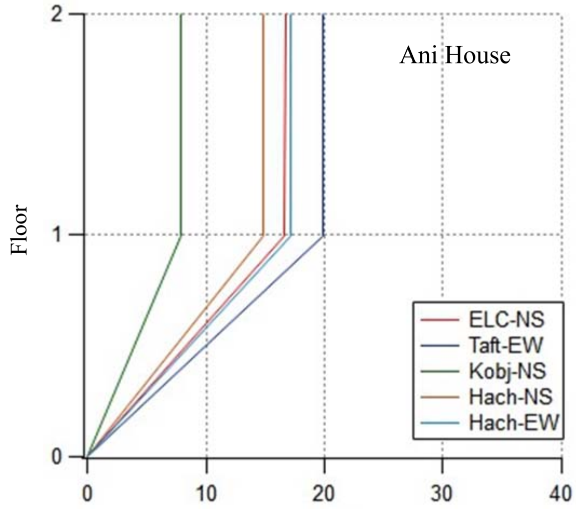


Fig. 9 Maximum displacement responses of target buildings

V. Conclusion

The use of isolation system for seismic retrofitting of historical building was investigated analytically using lumped mass models. Two kind of buildings were used, one is a wooden structure (light structure), and the other one is a masonry structure (heavy structure). Seismic response analysis was performed, and it is verified in both cases that seismic isolation can be used as retrofitting method of historical constructions. However, in the case of lightweight buildings, as is the case for wooden structures, the weight of reinforced concrete slabs needed to install the isolation devices is heavier than the superstructure. Therefore, isolation retrofitting could be more effective in case of masonry structure.

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