Reinforcement and effect evaluation of a middle school in Japan

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Abstract. In recent years, large earthquakes have occurred around the world frequently. In Japan, one of the world's most earthquake-prone countries, it is more important to ensure the seismic performance of buildings. School buildings are the refuge after the disaster, so it has an important meaning to improve the safety and seismic performance of existing school buildings. Most of the school buildings in Japan were built before the implementation of a new seismic standard. Reinforcement is the most important method to ensure safety and improve seismic performance. Based on the reinforcement and reconstruction project of a middle school in Japan, this study introduces the reinforcement design method based on the overall reinforcement concept. Because of the lack of effective methods for evaluating the effect of reinforcement, a micro-tremor observation experiment was carried out by using the wireless acceleration sensor vibration system before and after the seismic reinforcement of the school building. The effects can be evaluated by comparing and analyzing the changes in the acceleration response spectrum, natural period, vibration mode and other characteristics before and after reinforcement. Based on the overall reinforcement concept, it is more reasonable to fit the structural characteristics of the building. The application of a wireless vibration measurement system for evaluating the effect of reinforcement is feasible, it can provide scientific reference for reinforcement design and construction.

Keywords: School building; reinforcement; overall concept; effect evaluation; measurement.

1. Introduction

In recent years, major earthquakes have occurred frequently around the world. Japan, in particular, being a country with frequent earthquakes, has experienced earthquakes such as the China-Vietnam earthquake, Kumamoto earthquake, and the Nishinoshima earthquake in Fukuoka Prefecture, and is currently facing the risks of earthquakes in the Tokai, Nankai, and Tokyo regions, which threaten human lives and property safety. School buildings, as places for students' learning activities and shelters, play a crucial and urgent role in grasping and improving their seismic performance. In Japan, the Building Standard Law Enforcement Order, which was enacted in 1950, stipulated that the seismic performance of school buildings should be 25% higher than that of ordinary buildings. After the Great East Japan Earthquake in 2011, the Japanese government expanded the scope of seismic implementation based on the current seismic regulations and included "buildings around emergency transport routes" [1], and raised the seismic implementation rate target.

The age, quantity, and diverse types of school buildings make it difficult to research and develop methods to improve their seismic performance. In terms of materials, brick masonry and reinforced concrete structures account for a large proportion. In terms of structure, large classroom spaces and windows, as well as few and widely spaced partitions, lead to weak seismic performance and poor integrity. In terms of function, high personnel density and concentration of minors result in a large concentration of loads. In previous seismic damage events, reinforced concrete school buildings have suffered from damage to infill walls, weak columns, and stairwells. Therefore, it is urgent to grasp the seismic safety of existing school buildings and to reinforce and renovate existing school buildings that do not meet seismic design requirements and functional needs from the perspectives of improving seismic safety, economy, historical preservation, and environmental protection.

2. Current status and effectiveness evaluation of reinforcement

2.1 Current situation and problems

Currently, the reinforcement and renovation techniques for existing buildings and the treatment of structural damage mainly still follow the restoration theory from the early 20th century, which involves separate treatment of individual components. However, considering the complexity of buildings as a system that is interconnected and interacts with the external environment while maintaining unity with it, and constantly exchanging information with the outside world, it is difficult to fully consider the characteristics of the entire structure by simply isolating components for reinforcement. Therefore, it is necessary to pay attention to the effects of individual and local changes on other components and the overall structure during reinforcement and renovation and grasp the structural characteristics of the entire building from a holistic and global perspective. While domestic researchers have done some research on holistic theory evaluation and analysis of structural damage [2-3], there has been little research on reinforcement. Japan's 2nd and 3rd diagnostic methods calculate the annual index T by focusing on the visual identification of cracks, uneven sinking, exposed steel bars, etc., and statistically analyze the shape coefficient SD by horizontal and vertical stiffness distribution. Finally, the comprehensive seismic resistance index IS is calculated using the residual strength E0, the shape index SD, and the annual index T, as shown in Eq. (1).

$$I_s = E_0 \times S_D \times T \tag{1}$$

Although this method's calculation results consider the effects of evaluating the entire structure comprehensively, the design drawings and engineering experience have considerable weight in the identification and evaluation process. Moreover, the evaluation methods for the rationality of structural reinforcement design and the accuracy of construction for reinforcement and renovation projects can only be assessed by changes in design indicators (IS: comprehensive seismic resistance index; Ctu·SD: strength index) [4]. However, the reinforcement of existing buildings should be based on a comprehensive understanding of the building's current state and the selection of appropriate reinforcement methods. Therefore, relying entirely on design data or the experience of professional technicians for evaluation has certain drawbacks. The significant seismic resistance falsification incident in Japan in 2005 [5] raised questions about the current methods that rely solely on reinforcement design data or the experience of professional technicians for evaluation.

2.2 Reinforcement effect evaluation technology based on vibration testing

In recent years, Structural Health Monitoring (SHM) has become a research frontier in the field of civil engineering worldwide, and the rapid development of Micro-Electro-Mechanical Systems (MEMS) technology has greatly promoted the progress of civil engineering health monitoring [6-7]. Among them, MEMS technology has received special attention from researchers [8-9]. In recent years, many researchers have focused on using the micro-dynamic characteristics of buildings before and after reinforcement to evaluate the effectiveness of structural reinforcement. However, the evaluation indicators are mostly based on comparing the fixed periods and damping changes before and after structural reinforcement. This study analyzed the effectiveness of reinforcement on school building structures based on MEMS technology and holistic theory, focusing on the accuracy of the microtremors testing system, the appropriateness of analysis methods for periods, stiffness, and inter-story deformation, and from determination methods to seismic design methods, from qualitative analysis to quantitative calculation. A relatively systematic and rigorous foundational work was carried out around the applicability of reinforcement methods to school-building structures [10].

This paper discussed a case of reinforcement based on the concept of holistic reinforcement in a middle school building in Hiroshima, Japan. A wireless vibration testing system was used to conduct constant microtremors testing experiments before and after reinforcement, and a qualitative analysis was performed on the reinforcement effect. So far, most research results have been based on the changes in natural periods to diagnose and evaluate the structural safety of existing buildings. However, the natural periods obtained from constant microtremors testing are values when the building undergoes slight deformations. Therefore, the scope of use during testing and understanding of the surrounding environment is essential. Based on the natural periods, this study comprehensively evaluates the reinforcement effect of school building structures through a comparison of vibration modes and deformations, laying a foundation for the establishment of an objective and effective quantitative evaluation method.

3. Summary of reinforcement project

3.1 Building overview

This building is a middle school building built in 1980 in Hiroshima, Japan. Since it was constructed before Japan revised and promulgated the Building Standards Law in 1981, it urgently needs seismic reinforcement and renovation. The building has a total of three floors (partially two floors) and uses a reinforced concrete structure with a longitudinal frame structure system and a lateral frame shear wall structure system. The reinforcement and renovation project was implemented in 2012, and the main focus was on reinforcing the periphery without affecting normal school teaching activities. The reinforcement policy considered first improving the vertical and overall stiffness distribution of the structure.

3.2 Reinforcement overview

Based on the seismic assessment report of the school building and on-site inspections prior to the reinforcement and renovation, the most reasonable reinforcement and renovation plan was selected. Fig. 1 shows an overview of the reinforcement in the longitudinal and lateral directions. Based on the concept of overall reinforcement, a method was adopted to improve the ductility of the frame structure in the longitudinal direction by cutting 30mm structural separation joints on both sides of the ultra-short columns on the front staircase and changing the shear span ratio of the frame columns to prevent brittle failure caused by shear diagonal tension and improve ductility. To improve the overall ductility of the structure, according to the seismic design concept of "strong shear, weak bending", carbon fiber reinforcement was carried out on the back face of the frame columns that were susceptible to shear failure. In the reinforcement and renovation design of the lateral frame shear wall structure, the first consideration was to improve the plan stiffness distribution of the original structure and increase the SD index shown in Eq. (1). Therefore, the outer right face of the third floor was thickened by 180mm to improve the plan stiffness distribution and increase strength.

a) Front facade reinforcement a) Back facade reinforcement

Fig. 1 A Summary of the reinforcement (□ : Location of Reinforcement）

The reinforcement project adopted the method of improving ductility in the longitudinal direction and improving strength and plan stiffness distribution in the lateral direction. In each direction, the reinforcement and renovation concept based on the overall performance was used, and the reinforcement measures were taken by improving the force-bearing form of the structural system through a global understanding of the structural performance and starting from the structural system. The implementation of this reinforcement project has achieved the goal of reducing the number of local component reinforcements and improving the seismic performance of the original structural system, demonstrating the rationality of the overall reinforcement concept.

4. Experimental evaluation of reinforcement effectiveness

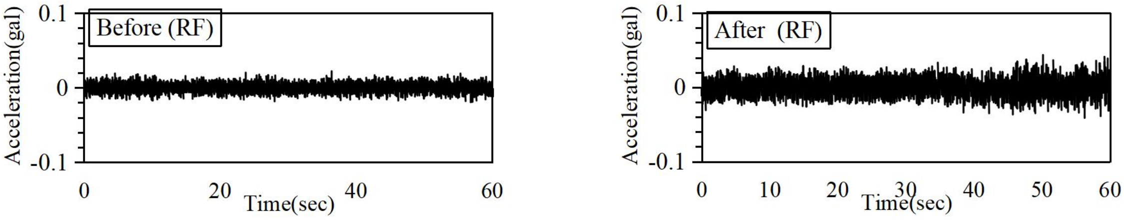
4.1 Overview of vibration Testing

Constant microtremors tests were conducted before and after the reinforcement and renovation, using the RS-network wireless vibration testing and analysis system developed by the Building Materials Research Laboratory of Hiroshima University in Japan. High-sensitivity MEMS acceleration sensors suitable for environmental vibration were used as sensors, with a sampling frequency of 100Hz, 1024 sampling points, simultaneous measurement in three axes, and a total measurement duration of 30 minutes. Sensors were set up according to two schemes: vertical layers and a three-story floor plan layout. Table 1 shows the first natural period obtained from the constant microtremors test and vibration analysis before and after the reinforcement and renovation. The first natural period of the longitudinal frame structure increased from 0.244 sec before the reinforcement to 0.266 sec after the reinforcement. With the total weight of the building remaining virtually unchanged before and after the reinforcement, the increase in the first natural period was attributed to the decrease in stiffness caused by the structural joints set on both sides of the stairwell columns. Although carbon fiber reinforcement was applied to some columns in the back facade, the reinforcement method and purpose were to improve the ductility of the frame columns and had no effect on stiffness changes. In contrast, the first natural period of the lateral frame shear wall structure decreased from 0.213 sec before the reinforcement to 0.195 sec after the reinforcement. The thickening of the three-story exterior shear walls increased the stiffness of the structure. Although the reinforcement was only applied to the third floor, the overall stiffness of the building increased, validating the effect. The changes in the first natural period before and after the reinforcement and renovation of the building and the speculation on the reasons are in complete agreement with the reinforcement design concept of the project, but further research is needed for a quantitative evaluation of the reinforcement effect.

Table 1. The natural period of microtremors observation

Natural period	Before reinforcement	After reinforcement
Longitudinal (X direction)	0.244 sec.	0.266 sec.
Lateral (Y direction)	0.213 sec.	0.195 sec.

Fig. 2 shows the acceleration spectrum of the roof before and after the reinforcement. Arbitrarily select a waveform of 60 sec for comparison, and the acceleration spectrum after reinforcement is larger than before reinforcement. The reinforcement method of increasing toughness was adopted in the X direction, the setting of structural slit reduces the overall stiffness of the structure. In addition, the experimental method of using micro measurement is greatly influenced by the testing environment, the experimental results that only use acceleration waveform for judgment have poor accuracy. This study compared the 1st vibration mode based on the vibration period.



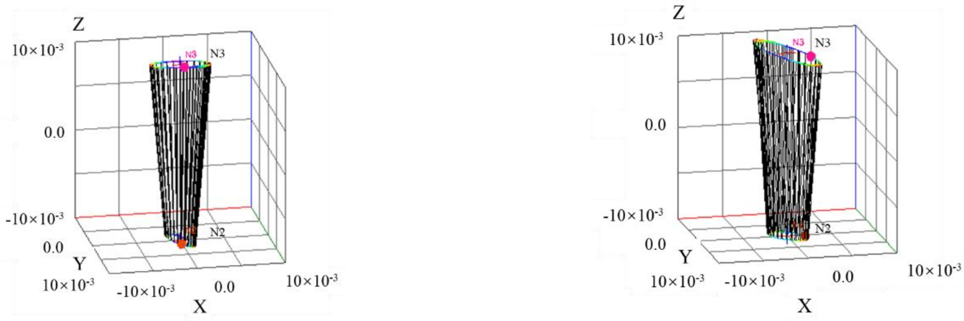
a) Before reinforcement b) After reinforcement

Fig. 2 The acceleration spectrum of the roof before and after the reinforcement (X direction)

Based on the extraction of the natural period, the acceleration data obtained from the vibration tests before and after the reinforcement and renovation were analyzed and processed. A band-pass filter (bandwidth 0.2Hz) was set near the first-order natural frequency to extract the first-order mode shape of the structure. Fig.3 shows the first-order mode shape of the three-story plane in the lateral direction (Y direction) before and after the reinforcement and renovation. Fig.4 shows the first-order mode shape along the vertical direction before and after the reinforcement and renovation. The changes in the first-order mode shape before and after the reinforcement show that the mode shape distribution after the reinforcement is more uniform compared to before the reinforcement. Before the reinforcement, the acceleration response on the right side was much larger than that on the left side. By increasing the thickness of the shear wall on the right side of the third floor, the plane stiffness distribution became more reasonable after the reinforcement and renovation, the plane eccentricity was reduced, and the difference in acceleration response between the two sides decreased. The consistency of the choice of lateral reinforcement methods and the reinforcement effect with the results reflected by the mode shape changes have been validated, and the application of vibration testing experiments in this project has confirmed the effectiveness of the reinforcement and renovation effect evaluation method based on vibration testing and analysis. The research work based on vibration modes has received attention from most researchers in recent years. The occurrence of structural deterioration and changes in stiffness can be intuitively judged through vibration modes. As a qualitative judgment method, it is worth conducting in-depth research on vibration modes in subsequent work.

a) Before reinforcement b) After reinforcement

Fig. 3 The 1st mode before and after reinforcement (Y direction)



a) Before reinforcement b) After reinforcement

Fig. 4 The 1st mode along the vertical direction before and after reinforcement (X direction)

5. Conclusions

With the rapid development of the economy, social transformation is imminent, and it is exigent to improve and upgrade existing building reinforcement and renovation technologies. The seismic safety of school buildings is an important issue in earthquake prevention and disaster reduction worldwide. This paper takes a school building in Hiroshima, Japan as an example for analysis and experimental research, and the following conclusions are drawn:

(1) The design concept based on overall reinforcement is more in line with the existing structural characteristics, making the development of reinforcement and renovation schemes more reasonable. When carrying out reinforcement and renovation, the spatial layout and overall action of the structure must be considered.

(2) The consistency between the analysis results of the data obtained from constant microtremors tests and the reinforcement scheme has been confirmed. The reinforcement and renovation effect can be evaluated by the changes in the natural period and the first-order mode.

(3) It is necessary to accumulate a large amount of data on buildings after reinforcement and renovation to establish a quantitative evaluation method for reinforcement and renovation, laying the foundation for the development of reinforcement and renovation techniques.

Acknowledgment

This research was funded by the Tianjin Research Innovation Project for Postgraduate Students(No. 2022KJ044).

References

[1] Matsuda Y., Kawamura K., Hiraishi J., et al. Integration of road structures based on optimal management of emergency transportation routes and seismic priority review. Journal of Traffic Engineering, 2016, 2(5): 31-40.

[2] Zheng H. B., Han D. J., Lu R.. M. Integrated theory and application of structural reinforcement, renovation and damage treatment technology. Journal of South China University of Technology (Natural Science Edition), 2006, 34(2): 118-123.

[3] Huang B. H.. Structural reinforcement design and analysis of the conversion of a multi-story general factory building into a high-rise building in the Waigaoqiao Free Trade Zone. Building Structure, 2020, 50(24): 69-73.

[4] Japan Building Disaster Prevention Association. Revised edition: Seismic diagnosis criteria for existing reinforced concrete buildings, reinforcement design guidelines, and explanations. Japan: Japan Building Disaster Prevention Association Publishing House, 2001.

[5] Yoshihiko B.. The merits and demerits of Jiechi architects. Japanese Earthquake Engineering Journal, 2007, 7(4): 2-4.

[6] Qi L., Akinori T., Yuichiro Y.. Fundamental Tests on a Structural Health Monitoring System for Building Structures Using a Single-board Microcontroller. Journal of Asian Architecture and Building Engineering, 2015, 14(3): 663–670.

[7] Hamamoto T.. Research on monitoring technology for evaluating the seismic performance of buildings. Measurement and Control, 2007, 46(8): 605-611.

[8] Wang S. Q., Li H. S., Wang S. R.. MEMS and building structure health monitoring. Industrial Control Computer, 2009, 22(7): 8-12.

[9] Wang B., Li A., Sun Y., et al. Strain transfer analysis of surface-bonded MEMS strain sensors. Chinese Journal of Scientific Instrument, 2016, 37(11): 2606-2612.

[10] Li L., Matsumoto S, Okubo T.. Comparative experimental study on seismic reinforcement and renovation before and after based on wireless vibration testing system. Japan Architectural Society Technical Report Collection, 2016, 22(51): 435-440.