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A preventive strengthening method for steel columns: Experimental study and numerical analyses

Weiwei Lin [a,*], Nozomu Taniguchi [b], Teruhiko Yoda [a]

[a] Department of Civil and Environmental Engineering, Waseda University, Shinjuku-ku, Tokyo 169-8555, Japan
[b] Department of Civil and Environmental Engineering, Maebashi Institute of Technology, Maebashi-shi, Gunma 371-0816, Japan

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ABSTRACT

Techniques for structural repair and maintenance are becoming increasingly important because of increasing problems associated with aging structures. This paper introduces a method for strengthening aged steel columns by using new construction materials such as glass-fiber-reinforced polymer (GFRP) plates, rapid-hardening concrete, rubber-latex mortar, and reinforcing bars. The purpose of the present study is to investigate the mechanical performance of steel columns before and after strengthening, thereby assessing the effectiveness of the proposed strengthening method. Depending on the possible directions of applied load (major axis or minor axis) and the corrosion conditions, three specimens were employed in the loading tests. Static loading tests were performed on steel columns with and without strengthening. Test results, including load–deflection relationships and the strain development process of the columns, were measured and compared between the original and strengthened columns. Moreover, three-dimensional finite-element models were built to compare the strengthened and original steel columns. Both the experimental and numerical results indicate that the proposed strengthening method can significantly enhance the stiffness in the elastic stage and the load-carrying capacities in the plastic stage, resulting in significant extension of residual service life under real service conditions and improvement of seismic performance during earthquakes.

1. Introduction

Steel columns are widely used in structures from buildings to bridge piers to railway-platform roofs. With aging, such steel columns are vulnerable to corrosion and fatigue, and can deteriorate for a variety of reasons. In an earthquake, steel columns can fail by buckling under lateral loads. Earthquakes occur frequently in Japan, recent ones being the Great Hanshin earthquake in 1995, the Chūetsu earthquake in 2004, the Tōhoku earthquake in 2011, and the Kumamoto earthquakes in 2016. As such, steel columns are in widespread use as bridge piers in Japan because they are lightweight and have better seismic performance. They are used particularly in bay areas where the ground is soft and in downtown areas where space is limited. However, because many of those steel columns date from the 1960s, 70s, and 80s (a period of rapid economic growth), most of them have now reached their design lives and are experiencing severe fatigue, corrosion, and other deterioration problems. Also, most of them were designed according to the old Japanese earthquake-resistance standards and do not satisfy the requirements of the new design specifications. In addition, steel columns are used for bridge accessory structures, such as electrification poles. After the 2011 Tōhoku earthquake, severe damage occurred to the electrification poles (over a distance of nearly 500 km) on viaducts of the Tōhoku Shinkansen (a Japanese high-speed rail line). Therefore, there is urgent need to replace or repair those aged steel columns. Considering the relatively high cost of either replacing them or strengthening them integrally, as well as the considerable negative impact that that would have on public transportation, preventive maintenance on the steel columns is a more effective way to proceed.

In recent years, engineers in Japan and other countries have been working on ways to repair or strengthen aged columns, particular on bridge piers. After the Hyogoken–Nanbu Earthquake in 1995, many studies were carried out in Japan to investigate the seismic performance of steel bridge piers. In 2000, Osada et al. performed experiments to investigate the seismic performance of tall piers [1]. In 2004, Nagata et al. performed loading tests to confirm the seismic performance of steel bridge piers damaged by corrosion, and concluded that suitable maintenance should be undertaken on corroded steel piers to avoid possible damage in an earthquake [2,3]. Goto et al. carried out cyclic bi-axial loading tests to examine the seismic behavior of thin-walled steel circular piers, and formulas for evaluating the seismic performance of arbitrary rectangular steel columns subjected to cyclic bidirectional loads were proposed [4–6]. In 2007, Aoki et al. carried out tests to investigate the strength and ductility of steel piers under simple hysteretic loading

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[*] Corresponding author.
E-mail address: linweiwei@aoni.waseda.jp (W. Lin).

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patterns such as linear, circular, oval, radial, square, and octagonal [7]. In 2011, Naito et al. performed a study to investigate the ductility of concrete-encased steel piers under cyclic lateral loading [8]. In 2013, Shimaguchi et al. proposed a method for strengthening steel bridge piers by filling circular steel tubes with concrete [9,10]. Cyclic loading tests were performed and the effectiveness of the proposed methods were confirmed. A seismic retrofit method for high piers involving carbon-fiber sheets was proposed and used to strengthen the hollow circular piers of an express highway in Japan.

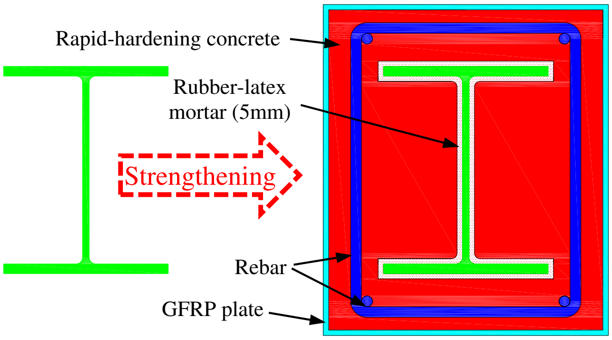
The practice of bridge-pier strengthening is also performed in countries other than Japan. In 2002, Hag-Elsafi et al. reported the use of laminated fiber-reinforced polymer (FRP) plates to strengthen the cap beam of Pier 3 of East Church Street Bridge in New York. To investigate the effectiveness of the strengthening scheme, service load tests were performed before and after the plates were installed [11]. In 2015, Deng et al. studied methods for repairing earthquake-damaged bridge piers [12]. They performed both experimental and finite element (FE) studies to confirm the seismic performance of reinforced-concrete bridge piers repaired with steel tubes, basalt-fiber-reinforced polymer (BFRP), and carbon-fiber-reinforced polymer (CFRP).

To avoid unrecoverable damage to existing steel columns (e.g., electrification poles, columns in railway-platform roofs or bridge piers), effective preventive maintenance methods for aged steel columns are necessary. With this background, a new strengthening method to improve seismic, corrosion, and fatigue performance of aged steel columns is reported in this paper.

2. Proposed maintenance strategy

Reflecting the issues of constructability, anticorrosion, damage limitation, and noise reduction for existing structural members, the proposed method for strengthening aged steel columns is illustrated in Fig. 1. An aged bridge pier is strengthened by encasing it in rubber-latex mortar, rapid-hardening concrete, reinforcement, and glass-fiber-reinforced polymer (GFRP) plates.

In steel-concrete composite structures, shear connectors are generally used to ensure transfer of the shear force across the steel-concrete interface. However, the use of shear connectors generally requires drilling and welding operations, which may cause new damage to the existing structural steel. In addition, specific apparatus and skilled workers are needed. To avoid those problems, the use of rubber-latex mortar was proposed instead of shear connectors. Rubber-latex mortar with styrene-butadiene rubber latex shows various abilities to increase adhesion bonding, waterproofing, shock absorption, and abrasion resistance as confirmed by a series of experimental studies performed on steel and composite structures [13–15]. Laboratory tests previously performed on a steel-concrete interface also confirmed the possibility of using rubber-latex mortar instead of shear connectors to strengthen aged structures [16]. Rubber-latex mortar was used in this study to enhance the bond strength of the steel-concrete interface, reducing noise and avoiding structural steel corrosion in the service stage.



(a) Before strengthening (b) After strengthening

Fig. 1. Schematic of the strengthening method.

Rapid-hardening concrete was used for rapid construction to reduce the stress levels and noise levels of the aged steel members. The possible buckling of steel columns in an earthquake can be restrained by the concrete as well as the transverse encased reinforcement. For aged structure maintenance or repair, rapid construction is always a key point. Thus, rapid-hardening concrete that has relatively high early-age strength is chosen for this strengthening method. For certainty, reinforcing bars are used to control the crack width after concrete cracking. GFRP plates are used as the formwork for concrete casting, but to confirm the cracking of concrete during the loading tests, GFRP plates were not used in this experimental study.

The strengthening sequence of the proposed method involves cleaning the structural steel, spraying it with rubber-latex mortar, reinforcement setup, setting the GFRP plates, and finally casting the concrete. The strengthening of the test specimens in this study is shown in Fig. 2.

In the fatigue design of steel structures, increasing the stiffness means decreasing the strain (or stress) under service conditions and extending the residual service life. In the seismic design of Japanese design specifications, two types of ground motion are specified, namely Level-I and Level-II earthquake motions [17,18]. Level-I earthquake motion is used in conjunction with the elastic design method, and is established as earthquake motion for static load analysis or elastic dynamic analysis. Level-II earthquake motion is used for ultimate limit-state design under huge earthquakes. Therefore, increasing the stiffness of columns in the elastic stage and increasing the yield load and ultimate load in the plastic stage after strengthening are of particular interest and will be investigated both experimentally and numerically in this paper.

3. Experimental program

3.1. Description of the test specimen

H-shaped steel columns (194 mm × 150 mm × 6 mm × 9 mm) were designed to simulate bridge piers, electrification poles, or columns in railway-platform roofs. Each specimen was 1.42 m in height, and the loading point was at a height of 1.2 m. Stiffeners were welded at the loading points to prevent buckling and crippling of the web before flexural failure. A 700-mm square steel plate with a thickness of 30 mm was used as the base plate and was connected to the steel column by welding. The original steel column was strengthen with rubber-latex mortar with a thickness of 5 mm, rapid-hardening concrete, and reinforcement with a nominal diameter of 10 mm.

The length (300 mm) and width (250 mm) of the concrete were designed to guarantee a minimum concrete cover thickness, which was taken as 24 mm according to the durability requirement specified in the design standards for railway structures [19] by also considering the aggregate size (20 mm in this study) used in concrete. For steel columns, the plastic hinge length is generally taken as 1.0D–1.5D, where D denotes the larger of the width (150 mm) and depth (194 mm) of the H-shaped section. Therefore, the height of the concrete is determined as 300 mm to cover the plastic hinge length (1.5 × 194 mm) of the steel columns used in this study. Vertical bars with a diameter of 10 mm and stirrups with a diameter of 6 mm were used as reinforcement for the retrofitted columns. The detailed positions of the vertical bars and stirrups are shown in Fig. 3(c) and (e), respectively. The typical geometries of the test specimens after strengthening are shown in Fig. 3.

To confirm the real effectiveness of the proposed strengthening method, three steel columns were used in the loading tests. The first column was tested with a concentrated load along its major (strong) axis (denoted as SC-S), while the second column was loaded along its minor (weak) axis (denoted as SC-W). The third column, denoted as SC-C, was designed with discontinuous (both top and bottom) flanges