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A PREVENTIVE STRENGTHENING STRATEGY FOR AGED STEEL STRUCTURES

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Steel columns are widely used in buildings, bridge piers, and railway platform roofs etc. With aging, those steel columns are vulnerable to corrosion and fatigue, and can deteriorate for a variety of reasons, especially in great earthquakes. In order to avoid the unrecoverable damage of existing steel columns, the high cost of the structure owners and the great impact on the public use, effective preventive maintenance methods on the aged steel piers are necessary. On this background, a strengthening method for 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, is introduced in this study. Depending on possible applied load directions and corrosion conditions, two specimens were used in the loading tests. Static loading tests were performed on steel columns with and without strengthening. Applied load and deflection relationship and strain distribution on original and strengthened columns were measured and compared. Moreover, three-dimensional FE models were built, and the numerical results were compared with the test results. Both experimental and numerical results indicate that the present strengthening method can significantly enhance both rigidity and ultimate load carrying capacity of aged steel columns.

Keywords: Steel columns, Rubber-latex mortar, Loading test, FE model.

1 INTRODUCTION

Steel column structures are used in buildings, bridges, railway platforms and other civil engineering structures around the world, due to their suppleness in both design and construction. In recent years, however, severe damages of aged steel columns were observed in earthquakes. For instance, a large amount of steel bridge piers damaged in the 1995 Hyogoken-Nanbu earthquake mainly because of either local buckling or rupture of welded corners (Chu 2011). During the 2011 Tōhoku earthquake, severe damage was caused to electrification poles on viaducts of Tōhoku Shinkansen. Based on the existing experience, Japanese design specifications have been revised and updated a lot, but they are mainly used for designing new columns. For aged steel piers constructed with old design methods, they are generally not satisfied to new design codes, thus they should be strengthened appropriately. On this background, seismic retrofit on existing steel column structures has become a major concern.

With the purpose of improving the seismic performance of existing steel columns, a preventive seismic retrofit method for existing steel column structures is proposed in this paper. Both static loading tests and numerical simulations were conducted to investigate the real effectiveness of the present strengthening method and its improvement on the seismic performance of existing column structures.

2 STRENGTHENING STRATEGY

In this study, a strengthening method using GFRP plates, rubber-latex mortar, rapid hardening concrete and reinforcing bars is proposed to strengthen the existing column structures. Rubber-latex mortar shows various abilities especially in adhesion bonding, waterproofing, shock absorption and abrasion resistance (Lin and Yoda 2013, Lin *et al.* 2014a), and significant contribution of rubber-latex mortar in enhancing bonding strength on steel-concrete interface was confirmed in previously performed bonding tests. In this method, the rubber-latex mortar is mainly used to enhance the integrity between aged structural steel and newly added surrounding concrete. Rapid hardening concrete is used for resisting the external loads together with the existing steel column, thereby increasing the rigidity and load carrying capacity. FRP plates are used as the formwork for concrete casting, and its contribution in the load carrying capacity is not considered in the design. Similar to other RC structures, reinforcements are used for controlling the crack width after concrete cracking.

This method was originally proposed by authors of this paper for strengthening superstructures of aged short-span railway bridges, and both laboratory loading tests and field loading tests were performed by authors' group (Lin *et al.* 2014b, 2014c, 2017, and Taniguchi 2016). Considering it outstanding effects in improving the structural performance of bridge superstructures, this study was performed to investigate its possibility in strengthening existing column structures.

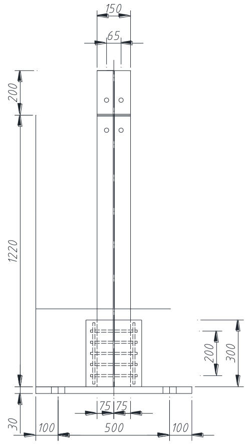
3 EXPERIMENTAL PROGRAM

3.1 Test Specimens

Two steel columns with same cross-section (an H-shape section of 194×150×6×9) were designed. Each of the specimens was 1.42m in height and the loading point was decided at the height of 1.2m. Stiffeners were welded at the loading point to prevent buckling and crippling of the web before flexural failure. A 700mm square steel plate with thickness of 30 mm was used as the base plate and connected with the steel column by welding. To strengthen the original steel column, the rubber-latex mortar with the thickness of 5mm was used on the surface of the aged structural steel. Reinforcement with a nominal diameter of 10mm for longitudinal reinforcement and 6mm for stirrups were used. Finally, rapid hardening concrete was casted. The test specimens were fixed through connecting the base plate with the ground by using 4 bolts with a circular diameter of 60mm. The geometry dimension of the test specimen is shown in Figure 1.

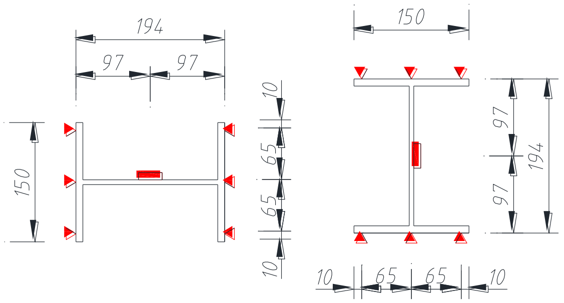
3.2 Static Loading Test Set-up

The load is applied by a jack in horizontal direction to simulate the earthquake load. For columns like electrification poles or columns in railway platform roofs, the axial force can be ignored in the design due to their negligible deadweight. In terms of steel pier in bridge structures, the axial force is generally designed as no larger than 20% of its yield load. Therefore, the axial force in the column is not considered in order to simplify the loading test. However, the influence of the axial force on mechanical behavior of steel columns will also be investigated in this study, by using the numerical results.



(a) Front view (b) Side View

Figure 1. Size dimensions of test specimen (unit: mm).



(a) Strong axis. (b) Weak axis.

Figure 2. Strain gauge locations (unit: mm).

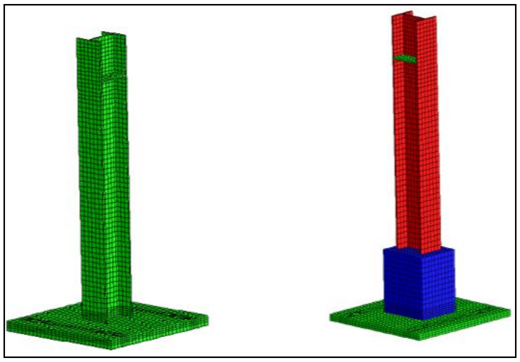
As shown in Figure 2, there are strong axis and weak axis in a typical column with an H-shape cross-section. In order to investigate the effects of the proposed method in two different directions, the horizontal load was applied in both strong and weak axis directions, respectively. For this reason, two specimens were used in this study. Before strengthening, static loading tests were performed on the two original steel columns, including SC-S-1 (original steel column under load in strong axis direction) and SC-W-1 (original steel column under load in weak axis direction). The applied load was controlled in a low level to avoid any possible damage on columns. After strengthening, SC-S-2 (strengthened steel column under load in strong axis direction) and SC-W-2 (strengthened steel column under load in weak axis direction) were tested again to compare with the original steel columns without strengthening.

In order to confirm the sectional strain distribution, 7 strain gauges were used to measure the normal strain in the web and steel flanges near the bot-tom section, as shown in Figure 2. LVDTs were also used to measure the horizontal displacement at the loading section and two sections.

4 NUMERICAL MODELING

The simulation of test specimen was carried out using the finite-element method and DIANA software. Solid elements were used to simulate the concrete, and shell elements were employed to model the steel column. Numerical models of steel column before and after strengthening were shown in Figure 3. To simulate the bond connection between the steel column and surrounding concrete, and the connection between the ground and the base plate, interface elements used in the numerical analysis, as shown in Figure 4. Rebar elements were used for modeling the reinforcement, as shown in Figure 4.

Material tests were performed, and the nominal compressive strengths of concrete achieved after 7 days and 11 days (test day) were 36.2 N/mm^2 and 39.3 N/mm^2, respectively. Experimental tensile stress-strain curve proposed by Nakasu *et al.* (1996) was used to simulate the tension softening behavior of concrete. The compression behavior of concrete was referred to JSCE (2002). The stress-strain curve considering the strain hardening was used to simulate the structural and reinforcing bars (JSCE 2002). The yield strength of the H-shape column was 309 N/mm^2 according to the material test report. The yield strength of reinforcement was yield strength: 295 N/mm^2. The simplified interface model developed from Dörr's bond-slip model is used to model the steel-concrete interface (Dörr 1980).



(a) Before strengthening. (b) Strengthened.

Figure 3. Numerical models for columns.

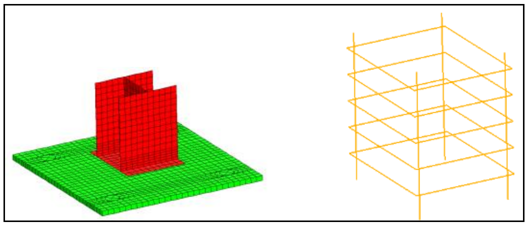


Figure 4. Simulation of interface and reinforcement.

5 RESULTS AND DISCUSSION

5.1 Applied Load in the Strong Axis Direction

When the steel column is subjected to a load in the strong axis direction (SC-S), the load-displacement curve obtained from the numerical analyses is compared to the experimental results as shown in Figure 5. For retrofitting of aged steel columns, increase of rigidities in service state and increase of load carry capacity in the ultimate state are major concerns for engineers. On the basis of the obtained results, both experimental and numerical results demonstrate increase of the column stiffness after strengthening. Taking the horizontal deflection of 6.3mm (the maximum displacement in loading test for SC-S-1) as an example, the test load changed from 24.9kN in SC-S-1 to 31.4kN in SC-S-2, in-creased by 26%. For the strengthened column, the numerical model was stronger than the test model, which might be due to the ignored residual stress at the welded section in the numerical analyses. The comparison between the numerical results also indicates that the ultimate load carrying capacity of the column has increased obviously after strengthening. Taking the horizontal displacement of 61mm as an example, the corresponding load increased from 79.8 kN in SC-S-1 to 98kN in SC-S-2, thus 22.8% increase was confirmed.

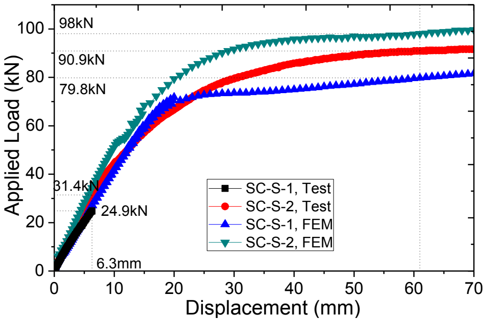


Figure 5. Load-deflection curve for SC-S.

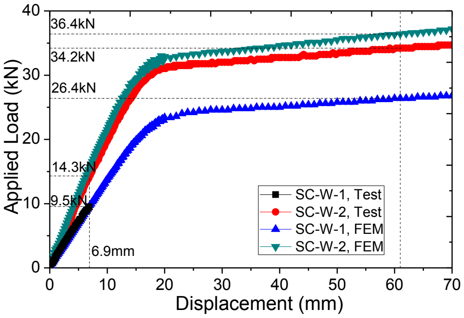


Figure 6. Load-deflection curve for SC-W.

5.2 Applied Load in the Weak Axis Direction

For the steel column under load in the weak axis direction (SC-W), the applied load and deflection relationship was given in Figure 6. According to the comparison, significant increase of the column stiff-ness and ultimate load carrying capacity in the weak axis direction were also confirmed. Taking the horizontal deflection of 6.9mm (the maximum displacement in loading test for SC-W-1) as an example, the test load changed from 9.5kN in SC-W-1 to 14.3kN in SC-W-2, increased by 51%. The ultimate load was increased from 26.4kN in SC-W-1 to 36.4kN in SC-W-2, thus 38% increase can be confirmed. The significant increase of the rigidity and load carrying capacity demonstrate the improvement of the seismic performance during earthquakes. Also, the comparison indicates that the numerical results agree well with the test results, indicating the validity of the numerical models used in this study.

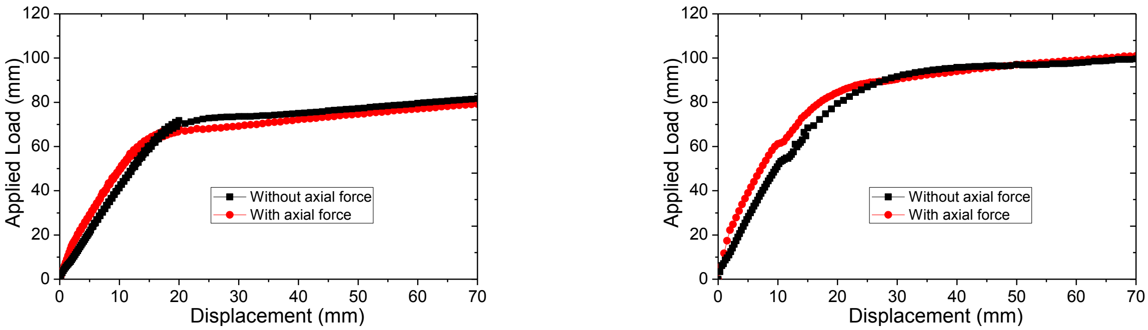
5.3 Effects of Axial Force

In this study, the axial force for columns was ignored in order to simplify the loading tests and numerical analyses. This assumption will not affect the behavior for steel columns with negligible axial force, e.g. electrification poles or columns in railway platforms. For other columns subjects to unneglectable axial forces, e.g. steel piers, the effect of due axial force on the structural behavior of column structure is still known and needs to be investigated.

Phase analyses (two steps) were performed in the numerical analyses. In phase-1, the axial force considering the loads due to a bridge superstructure was applied at the top of the column. The axial force was taken as 20% of its yield load, according to the existing studies in Japan. Thereafter, the horizontal load was applied in phase-2 until the ultimate state of the column models.

For a column subjected to a horizontal load applied in strong axis, the load-displacement curves of both original and strengthened columns with and without considering axial force were shown in Figure 7 (a) and Figure 7 (b), respectively.

It is found that if the axial force was considered, the rigidities of columns (both original and strengthened columns) were increased slightly. However, no matter the axial force is taken into account or not, the effects of the proposed strengthening method can be confirmed. In addition, the ultimate load was affected little by the applied axial force. Therefore, it can be concluded that the present strengthening method is still effective even if a certain level (≤20%) of axial load is considered. Thus, this method can also be used for strengthening steel columns with axial force, like steel piers.



(a) SC-S-1.

(b) SC-S-2.

Figure 7. Load-displacement curve between numerical models with and without axial force.

6 CONCLUSIONS

A strengthening method for existing steel columns was introduced in this paper. In order to confirm the effect of this method, static loading tests were performed on two original steel columns and columns strengthened with rubber-latex mortar, rapid hardening concrete and reinforcing bars. Detailed load-deformation response, and strain distribution on the steel columns were reported in this paper. Easily obtained construction materials and simple operated construction methods make this method competitive in comparison with other repairing methods. Static loading tests were performed to confirm the effects of the present strengthening method. On the basis of the test results, the present strengthening method was proved to be effective for increasing both rigidity and load carrying capacity of the aged steel columns, resulting in improvement of seismic performance of aged steel columns.

A 3-D nonlinear finite element model was established for simulating the present test specimens. The ultimate load carrying capacity, load-displacement curves and strain development process predicted by FE models agree well with those obtained from the experiments, which demonstrates the accuracy and efficiency of proposed FE models. In addition, the influence of axial force in steel columns was investigated in the numerical analyses. For a column subjected to an axial force in service condition (where the axial force is relatively small compared with its yield strength), the proposed strengthening method is still effective.

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