UPGRADING OF STEEL BOX PIER UNDER CYCLIC LATERAL LOADING

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SUMMARY

Failure mechanism of bridge piers under earthquake excitation usually starts from the formation of plastic hinges located at column bottoms that sustain maximum bending moments. It has been shown in previous study that the propagation rate of relative deformation between the opposite plates of a locally buckled section is the major parameter governing the post-buckling performance. In order to enhance the member efficiency in the post-buckling range, the deterioration rate must be controlled and reduced. In this study, the authors developed a strengthening mechanism added to the possible plastic hinge zones so that the ductility performance of such members can be enhanced. This mechanism is composed of ductile grids and cross tie bars attached to the inner side of the member to support the member wall plates. When local buckling of member plates occurs, the added mechanism deforms accordingly forming inelastic deformation to help stabilize member and dissipate seismic energy. This paper presents experimental information on the cyclic behavior of steel box piers with strengthening mechanisms added internally. Test results show that elastic stiffness of upgraded members stays at equivalent levels as those of original members, however, energy dissipation capacities of such members are substantially increased and deterioration rates in strength are also significantly reduced. Relationship between performance enhancement of members and characteristics of strengthening mechanisms is also reported.

INTRODUCTION

The use of steel box sections for bridge pier construction is common and is considered to be advantageous in urban areas and in areas with high seismic activities because they possess high strength/mass ratios and significant ductility which greatly enhance the structural performance during a strong earthquake. Although construction structural steel sections possess high flexural capacity, the open cross sections are also susceptible to lateral or local buckling if the structural system is not adequately proportioned or detailed. Since a steel box member is an assembly of thin-walled plates, the parameter that governs the member behavior is the width/thickness ratios of the plates. In order to be economical, requirement of width/thickness ratio not exceeding specified limits in box section design is usually achieved by using thin plates and welded stiffneners on the plates. This fabrication method of steel box members requires extensive welding work to form the design sections and inevitably induces heavy welding stresses on the plates and the corners of the box sections. The welding-induced brittleness on the wall plates also hampers the inelastic deformation capacity of members. For examples, in the recent work of Terayama and Otsuka[1997], severe fracture of welds on the corners of steel box columns subjected to repeated loading was reported. This brittle fracture significantly influenced the performance of such members under earthquake and should be effectively remedied to improve the member behavior. For bridge piers subjected to earthquakes, the column bottoms sustain maximum loading and the failure mechanism usually starts from the formation of plastic hinges on those regions. In general, local buckling of plates due to large member deformation takes place during the plastic hinge formation process. This phenomenon will finally lead to the fracture failure of the buckled zones. It has been shown in previous studies [Chiew. et. al. 1987; Usami and Fukumoto 1982; Fukumoto et. al. 1997; Watanabe et. al. 1992] that the propagation rate of the member plate deformation is the major parameter in governing the post-buckling performance. Therefore, development of methods to delay the occurrence of local buckling and to reduce the

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propogation rate of relative deformation of the member plates so that member performance can be enhanced is essential.

As stated in previous study [Chiew et. al. 1987], the length of buckling region at bridge pier bottom was approximately equal to the dimension of the section depth. Therefore, when improvement of post-buckling performance is considered, the control of the buckling zone must be conducted. In this paper, the authors developed a strengthening device to be added to the inner side of the possible buckling zone to strengthen and help stabilize the section integrity during the post buckling range. This device is composed of ductile grids and a pair of cross tie bars. When local buckling occurs, the added mechanism deforms accordingly forming inelastic deformation to help stabilize member and dissipate seismic energy. This paper presents the experimental information on the cyclic behavior of strengthened members.

EXPERIMENTAL PROGRAM

Specimens

In order to investigate the effect of plate width/thickness ratios on the member performance, specimens with width/thickness ratios equaling 38, 48, and 60 were fabricated using JIS SS41-grade plates with different thickness. These three test series were designated as: B38, B48 and B60, respectively. Width/depth ratio of the cross section for all specimens was 0.75. The corners of the box sections were fabricated by fillet welding. Each test series include four specimens: one unstrengthened member and three strengthened members. The strengthened members differ in the height of ductile grids: 1d, 1.5d and 2d, where d is the depth of the section. Ductile grids were made by welding thin steel strips on the ends. Description of the specimens is shown in Figure 1. Dimensions of the cross sections are also listed in Table 1.

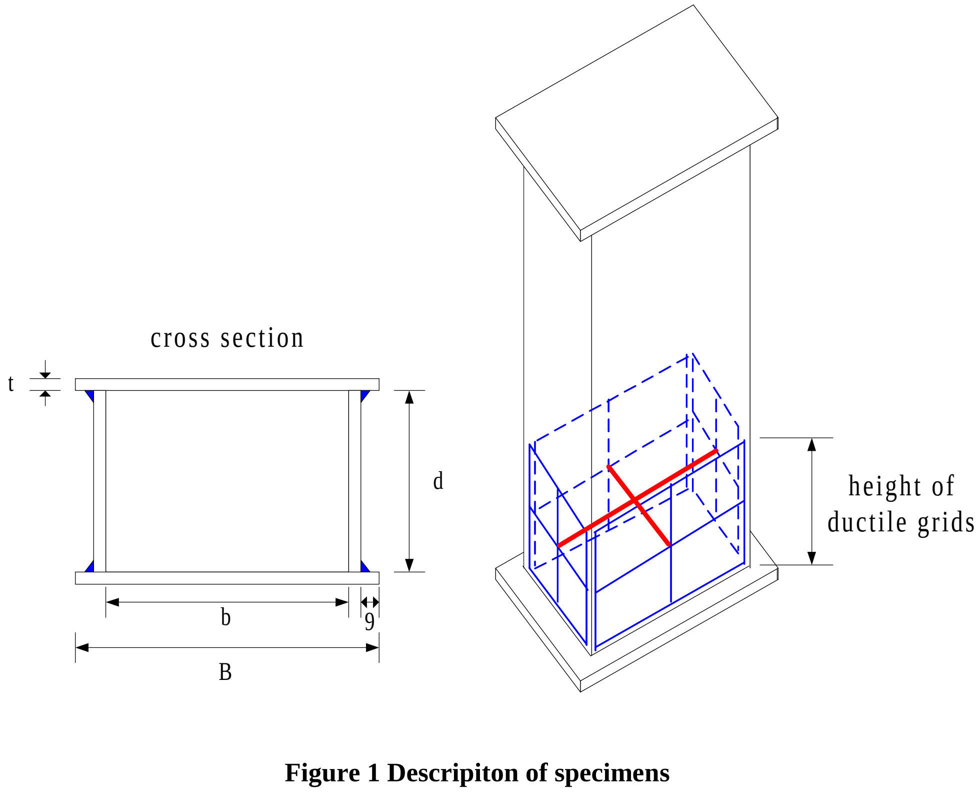

Figure 1 Descripiton of specimens

Table 1 Dimensions of cross sections

	B38 Series	B48 Series	B60 Series
B(mm)	260	320	300
b(mm)	230	290	273
d(mm)	172	218	204
t(mm)	6	6	4.5
b/t	38	48	60

The specimens were finished by attaching the ductile grids with cross ties to the plates of the box section. The cross ties were bolted on the inner and outer sides of the plates, therefore also provided compressive or tensile support when plates buckled inward or outward.

Test procedures

The specimens were tested under combined axial load and cyclic lateral force. A servo-controlled hydraulic actuator was used to generate cyclic lateral force. A constant axial force equal to 13 percent of the member's yield strength was applied to the specimen by a hydraulic jack. Actuator which generated cyclic lateral load was moved under displacement control. Displacement commands applied to the top of the specimens are shown in Figure 2. In Figure 2, δ_{y0} is the yielding displacement of the specimen, and can be expressed as:

$$\delta_{y0} = \frac{H_{y0} h^3}{3EI} \tag{1}$$

in which h is the length of the specimen, E is the Young's modulus, I is the moment of inertia, and Hyo is the yielding strength of the section. The applied lateral force and the corresponding displacement were measured through the internally mounted LVDT and load cell.

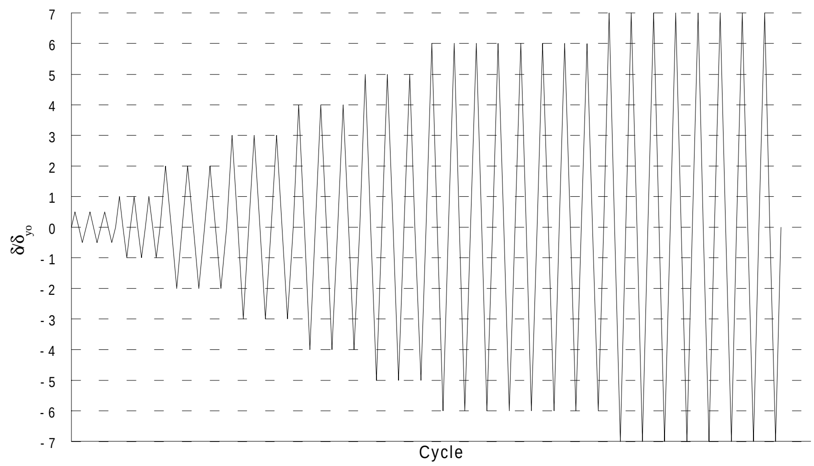

Figure 2. Displacement commands

Observations

For unstrengthened member, the member performance solely depent on the section integrity. Once the local buckling of section occurred, the deformed section exhibited significant deterioration in strength and in energy dissipation accordingly. However, for strengthened members, the coupled mechanism between infilled strengthening device and the box section prevented change in section geometry and thus maintained the member's carrying capacity. It was observed from the tests that member performance sustained during the plastic hinge formation process until the cross ties ruptured or buckled due to excessive tension or compression, or when ductile grids fractured due to excessive deformation. This phenomenon validated the effectiveness of the infilled strengthening device in improving member performance. The failure modes of the strengthened member is shown in Figure 3.

Figure 3. Failure modes of the strengthened member

Characteristics of strengthening mechanism

For member with strengthening devices, the stiffness of the devices must be defined first. Since the device was composed of cross ties and ductile grids, therefore, when unit out of plane deformation was induced due to local buckling of plates, the corresponding stiffness of the strengthening device was contributed by the tie and the grids, as shown in Figure 4.

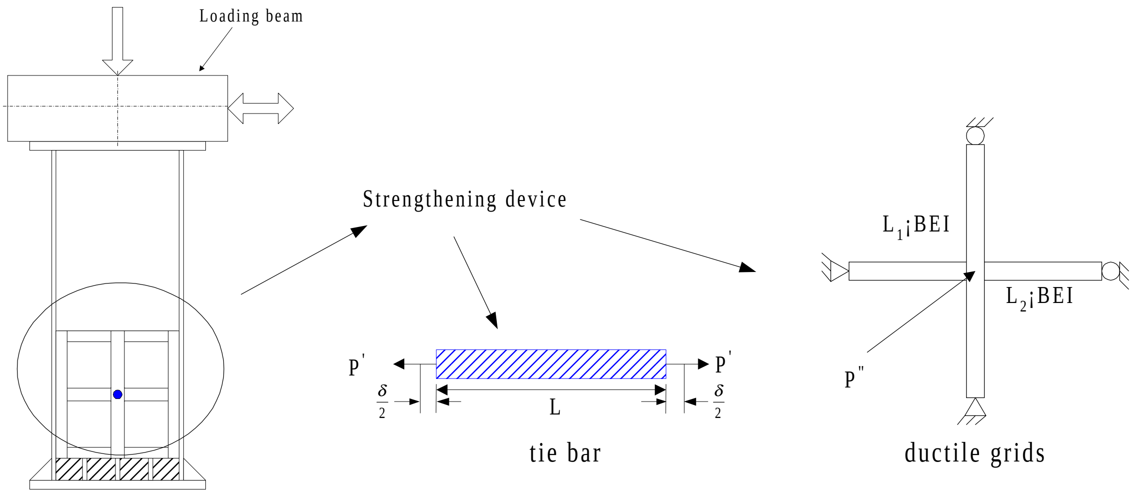

Figure 4. Stiffness of strengthening device

Therefore, the stiffness of tie k_s is equal to

$$k_s = \frac{EA}{L} \tag{2}$$

in which A and L are the cross section area and length of the tie, and the stiffness of the grids k_t' can be expressed as:

$$k_t' = \frac{48EI(L_1^3 + L_2^3)}{L_1^3 \times L_2^3} \tag{3}$$

where L_1 and L_2 are the lengths of the vertical and horizontal steel plates, respectively, and EI is the flexural rigidity of the plate.Therefore the total support on the member plates due to the strengthening device, Ks is:

$$K_S = k_s + k_t' \qquad (4)$$

COMPARISONS

The member performance can be compared based on the following criteria: (a) strength; (b) stiffness; and (c) energy dissipation.

Strength

The ultimate strengths of strengthened members were normalized with respect to that of unstrengthened one. As listed in Table 2, the largest strength gains of the test specimens are 6 percent for B38 test series, 2 percent for B48 test series, and 10 percent for the non-compact B60 test series, respectively. In general, the strength of the strengthened member stays at the same level as the original member.

Table 2. Normalized strength

	B38 Series	B48 Series	B60 Series
N	1	1	1
1d	1.01	1.01	1.10
1.5d	1.06	1.00	1.02
2d	1.06	1.02	1.03

Stiffness

The comparison of stiffness is based on the averge cycle stiffness defined as the slope of the line connecting the two extreme points of each cycle on the hysteretic curves. For B38 test series, the stiffness of members equipped with 1d, 1.5d, and 2d grids were 2, 10, and 6 percents respectively, higher than the unstrengthened member. For B48 test series, a maximum 4 percent increase in stiffness was achieved. For B60 test series, the largest stiffness gain, 10 percent, was achieved in the member equipped with 1d grids. These valuses showed that the levels of stiffness of members strengthened with ductile grids were not significantly influenced, therefore, members would not sustain excessive shear forces and no complicated structural responses needed to be re-analyzed.

Energy dissipation

In order to evaluate the performance of the strengthened members, a comparison on the energy dissipation capacities was conducted. Energy dissipation was obtained by calculating the areas bounded by the hysteretic curves. In order to prevent excessive p-Δ effect, a failure criterion was set when member strength dropped to 80 percent of the maximum strength of the unstrengthened member. This criterion was set so that ductility and member stability could both be balanced. The relationship between strength and cumulative energy for the three test series is shown in Figure 5. A comparison on energy dissipation capacity based on above criterion is shown in Figure 6. It was found from the comparison that whenever the strengthening device was installed, the energy dissipation capacity was improved. Figure 6 also shows the relationship between the performance enhancement and the stiffness ratios between strengthening device (K_S) and member plates (K_P).

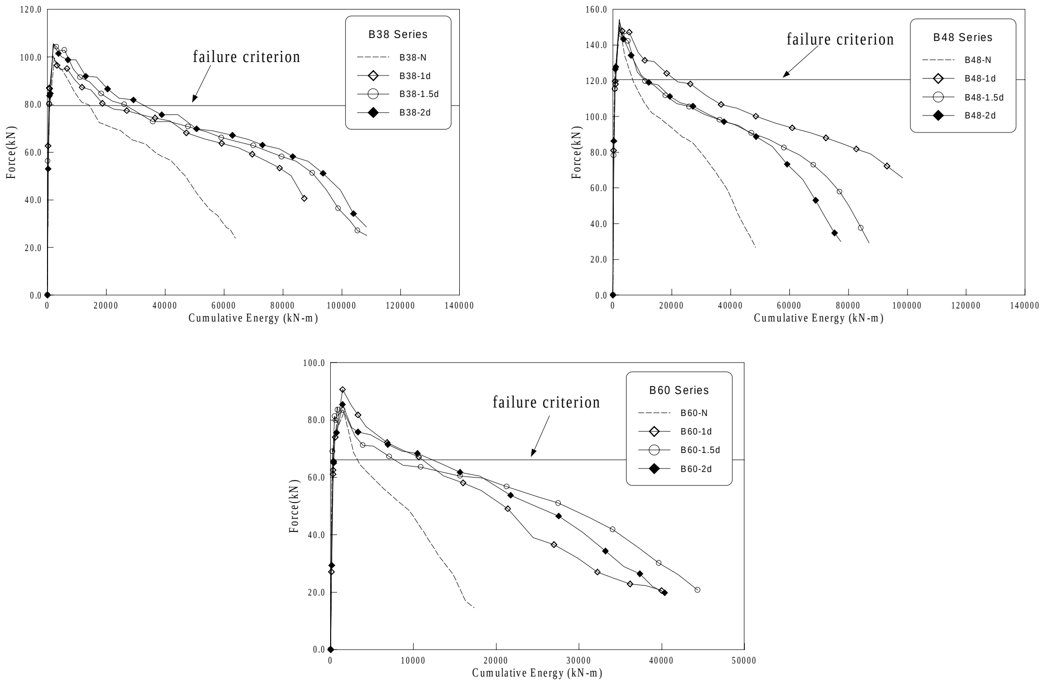

Figure 5. Relationship between strength and cumulative energy

CONCLUSIONS

The occurrence of local buckling on a pier column leads to deterioration in member strength, stiffness and energy dissipation. In order to maintain the member performance, the deterioration rate must be controlled and reduced. This paper presents experimental information on the cyclic behavior of steel box members strengthened with proposed sacrificial devices. Performance of members was compared based on strength, stiffness and energy dissipation capacity criteria. Test results showed that the strength and stiffness of strengthened members were maintained at the same level of original member. Therefore, structures after strengrhening are not required to be re-analyzed. Substantial improvement in energy dissipation capacity validates the applicability of the strengthening method. It is found that higher performance gains can be achieved for members with larger width/thickness ratios.

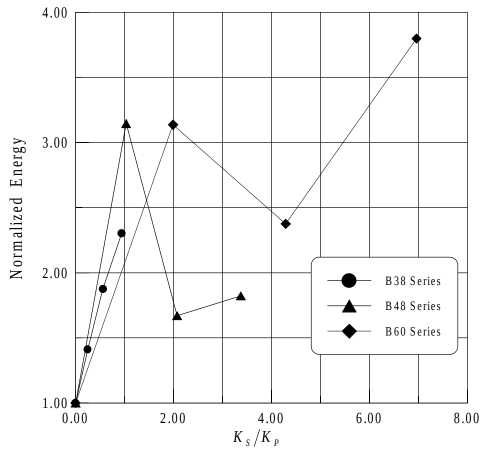

Figure 6. Normalized energy dissipation

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