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Fire performance of restrained welded steel box columns

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ABSTRACT

The objectives of this study is to investigate the effect of weld details (CJP or PJP), the load ratios, and the width-to-thickness ratios on the fire performance of unprotected welded steel box columns at 500 °C. Upon the experimental works, five column specimens were loaded to their ultimate state at room temperature and ten unprotected column specimens were loaded by steady-state method up to 500 °C.

In this study it is found that local buckling is the failure mode observed for the column specimen tested either at room temperature or in the fire condition. At 500 °C, unprotected CJP steel box columns show superior fire behavior compared to the columns fabricated by PJP which are more susceptible to premature cracking at the corner welds. CJP box columns with non-compact sections and no discernible cracks are able to sustain design loads of $0.8\phi P_n$ for 2 h under temperature conditions of 500 °C. At 500 °C, the fire resistance of PJP box columns can be enhanced by decreasing the applied loads and/or the width-to-thickness ratios. But, the fire resistance of steel box columns would be reduced significantly whenever the premature cracks were existed in the corner welds. Based on the result of this study, it is found that CJP box columns would be a better choice than PJP box columns for unprotected steel box columns under 500 °C. If CJP is not feasible in practical application and PJP is used instead, it is strongly suggested to design a compact section for those PJP box columns.

1. Introduction

Due to their higher strength and torsion rigidity, the application of steel box columns has become prevalent in high-rise buildings around the world. In counties or regions located in seismically zones, such as Taiwan, the steel box columns used are normally fabricated from four steel plates instead of the cold-formed steel hollow sections for better seismic behavior. The corners of the steel box columns are welded together either by complete-joint-penetration groove welds (CJP) or by partial-joint-penetration groove welds (PJP) as shown in Fig. 1.

The behavior of welded steel box columns appears to be different from those of cold-formed steel hollow sections and H-shape steel columns, due to differences in respect of residual stress distribution characteristics, types of welds used and width-to-thickness ratios [1,2]. Previous studies [2,3] have demonstrated that the types of groove welds, CJP or PJP, used to fabricate the steel box columns is one of the key factors that affect the strength and ductility of the steel box columns when they are subjected to axial and cyclical loads. Steel box columns with premature cracks in welds appear to have great reduction on their strength and deformation capacity, and thus the PJP box columns with the crack-like root openings in the corner welds would tend to be less ductile than CJP box columns.

Upon the seismic design requirement, CJPs must be used in the panel zone plus the distance of one width of the box column [4] for a steel moment-resisting frame to reach the sufficient plastic deformation capacity while PJPs are only allowed in the column sections away from the required CJP zone when the design axial compression less than 80% of the nominal design strength ($0.8\phi P_n$) of box columns.

In addition to the seismic behavior, the fire performance of steel box columns is also very important in the design of steel structures. The critical section in the fire event is normally located in the middle of the column length, unlike in a seismic event, where the failure often takes place in the beam-to-column connection. It is believed that the application of PJP in the middle section of a column may cause the reduction of fire resistance of steel columns. In order to establish a better structure both for seismic and fire conditions, it is very important to study the fire performance of CJP and PJP columns.

Researchers have paid a lot of attention to the fire performance of steel columns [5–18]. Most of those studies focused on the global behavior of cold-formed steel columns subjected to fire conditions by examining parameters such as load ratios, slenderness of the columns and end restraints [5–14]. However, as local buckling of column plates and the cracking of welds (Fig. 2) are commonly observed when welded steel box columns under fire attack so these two failure modes should be included in the studies. The influence of local buckling on the steel columns under fire has been examined previously [15–17], and the experimental results show that the strength reduction is much smaller for columns that fail due to local buckling compared to columns that fail due to global buckling [17]. But the influence of welding details on the fire performance of steel columns has not been discussed. Because premature cracking of the corner welds reduces the strength and

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Nomenclature

A_g	Cross-sectional area;
b/t	Width-to-thickness ratio;
CJP	Complete-joint-penetration groove weld;
Δ_u	Ultimate displacement of steel column;
Δ_y	Yielding displacement of steel column;
F_{yn}	Minimum yield stress of steel at room temperature;
F_{yt}	Yield stress of steel from tensile coupon test at room temperature;
F_{un}	Minimum tensile stress of steel at room temperature;
F_{ut}	Tensile stress of steel from tensile coupon test at room temperature;
γ_1	The load ratio of initial load applied on column specimen to design column strength specified in the code ($P_i/\phi P_n$);
γ_2	The load ratio of initial load applied on column specimen to the ultimate column strength from experimental tests at room temperature (P_i/P_u);
ϕP_n	Design column strength specified in the code;
P_i	Initial load applied on column specimen;
P_n	Nominal column strength specified in the code;
P_u	Ultimate column strength from experimental tests at room temperature;
PJP	Partial-joint-penetration groove weld
K	Effective length factor
L	Column length
r	Radius of gyration
λ_p	Width-to-thickness ratio to distinguish between compact section and non-compact section
λ_{pd}	Width-to-thickness ratio to distinguish between plastic design section and compact section
λ_r	Width-to-thickness ratio to distinguish between non-compact section and slender element
μ	Ductility of column specimen ($=\Delta_u / \Delta_y$)

ductility of PJP column it is believed that this might also cause a PJP column to have insufficient fire resistance when it is subjected to a fire attack.

To evaluate the effect of the fire performance of using PJP and CJP on unprotected welded steel box columns, a total of fifteen unprotected column specimens were tested in this study. These include five column specimens loaded to their ultimate at room temperature and ten column specimens with same end thermal restraints tested under uniform temperature up to 500 °C. The effects of load ratios, welding details, and width-to-thickness ratio of column plates on the failure mode and fire resistance of welded steel box columns have been examined in this study.

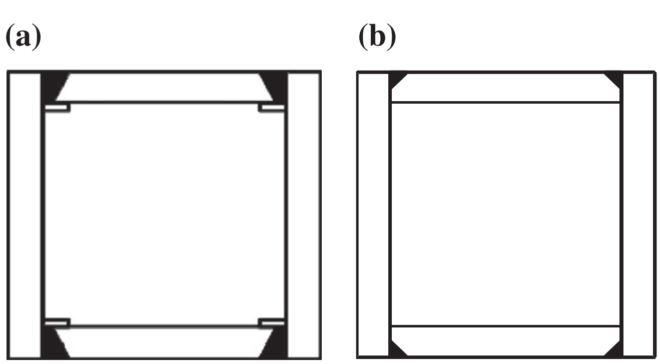

Fig. 1. Sketch of welded steel box columns: (a) complete-joint-penetration groove weld (CJP) box column; (b) partial-joint-penetration groove weld (PJP) box column.

Fig. 2. Failure of PJP box column in the fire event. (Courtesy of C.P. Chen).

2. Material properties of structural steel

The column specimens were made of SN490 steel with a minimum yield stress (F_{yn}) and tensile stress (F_{un}) of 325 MPa and 490 MPa at room temperature, respectively [19]. These specimens are made from plates with thicknesses of 16, 20 and 28 mm. Table 1 sets out the yield stress (F_{yt}) and tensile stress (F_{ut}) derived from the tensile coupon tests. Table 1 also compares the stress values derived from tensile coupon tests to those of the minimum values specified in the code. The yield stresses derived from testing are 19–23% higher than the minimum yield stress; the tensile stresses derived from testing are 10% higher than the minimum tensile stress.

3. General description of experimental plan

The fire resistance is one of the major concerns in designing steel columns. The fire resistance of steel columns is commonly defined as the duration that the columns can sustain without losing their load-carrying capacities in the standard time–temperature relationship. However in this study the standard time–temperature relationship has not been used because a single standard time–temperature relationship is not possible to represent the real fire [20]. Therefore the

Table 1
Material properties of the steel plates used in this study.

Plate thickness (mm)	Yield stress, F_{yt} (Mpa)	F_{yt}/F_{yn}	Tensile stress, F_{ut} (Mpa)	F_{ut}/F_{un}
16	387	1.19	540	1.10
20	401	1.23	539	1.10
28	393	1.21	540	1.10