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Experimental and analytical investigation of transition steel connections in traditional-style buildings

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ABSTRACT

This article examines experimentally the behavior of transition steel connections between smaller rectangular and larger circular tubes in traditional-style Chinese buildings. The steel connections were subjected to combined constant axial load and lateral cyclic displacements. Tests were carried out on four 2/3 scale connections extracted from a prototype with two upper column lengths (or slenderness) and two levels of axial force. The influence of axial compression ratio and slenderness ratio on the mechanical behavior of the connections was assessed by looking at hysteretic performance, backbone curves, characteristic loads and corresponding displacements, ductility, energy dissipation capacity, and stiffness degradation. Test results showed that the primary failure modes were cracking of welds or base metal around the welds, and local buckling of the flange at the base of the rectangular steel tube column. The hysteresis loops were full and showed moderate degradation, indicating very good seismic performance for these steel connections. When failure occurred, the interstory displacement angle was between 2.2% and 2.8%, and the equivalent viscous damping coefficient was about 0.26–0.29. Based on the experimental research, an idealized bilinear backbone curve model was developed considering both stiffness degradation and second order effects. This simplified model provides both a yield and an ultimate strength and deformation capacity that can be used in design.

1. Introduction

Ancient Chinese timber buildings reflect distinctive national characteristics, and show very high standards in artistic and structural expression as well as in construction technology [1]. Many of these buildings consist of complex wood structures (Fig. 1(a)) that require constant expensive maintenance; consequently, only a few have survived after thousands of years of natural disasters and wars. However, there is a strong desire in many regions of China to preserve ancient architectural styles, and thus wood has been replaced by modern building materials (i.e. steel, concrete) to build traditional style buildings [2]. In ancient timber buildings, columns and beams are connected by mortise-tenon joints (Fig. 1(b)). Pocket holes need to be drilled in the timber columns to insert the beams and connect the structural members. When the structure is subjected to lateral or gravity loads, the mortise-tenon joint is able to resist limited bending moments and allow significant rotations. However, in the modern steel manifestation of these traditional buildings, the structural components are mostly welded [3]. Modern traditional-style steel structures overcome the disadvantages of poor durability and high initial and maintenance costs associated with wood structures. In addition, they allow designers to also take advantage of the higher strength and stiffness of steel, as well as its ability to provide good seismic performance. These modern structures that mimic traditional Chinese architectural styles will be called Modern Traditional Steel (MTS) structures in this paper.

Most research on steel components and connections has concentrated on traditional bolted and welded connections and beam-columns ([5–6], for example), and only recently has the interest shifted from W shapes to tubular elements and high strength steels. For example, Shi et al. [7] carried out quasi-static test on 1.97 m long 460 MPa steel welded box columns, which showed that these columns possess excellent ductility and energy dissipation capacity. They are ideal for use in seismic steel frames, with the proviso that the width-to-thickness ratio be related to the axial compression ratio. Yang and Tan [8] presented a numerical study of steel beam-column joints using six types of connections, and showed that current design criteria for rotation capacities of web cleat, fin plate, and flush end plate connections are probably too conservative

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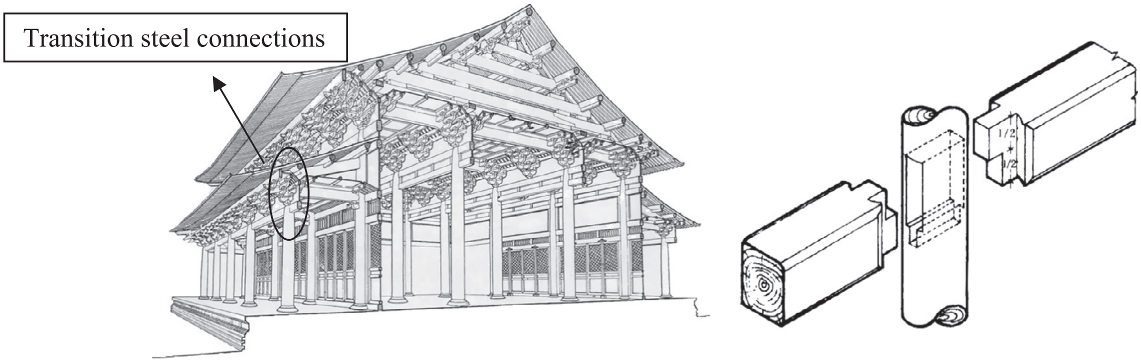
Nomenclature

f_y	yield strength of steel
ε_y	yield strain of steel
f_u	ultimate strength of steel
E_s	elastic modulus
n	axial compression ratio
ζ	slenderness ratio of rectangular steel tube
F	horizontal force
t	thickness of steel tube
F_y, Δ_y	yield load and corresponding displacement on backbone curves
F_u, Δ_u	ultimate load and corresponding displacement on backbone curves
h_{ey}, h_{eu}	equivalent viscous damping coefficient corresponding to the yield load and ultimate load, respectively
K_e	elastic stiffness
K_p	plastic stiffness
M_y	yield moment
M_u	ultimate moment
A	cross-sectional area
I	inertia moment
S	elastic section modulus
Z	plastic section modulus
h	height of specimen
I_1, h_1, A_1	inertia moment, height, cross-sectional area of circular pipe
I_2, h_2, A_2	inertia moment, height, cross-sectional area of rectangular tube
I_3, h_3, A_3	inertia moment, height, cross-sectional area of the strengthen part between two tubes
A_4	web cross-sectional area of rectangular tube
G	shear modulus
b	width of rectangular cross-section
D	diameter of circular cross-section
t_1	thickness of circular steel pipe
t_2	thickness of rectangular steel tube
η	second stiffness coefficient
β	shape factor of cross-section
δ	web thickness of cross-section



(a) Timber frame structure (b) Mortise-tenon joint [4]

Fig. 1. The ancient wood building [4].

as they only consider pure flexural resistance. Lew et al. [9] conducted an experimental study of two full-scale steel beam-column assemblies, each comprising three columns and two beams. These tests provided experimental data for validation of beam-to-column connection models to be used in assessing the robustness of structural systems. The Lew et al. [9] results indicated that the rotational capacities of connections under monotonic column displacement are about twice as large as those based on seismic testing protocols. Newell and Uang [10] performed cyclic tests of nine full-scale W14 column specimens representing a practical range of flange and web width-to-thickness ratios, which were subjected to different levels of axial force demand. These test indicated that the ASCE 41 [11] predicted plastic rotation capacities are very conservative, and the ASCE 41 criteria do not specify plastic rotation capacity at axial load ratios greater than 0.5. The specimens tested exhibited plastic rotation capacities of approximately 15–25 times the member yield rotation.

The members and connections studied in the research projects briefly described above are very different from those in MTS structures. In MTS structures, circular columns are labelled as eave columns, hypostyle columns and other columns based on column position and function in ancient wood buildings [12]. The shape of columns in MTS architecture is consistent with that of ancient wood structures, and the construction is quite complicated [13]. These columns include brackets located above the eave columns and hypostyle columns and sudden changes in cross-section as they approach the roof, as shown in the two perpendicular views in Fig. 2(a) and (b). These transitions have to be preserved for aesthetic reasons in MTS buildings; clearly more economic and structurally efficient solutions exist outside that constraint. The thicker line in these figures indicates the locations from which test specimens used in this project were extracted. There is a sudden change of strength and stiffness in the connecting section between upper columns and lower columns; the upper column is a smaller rectangular steel tube which is connected to a larger lower circular steel pipe. The rectangular tube is inserted into the circular pipe and the insertion depth is extended to the bottom beam flange. Several stiffeners and a circular ring plate are welded to ensure robust force transfer. The details are illustrated in Fig. 2(c), which shows a MTS portion of the traditional one shown in Fig. 2(b).

The force flow in this section is obviously very different from that of mortise-tenon joints used in older wooden buildings. In this