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Structural behavior of centrally loaded steel columns at elevated temperature

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ABSTRACT

A series of experimental studies is conducted to examine the behavior of SN490 steel column subjected to axial load in the fire condition. This experimental work is aimed at examining the effect of the width-to-thickness ratio of flanges, the slenderness ratio of steel columns and residual stresses on the ultimate strength of an SN490 steel column at a specified temperature. From these studies, it is found that the column strength decreases with the increase of width-to-thickness ratio and slenderness ratio. Column behavior is sensitive to width-to-thickness ratios and the slenderness ratio at temperatures below 550 °C. However, the influence of width-to-thickness ratios and the slenderness ratios is not severe when the temperature is higher than 550 °C. When the temperature is above 550 °C, the column strength deteriorates rapidly. It is also found that the failure mode of steel columns changes from inelastic global buckling at room temperature to inelastic local buckling at elevated temperature, due to the release of residual stress in a fire. Based on the results of this study, local buckling criteria and column strength at specified temperatures are suggested.

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1. Introduction

The ultimate strength of steel columns at room temperature has been studied thoroughly in the past [1]. The aspects that affect the strength of the column, such as residual stress, initial imperfections, the width-to-thickness ratios of stiffened and unstiffened elements, and the slenderness ratio of steel columns, have been examined extensively. As a result, the SSRC column curves have been adopted as the basis for steel column design in a number of specifications [2–4]. However, the strength design criteria of steel columns under fire load have not been examined thoroughly.

To determine the strength of steel columns at elevated temperature, American Institute of Steel Construction (AISC) [2], European Committee for Standardization (EC3) [3] assume that column strength degrades with the combined effects of the degradation of elastic modulus and yield strength. The identical equations for calculating the buckling strength at ambient temperature are adopted to determine the strength of the column at elevated temperatures, except the degraded elastic modulus and yield strength at the corresponding temperature are used. It is assumed that the influence of column slenderness, width-to-thickness ratio and residual stress on column strength in the fire condition is the same as that at room temperature. On the other hand, Architectural Institute of Japan (AIJ) [4] assumes that at elevated temperatures column strength varies with column slenderness and the decrease of yield strength, disregarding the deterioration of the elastic modulus.

A discrepancy is also found between the design codes and those observed in the experimental works. Fig. 1 compares the column strength of A36 steel at elevated temperature between the experimental results and those determined from the codes, in which P_{AIJ}, P_{AISC}, and P_{EC3} represent the column strength determined from the codes. $P_{exp.}$ is the column strength obtained from the experimental test [5]. The column strength has been underestimated at 500 °C if the slenderness ratio of column is less than 52, while, column strength was overestimated more than 50% if the slenderness of the column is larger. Besides the deteriorated yielding strength and elastic modulus of steel, the strength of steel column is also affected by the factors such as the slenderness ratio (L/r), width-to-thickness ratio (b/t), residual stresses, and end restraints. It is not appropriate to apply the same reductions of strength for columns at elevated temperature and at room temperature. To provide an economic fire design for the steel columns without sacrificing safety, there is an urgent need to establish the basic information of the structural behavior of steel column at elevated temperatures.

The fire behavior of steel columns has been investigated by various researchers experimentally and theoretically [6–10]. The parameters such as the axially or rotational restraint, load ratios, slenderness ratios have been examined in these studies. However, previous researches were aimed at seeking the critical temperature of steel columns with or without restraint. The knowledge related to the column strength at elevated temperature is limited [5,11,12]. In this reported study, the experimental works was carried out on 42 SN490 steel columns by considering the width-to-thickness ratio, slenderness ratio, and temperature, to evaluate the behavior of steel columns during a fire event. The effects of residual stress and boundary condition on the fire performance of steel columns were also examined.

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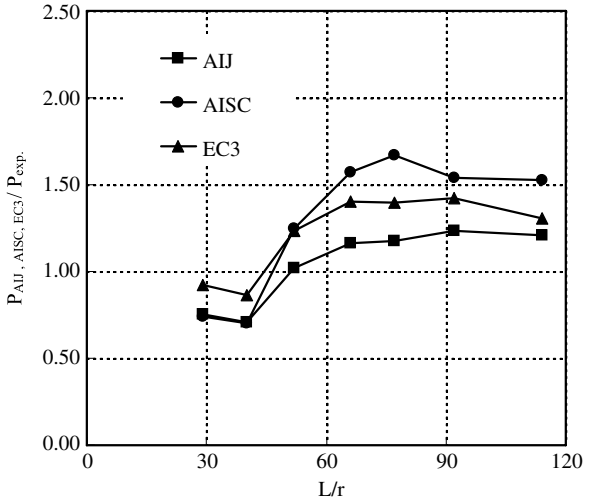

Fig. 1. Comparisons of A36 steel column strength at 500 °C.

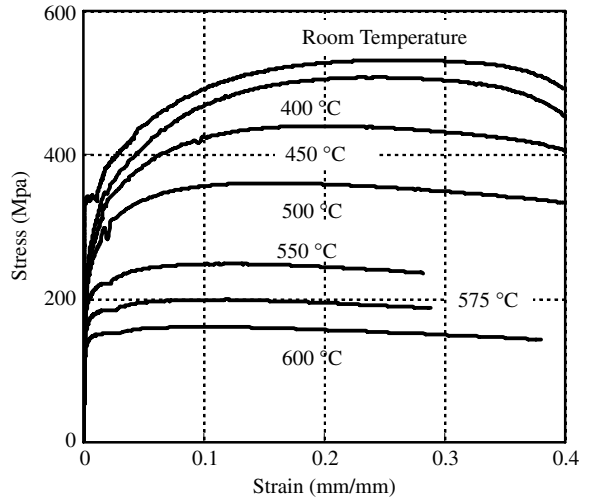

Fig. 2. Stress–strain relationship of steel at elevated temperature.

2. The material properties of structural steel at elevated temperature

In this study, column specimens were made of SN490 steel with a minimum nominal yield stress of 343 MPa and elastic modulus of 200 GPa at room temperature. The material properties of the SN490 at elevated temperature are shown and Fig. 2. Table 2 compares the deterioration of the material properties with the codes. The yield stress and the elastic modulus decrease at different rates as the temperature increases. At 500 °C, the steel retains more than 60% of the nominal yield stress of that at room temperature; while, the yield stress drops significantly to approximately 40% of the nominal yield stress at room temperature as the temperature rises above 600 °C. On the other hand, the deterioration of the elastic modulus is not as severe as that of the yield stress. At 600 °C, SN490 steel retains 60% of its elastic modulus as at room temperature. It is also noted that the strain hardening of steel is insignificant when the temperature is higher than 550 °C. The enhanced stress due to strain hardening decreasing with the increase of temperature. As temperatures reach 600 °C, strain hardening of steel almost vanishes (Fig. 2).

Nomenclature

b/t	Width-to-thickness ratio
$F_{y,exp}$	Yield stress of steel from stub column test at elevated temperature
Δ_u	Ultimate displacement of steel column
Δ_y	Yielding displacement of steel column
$F_{r,\max}$	Maximum residual stresses $= F_{y,exp} - F_{yT}$
F_y	Yield stress of steel at room temperature
F_{yT}	Yield stress of steel at elevated temperature T
P_{AIJ}	Column strength at elevated temperature based on Architectural Institute of Japan
P_{AISC}	Column strength at elevated temperature based on AISC-LRFD specification
P_{EC3}	Column strength at elevated temperature based on Eurocode 3
$P_{exp.}$	Ultimate strength of steel column at elevated temperature from experimental test
P_{yT}	The yield load at temperature T
P_n	The nominal column strength based on AISC-LRFD specification
K	Effective length factor
L	Column length
L/r	Slenderness ratio
λ_p	Width-to-thickness ratio for distinguishing compact section and non-compact section
λ_{ps}	Width-to-thickness ratio for distinguishing seismically compact section and compact section
λ_r	Width-to-thickness ratio for distinguishing non-compact section and slender element

3. Studies of axially loaded steel column under uniform temperature

To evaluate the performance of steel columns under fire loads, a total of forty-two steel H-column specimens have been designed and centrally loaded to their limit state under uniform temperature conditions. Among these column specimens, twelve specimens (Specimen Nos. 1–12) were designed as stub columns with varying width-to-thickness ratios. The stub column test is aimed at determining the effect of local buckling on the column performance [1]. This series of studies was to investigate the effect of the width-to-thickness ratios to the strength and ductility of steel columns at elevated temperature. Residual stress in an H-section due to thermal effects was also examined.

Another five steel columns (Specimen Nos. 13–18) were designed as seismic sections with a slenderness ratio of 34. These columns were loaded at different temperature varying from room temperature to 600 °C with a temperature increment of 50 °C. This series of column specimens was to evaluate the strength degradation characteristics of steel columns commonly used in steel buildings. The remaining twenty-four steel column specimens (Specimen Nos. 19–42) were the columns of seismic section with varying slenderness ratios. The purpose of these specimens was to examine the effect of the column slenderness on their ultimate strength when steel columns are loaded under uniform elevated temperature.

During the experimental work, it is important to secure a uniform stress distribution over the cross-section of the column specimen. To minimize initial geometrical imperfections of the specimen, the column specimen was carefully fabricated to fulfill the construction criteria so that the maximum initial imperfection is less than $L/1000$ [2]. All of the column specimens were milled at both ends to ensure the flatness at the loading surface. The

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