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Restraining requirements for lateral elastic-plastic buckling of columns accounting for random imperfections

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ABSTRACT

This paper dealt with the restraint stiffness and strength requirements for axially loaded columns with lateral restraints, accounting for inelastic flexural buckling and random imperfections. Firstly, the buckling behaviour of restrained columns with classic deterministic imperfections was discussed to verify the effect of section dimensions, material properties and imperfection shapes. Then by using probabilistic distribution of imperfections along the column, extensive numerical results were gained through random imperfection finite element analyses, followed by restraint stiffness and restraint force proposed statistically corresponding to full restraining for columns. Results showed that, the full restraining stiffness of perfect columns proposed by Winter is sufficient for columns with imperfections and inelastic buckling. The traditional approach with predetermined artificial imperfections is deficient to evaluate the restraint force properly and rationally, due to ignoring the effect of random imperfections.

1. Introduction

Lateral restraints are adopted to increase the flexural buckling strength of columns about the weak axis. To be effective, 'full restraining' is desired and defined as the load-carrying capacity of the restrained column achieves the buckling strength of the column segment between restraining points [1,2]. In practical design to achieve full restraining, adequate restraint stiffness and restraint strength to withstand the reacting force should be satisfied [1–4].

Extensive investigations have been conducted into elastic buckling of laterally restrained columns by using analytical approaches [1–11]. Winter [2] developed a simplified rigid link model with fictitious hinges and proposed equations for the restraining requirements, which became the foundation of later studies and design codes [3–13]. However, in practical design, due to increasing of stability by lateral restraints, a restrained column usually buckles in inelastic range, thus the state of material is altered and the derivations based on elastic buckling theory may not be applicable. However, studies related to inelastic buckling of restrained columns are lacking. Winter [2] stated that the proposed equations can be directly applied to inelastic columns. In contrast to Winter's model with fictitious hinges, Pincus [13] introduced a rotational spring at the restraining point and found that the full restraining stiffness by Winter [2] was insufficient for inelastic buckling columns. Gil and Yura [14] concluded that the full restraining stiffness was independent on the state of material elasto-plasticity. Thus it can be seen that, while restraining requirements for elastic columns are well explained, those have not been fully developed for inelastic columns with lateral restraints. It has not been verified whether the elastic conclusion can be applied in inelastic buckling of restrained columns.

The other important issue is the significant effect of imperfections on the restraining requirements for columns with lateral restraints. Winter [2] incorporated artificial zigzag-shaped imperfections for restrained columns based on the fictitious hinge model. Plaut and Yang [8] and Plaut [9] adopted the buckling mode as imperfections for restrained columns. In the finite element analyses (FEA) by Gil and Yura [14], imperfections were assumed as a symmetric one wave, an antisymmetric double wave, and a nonsymmetric double wave respectively, where results showed that buckling of restrained columns was very sensitive to imperfection shapes.

Geometric imperfections of steel structures originated from manufacturing and erection are essentially stochastic in nature [15–22]. To accounting for random geometric imperfections, large amount of data from site measurement is need, and based on random field theory the random imperfections can be modeled, as indicated by Kala et al. [21] and Xi et al. [22]. However, in the previous studies on restrained columns, random imperfections have hardly been considered and

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Nomenclature

A	area of cross-section
b	width of an I-section
E	steel modulus of elasticity
E_t	hardening modulus of steel material
F_R	restraint force
F_{R95}	restraint force corresponding to full restraining with 95% guaranteed rate based on random analyses
f_y	steel yield stress
G	steel shear modulus of elasticity
h	overall height of an I-section
k	restraint stiffness
k_{ie}	full restraining stiffness for elastic columns without imperfections, from Winter's theory
k_{iu}	full restraining stiffness for elastic-plastic columns without imperfections, from Winter's theory
L	entire length of the restrained column
l	length of column segments between restraining points
n	number of lateral restraints
P	compression load on columns
P_{el}	Euler critical load for the individual column segment with length l
P_u	inelastic buckling strength of the entire column with lateral restraints
P_{ul}	inelastic buckling strength for the individual column segment with length $l$full restraining strength of the restrained column
t_f	flange thickness of an I-section
t_w	web thickness of an I-section
Δ_i	additional deflection at the ith restraining point under loading
$[\Delta]$	permitted imperfections tolerance
λ_{z0}	slenderness of the column segment between restraining points

imperfections were mostly defined artificially as one specified deterministic shape, either sine waves or buckling modes. This simplified treatment might not reflect the effect of random imperfections in real columns, thus would lead to unconvincing results for the restraining requirements [15–23].

In the study of Dou and Pi [23], the effects of geometric imperfections of axially loaded columns with lateral restraints were investigated on flexural inelastic buckling resistance, and a simplified way forming the critical geometric imperfection in FEA was proposed leading to rational results for buckling resistances. However, it did not answer the question how to determine the restraint stiffness and force in design for columns in inelastic buckling and with random imperfections.

Therefore, the aim and significance of this paper is to investigate the restraining requirements for laterally restrained columns, accounting for inelastic buckling and random imperfections by using finite element analyses, to provide rational evaluations on the full restraining stiffness and restraint force in practical application. Firstly, the effect of various factors on buckling of restrained columns is considered, namely the section dimensions, material inelastic constitutive relations and the imperfection shapes. Then based on the measured probabilistic distribution of imperfections, random numerical analyses are conducted dealing with uncertainties of imperfections in columns, and the statistical results for restraint force are obtained and discussed.

2. Scope and finite element model

Since the sectional bending rigidities of I-sectional columns about two major axes are quite different, the flexural buckling load about the weak axis needs to be enhanced by arranging lateral restraints. I-sectional hinged columns with discrete lateral restraints under axial loading are concerned in this paper, as shown in Fig. 1. The lateral restraints are equally spaced and assumed elastic with the same spring stiffness k, and the column material is elasto-plastic.

It is worth noting that, lateral restraints are usually set along the direction perpendicular to the weak axis of cross-section (z-axis), to increase the flexural buckling load about z-axis until it is close to the buckling load about the strong axis o-y. Thus, the restraint requirement related to the flexural buckling about the weak axis is considered, which is the fact in practical engineering design. Only the imperfections and flexural buckling along y-axis are concerned.

Finite element package ANSYS R13.0 [24] is adopted in flexural buckling analyses of restrained columns, with elasto-plastic nonlinearity, large deformation and imperfections all taken into account. The column is modeled with three-dimensional finite-strain beam

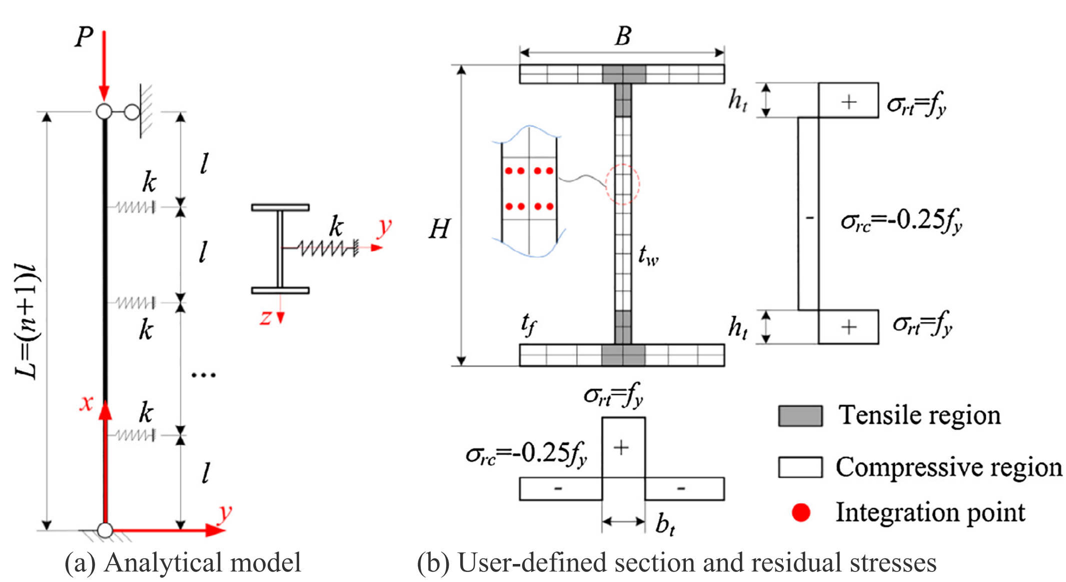

Fig. 1. Axially loaded columns with n lateral restraints.