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Study on mid-height horizontal bracing forces considering random initial geometric imperfections

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ABSTRACT

In order to investigate the different mid-height horizontal bracing forces of column–bracing system between pin-ended column base and fixed-ended column base, a large number of column–bracing systems with pin-ended column base and fixed-ended column base have been modeled and analyzed using finite element method, in which the random combination of the initial geometric imperfections between columns and braces was well considered by the Monte Carlo method. Based on the above comparative study, the probability density function of mid-height horizontal bracing forces was found through probability statistics and the design bracing forces were also obtained. It is founded that the buckling mode of columns for pin-ended column base is three half-waves of bending while the buckling mode of columns for fixed-ended column base is two half-waves of bending, so that the ultimate load-carrying capacity and the mid-height horizontal bracing forces of column–bracing systems with pin-ended column base are higher than those of column–bracing systems with fixed-ended column base, and the relative high ultimate load-carrying capacity of the former more significantly increases its mid-height horizontal bracing forces. The results also indicate that random combination of the initial geometric imperfections between columns and braces leads to the randomness of mid-height horizontal bracing forces in compression or in tension, so that the design bracing forces can be reasonably reduced which are smaller than those stipulated in GB50017-2003, Eurocode3-1992 and AS4100-1998. Moreover, practical design formulas of mid-height horizontal bracing forces are proposed.

1. Introduction

Bracing members in structural systems have manifold functions among which the most important might be the role of providing intermediate lateral support to compression members for enhancing their stability. The behavior of braces had not been understood in civil engineering circle until Winter published his comprehensive work in 1958 [1]. Since then many researchers have contributed to promoting the knowledge of bracing performance and design for a single column–brace model [2–5]. Among more recent works, Tong, Li and Zhang have contributed analytical solutions and practical formulas of the design bracing forces for column–bracing systems with pin-ended column base as shown in Fig. 1(a) [6–8], and a very limited number of studies have been carried out to determine the design bracing forces for column–bracing systems with fixed-ended column base as shown in Fig. 1(b).

The longitudinal bracing systems of industrial buildings usually consist of diagonal bracings and horizontal braces which are to maintain longitudinal stability and to reduce the out-of-plane effective column lengths. In past studies on column–bracing systems, the random combination of the initial geometric imperfections between columns and braces was rarely considered and the mid-height horizontal braces were usually assumed to be effective only in compression [6–8]. In reality, the initial geometric imperfections of both columns and braces are independent random variables, and the combination of the initial geometric imperfections between them is also random. In general, such random combination has a very favorable effect on the braces as the mid-height horizontal braces may be in compression or tension when the ultimate load P of the braced columns is reached. This complex random problem cannot be solved by theoretical analysis, but can be well dealt with using the Monte Carlo method [9].

In this paper, a large number of column–bracing systems with pin-ended and fixed-ended column base have been carried out by second-order analysis using ANSYS, in which the random combination of the initial geometric imperfections of both columns and braces was well considered by the Monte Carlo method. Moreover, the probability density function of mid-height horizontal bracing forces was found, the design forces of mid-height horizontal braces were obtained, and comparative study on mid-height horizontal bracing forces between pin-ended column base and fixed-ended column base was also conducted. In addition,

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Nomenclature

A_c	cross-sectional area of column
A_m	cross-sectional area of mid-height horizontal brace
A_t	cross-sectional area of top horizontal brace
A_d	cross-sectional area of diagonal bracing
L	column height
b	brace span
n	the number of braced columns
δ_{0i}	the initial bow imperfection of the ith column taken randomly by Monte Carlo method
Δ_{0i}	the initial sway imperfection of the ith column taken randomly by Monte Carlo method
u_{0i}	the initial bow imperfection of the ith mid-height horizontal brace taken randomly by Monte Carlo method
v_{0i}	the initial bow imperfection of the ith top horizontal brace taken randomly by Monte Carlo method
λ_c	the half slenderness ratio of column around week axis
λ_b	the slenderness ratio of horizontal brace
P	ultimate load capacity of column
F	the maximum axial force of mid-height horizontal brace

the design mid-height horizontal bracing forces obtained considering random initial geometric imperfections were compared with the relevant codes and practical design formulas of mid-height horizontal bracing forces were proposed at the end of the paper.

2. Analytical model and parametric selection

The analytical models of column–bracing systems with pin-ended and fixed-ended column base are shown in Fig. 1(a) and (b) respectively. The n-columns in the row which are equally spaced have the same axial force. The hinged joints between the columns and the braces pass through the shear center of the column sections, so that only out-of-plane flexural buckling of the columns occurs. The cross-sectional areas of the columns are the same and are denoted by A_c; the cross-sectional areas of the horizontal braces at mid-height or the top of the columns are the same and are denoted by A_m or $A_{t,}$ respectively; the cross-sectional areas of the diagonal bracings are the same and are denoted by A_d.

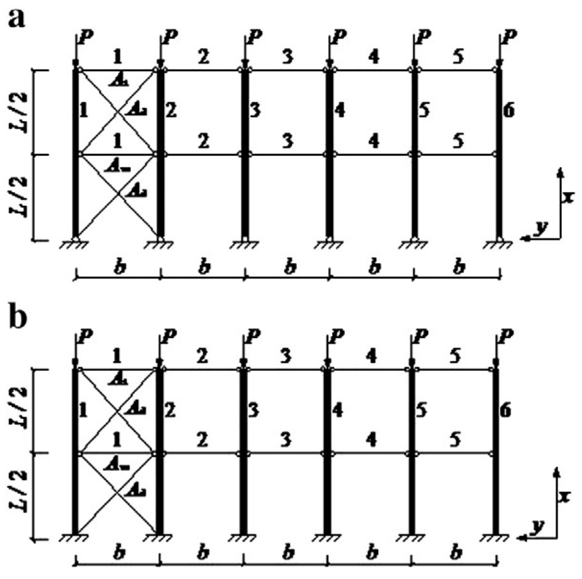

Fig. 1. Column–bracing system. (a) Pin-ended column base; (b) fixed-ended column base.

The parameter selection of the analytical models is mainly based on Ref. [10]: the slenderness ratio of the brace λ_b and the ratio of the brace length over the column height b/L. In this paper, another parameter is added: the half slenderness ratio of the column about the minor axis λ_c. In most cases of practical design, the parameters in common use are: $b = 6$ m, $100 \le \lambda_b \le 200$ and $0.4 \le b/L \le 0.7$.

A biaxially symmetric I-section is selected in the study and flexural buckling along the longitudinal direction of building occurs about the minor axis of the column. The cross-sectional areas of the columns are the same and are equal to 250 cm^2, and the geometrical dimensions of the cross-sections of the columns are shown in Table 1.

The horizontal braces are designed according to the ultimate loads of the columns, and circular tube-sections are used. The geometrical dimensions of the horizontal braces for $n = 6$ are shown in Table 2.

The diagonal bracings against tension only are designed according to the horizontal bracing forces, and circular solid bars are used. The cross-sectional areas of the diagonal bracings A_d for $n = 6$ are shown in Table 1.

3. Tolerance of initial geometric imperfections

Eurocode 3-2003 specifies that the effects of imperfection should be allowed for in the analysis of bracing systems in the form of an initial bow imperfection [11]:

$$e_0 = K_r L/500 \tag{1}$$

where L is the span of the bracing system and $K_r = (0.2 + 1/n_r)^{0.5}$ but $K_r \le 1.0$ in which n_r is the number of members to be restrained. From Eq. (1) it can be seen that the randomness of the initial bow imperfections for multiple members is considered by means of an equivalent coefficient K_r and the initial bow imperfection of a single member is $L/500$ which covers the effects of practical imperfections, including residual stresses and geometrical imperfections such as lack of verticality, lack of straightness, lack of fit and the unavoidable minor eccentricities present in practical connections.

However, the tolerance of the initial bow imperfection of a single member seems to be rather conservative in Eurocode 3. In practical design, the ultimate load-carrying capacity of an axially loaded compression member depends on its stability factor which is well known to have been obtained considering the effects of residual stresses and initial geometrical imperfections. Therefore, the effects of practical imperfections should not cover residual stresses and partial geometrical imperfections which include the unavoidable load eccentricities for the analysis of bracing systems.

According to the "Code for Acceptance of Construction Quality of Steel Structures" in China (GB 50205-2001) [12], the allowable fabrication deviations of columns for one-story steel structures are given as follows: the maximum value of initial bow imperfection should be less

Table 1
Geometrical dimensions of column sections.

L (m)	b/L	λ_c	B (mm)	H (mm)	t_f (mm)	t_w (mm)	A_d (cm^2)
15	0.4	50	639.93	800	12.88	11	15.5
15	0.4	75	446.65	800	16.83	13	14.5
15	0.4	100	352.54	800	19.26	15	14.0
12	0.5	50	523.54	800	15.05	12	14.5
12	0.5	75	376.58	800	17.98	15	13.5
12	0.5	100	298.81	800	20.22	17	12.0
10	0.6	50	446.65	800	16.83	13	13.5
10	0.6	75	322.28	800	19.92	16	12.5
10	0.6	100	256.49	800	22.22	18	11.2
8.57	0.7	50	392.45	800	18.23	14	12.5
8.57	0.7	75	284.23	800	21.33	17	11.8
8.57	0.7	100	226.98	800	23.56	19	10.5

Note: B, H — width and height of I-section, respectively; t_f, t_w, — thickness of flange and web, respectively; A_d — the cross-sectional area of the diagonal bracings.