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Reliability assessment of aluminum alloy columns subjected to axial and eccentric loadings

Yuanzheng Zhao *, Ximei Zhai

Key Lab of Structures Dynamic Behavior and Control of Ministry of Education, Harbin Institute of Technology, Harbin 150090, PR China
Key Lab of Smart Prevention and Mitigation of Civil Engineering Disasters of the Ministry of Industry and Information Technology, Harbin Institute of Technology, Harbin 150090, PR China

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ABSTRACT

The reliability and safety of aluminum alloy columns used in China is not well understood. This paper develops an improved probabilistic model for the reliability assessment of axially and eccentrically loaded columns, designed based on the aluminum alloy structure design codes of China. A comprehensive database, including 272 axially and 116 eccentrically loaded columns mainly made of 6061-T6 and 6082-T6 aluminum alloy in China, was established. Using this database, a statistical analysis of test results was conducted to determine the optimal probability distribution which can provide the best fit to the model error (ME) data and the relevant distribution parameters. The statistical parameters of ME, material strength, geometrical properties, load type, and load ratio were considered in the reliability evaluation, and a sensitivity analysis was performed to investigate the effect of these variables on the reliability indices. Then, the structural reliability levels of aluminum alloy columns in compression designed according to Chinese, American, and European codes were compared. By analyzing the optimal probability distribution of ME, the calculation results showed that the safety level of Eurocode 9 was the highest, while that of the American code was the lowest, with the Chinese code being in between. Additionally, the reliability index of 6082-T6 aluminum alloy columns was higher than that of 6061-T6. In view of the analysis results showing that the Chinese code barely met the target reliability index of 3.70, the material partial factor γ_R was modified for a capacity prediction model of aluminum alloy columns in compression designed according to Chinese code, to ensure that it reached the reliability requirement.

1. Introduction

Aluminum alloys have been used commonly as building materials in space structures, glass curtain walls, and other structures in America and Europe due to their high strength, low density, excellent corrosion resistance, and ease of maintenance and utilization [1,2]. In the last two decades, aluminum alloys have been used increasingly in the construction industry in China, and the most frequently used grades of aluminum alloy in China are 6061-T6 and 6082-T6. Although aluminum alloys show good ductility as metallic materials, their Young's modulus are approximately one-third that of steel, and instability caused by local and overall buckling occurs readily with aluminum alloy columns and beams.

In America and Europe, there is a long history of conducting experiments and reliability analyses of aluminum alloy members. Since the 1970s, based on test and analysis results, various design codes for aluminum alloy structures have been used, including an American code (ADM-2005) [3] and European code (Eurocode 9) [4]; these codes were designed to ensure the safety and reliability of structures. Recent analyses of the reliability of the design codes were done by Jihua Zhu and Ben Young [5]. They performed experimental investigations of aluminum alloy columns under axial compression and evaluated the reliability of the American, European, and Australian/New Zealand (AS/NZS) codes. In China, however, the safety and reliability of aluminum alloy members and structures have received little attention from researchers. Only Shen and Guo [6,7] assessed the safety of 6061-T6 aluminum alloy columns and beams according to probabilistic theory, and the Chinese code (GB 50429-2007) [8] issued in 2007 was exactly enacted based on the analysis of Shen and Guo. Previous reports have yielded only very basic statistics and reliability analyses of 6061-T6 aluminum alloy members, and did not explore the effect of

* Corresponding author at: Key Lab of Structures Dynamic Behavior and Control of Ministry of Education, Harbin Institute of Technology, Harbin 150090, PR China.
E-mail addresses: zhaoyuanzheng1993@yahoo.com (Y. Zhao), xmzhai@hit.edu.cn (X. Zhai).

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analysis parameters such as the probability distribution of model error (ME), load ratios, aluminum alloy grades, and the limit state equation on structural reliability. Additionally, test results on aluminum alloy members were limited before 2006, and the tests were insufficient in terms of assessing different types of materials and sections. Further experiments have been performed with different aluminum alloy grades and section types since 2006, and any reliability analysis might show inaccurate results if these data are not considered.

For these reasons, in this study, we performed a comprehensive set of experiments on aluminum alloy columns under axial and eccentric compression from 1999 to 2016 [9–24], and report the results of material tests, as well as data on the section dimensions and bearing capacities of the tested columns. Based on the database that we established, we performed a reliability analysis of the bearing capacity calculation formulae for axial and eccentric compression columns, and the sensitivity of different variables to the reliability calculation was then analyzed. This analysis covered Chinese (GB 50429-2007) [8], American (ADM-2005) [3] and European (Eurocode 9) [4] codes. Finally, the material partial factor, $\gamma_R = 1.2$, in the Chinese code was revised based on the reliability analysis results showing that the calculated indices were less than the target reliability index $[\beta] = 3.7$.

2. Review of design code provisions for aluminum alloy structures

2.1. GB 50429-2007

Local buckling, which is more likely to occur in plates of aluminum alloy members due to their low Young's modulus, decreases the bearing capacity. To best exploit the post-buckling strength of the plates, the Chinese code (GB 50429-2007) includes a series of limiting values with respect to the width-thickness ratio for the plates in compression, as shown in Table 1. If the width-thickness ratio of the plates exceeds the values in Table 1, thickness reduction factors need to be multiplied by the thickness to generate the "effective thickness," [25] which can be used to calculate the bearing capacity of the aluminum alloy members directly. The design formulae for axial and eccentric compression strength are shown as Eqs. (1) and (2).

For axial compression columns, the slenderness ratio λ can greatly affect the bearing capacity, and thus a stability factor $\bar{\varphi}$, calculated with the Perry-Roberson equation, is multiplied by the cross-section bearing capacity to determine the buckling resistance of members. For eccentric compression columns, the axial force and bending moment are processed separately to calculate the ultimate stress for in-plane and out-of-plane capacity. A stability factor is introduced for calculating the axial force, while plastic adaption coefficient and elastic buckling stress are used for calculating the bending moment.For axial compression columns:

$$\sigma = \frac{N}{\bar{\varphi}A} \leqslant f_{0.2} \tag{1}$$

For eccentric compression columns:

$$\text{For in-plane capacity}: \frac{N}{\bar{\varphi}_x A} + \frac{\beta_{mx} M_x}{\gamma_x W_{lex}(1 - \eta_1 N/N'_{ex})} \leqslant f_{0.2} \tag{2a}$$

$$\text{For out-of-plane capacity}: \frac{N}{\bar{\varphi}_y A} + \eta \frac{M_x}{\varphi_b W_{lex}} \leqslant f_{0.2} \tag{2b}$$

where $N'_{ex} = \frac{\pi^2 EA}{1.2\lambda_x^2}$, $\bar{\varphi} = \eta_e \eta_{haz} \varphi$, $\varphi = \frac{1}{2\bar{\lambda}^2}\left[(\bar{\lambda}^2+1+\eta) - \sqrt{(\bar{\lambda}^2+1+\eta)^2 - 4\bar{\lambda}^2}\right]$.

where $f_{0.2}$ is the nominal yield strength (0.2% proof stress), N is the bearing capacity of the loaded columns, β_{mx} is the equivalent moment coefficient, M_x is the bending moment of the loaded columns, A is the cross-sectional area, $\bar{\varphi}_x$ and $\bar{\varphi}_y$ are the stability factors for axially loaded columns in-plane and out-of-plane, γ_x is the plastic adaption coefficient of the cross section, W_{lex} is the effective modulus of the section, η_1 is a correction factor for the alloy types, and $\eta_1 = 0.75$ for the 6061-T6 and 6082-T6 aluminum alloy, N'_{ex} is the elastic buckling stress, φ_b is the stability factor for bending columns, E is the elasticity modulus, λ_x is the slenderness ratio in-plane, η_e is the correction factor for the effective section, η_{haz} is the welding influence coefficient, φ is the stability calculation coefficient, η is the defect coefficient for geometric dimensioning, and $\bar{\lambda}$ is the regularized slenderness ratio.

2.2. ADM-2005

The American code (ADM-2005) uses two types of design method, allowable stress design (ASD) and building load and resistance factor design (LRFD), to calculate the bearing capacity. ASD and LRFD use the same design for all bearing capacity formulae and the most important difference between them is the source of their resistance partial coefficient. For ASD, a safety factor n is adopted to ensure the reliability of the designed structures and columns, while the resistance factor ϕ is used instead of n in LRFD. n is given based on long-term design experience, while ϕ is determined by the probabilistic and statistical analysis to guarantee the safety and economy of the structure design. For the local buckling problem, the ultimate stress of local plates with various width-thickness ratios, and whole columns with various slenderness ratios, are both calculated, and the smaller stress is selected as the final ultimate stress for the aluminum alloy member. The design formulae of the ultimate stress for the whole columns are shown in Eqs. (3) and (4).For axial compression columns:

$$\phi F_L = \begin{cases} \phi_{cc} F_{cy}, & \text{if } \lambda \leqslant S_1^* \\ \phi_{cc}(B_c - D_c^* \lambda) & \text{if } S_1^* < \lambda \leqslant S_2^* \\ \phi_{cc} F_{cy}/\lambda^2 & \text{if } \lambda > S_2^* \end{cases} \tag{3}$$

For eccentric compression columns:

$$\frac{f_a}{F_a} + \frac{C_{mx} f_{bx}}{F_{bx}(1 - f_a/F_{ex})} + \frac{C_{my} f_{by}}{F_{by}(1 - f_a/F_{ey})} \leqslant 1.0 \tag{4a}$$

and if $f_a/F_a \leqslant 0.15$, the following Eqs. (4b) can be used to replace Eq. (4a):

Table 1
Limiting values of width-thickness ratio for GB 50429-2007.

Hardening degree	Stiffened plate		Unstiffened plate	
	Without welds	With welds	Without welds	With welds
Weak hardening	$21.5\varepsilon\sqrt{\eta k'}$	$17\varepsilon\sqrt{\eta k'}$	$6\varepsilon\sqrt{\eta k'}$	$5\varepsilon\sqrt{\eta k'}$
Strong hardening	$17\varepsilon\sqrt{\eta k'}$	$15\varepsilon\sqrt{\eta k'}$	$5\varepsilon\sqrt{\eta k'}$	$4\varepsilon\sqrt{\eta k'}$

Note: $\varepsilon = \sqrt{240/f_{0.2}}$; η is the correction coefficient of stiffener; k' is the local stability factor for the plates.