Journal of Constructional Steel Research 133 (2017) 282–299

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

Experimental investigation and numerical simulation of pallet-rack stub columns under compression load

Peng Zhang, M. Shahria Alam *

School of Engineering, The University of British Columbia, Kelowna, BC V1V 1V7, Canada

ARTICLE INFO

Article history:
Received 26 May 2016
Received in revised form 16 February 2017
Accepted 17 February 2017
Available online xxxx

Keywords:
Pallet-rack stub column
Initial geometric imperfection
Compression capacity
Stiffness
Stress-strain curve
Finite element analysis

ABSTRACT

North American standard requires physical tests to determine the capacity of a pallet-rack stub column. While predicting the column capacity and stiffness, finite element method based numerical simulation may not be considered reliable due to the existence of Initial Geometrical Imperfection (IGI). In this study, an expanded Ramberg-Osgood model is proposed to describe the stress-strain behavior of steel sheet material that exhibits a discontinuous yielding (i.e. relatively long yield plateau). The model was successfully employed in the simulations of the pallet-rack stub column. In order to reduce the prediction error caused by the IGI, an improved numerical simulation strategy was proposed. The strategy was validated by experimental tests, and it was compared with two classical strategies in terms of their prediction accuracy for the column's compression capacity and stiffness. Nonlinear analyses were performed by using a finite element analysis software, ANSYS, and the results show that the improved strategy is more unbiased and accurate.

1. Introduction

Pallet-rack columns are generally made of thin-walled steel sheets, and they usually have perforations uniformly distributed along their lengths. The columns are widely used for storage purposes as they have high capacity/weight ratios and good salvage values. A pallet-racking system is shown in Fig. 1. This pallet-racking is protected by a peripheral structure from the snow and wind loads. It may extend into a Rack Clad Building (RCB) when it is independently built with side cladding and roofing. An RCB under construction is shown in Fig. 2.

During the fabrication (coiling or cold-forming), shipping, and storage, pallet-rack columns are subjected to Initial Geometrical Imperfection (IGI) [2]. The IGI is defined as the deviation of an element profile from the designed or nominal geometry [3]. It can be classified into a Cross-Sectional Imperfection (CSI) and Global Imperfection (GI). The CSI includes dimensional differences, plate dents, concave plates, and undulations, and it can be further subcategorized into a local and distortional imperfection. The GI refers to a cross-section twisting, a global bending, or a combination of torsion and bending [2,3]. Mode and magnitude are the two terms used to describe the IGI.

Pallet-rack stub column is a column with a length not less than three times of the maximum value between the greatest cross-section width and perforation pitch, and <20 times of the minimum radius of gyration. The first condition has a priority when the two conditions are in conflict [4]. Buckling is a common failure mode when pallet-rack columns are subjected to compression loads, and the stub columns suffer from local buckling. The IGI plays an important role in the column's buckling behavior. Yu and LaBoube [5] pointed out that the IGI may affect the column's buckling, especially when the IGI mode is periodic and has a half-wavelength close to the column's buckling half-wavelength. Freitas et al. [6] reported that the IGI will decrease the resistance of pallet-rack column. Influences of the IGI on the failure mode of pallet-rack stub column were observed by Roure et al. [7]. Pastor et al. [8] emphasized that the resistance and post-buckling behavior of the pallet-rack column are sensitive to imperfection.

Determining a pallet-rack Stub Column's Ultimate Capacity (SCUC) under uniaxial compression load is the primary work before it is designed into a flexural or concentrically loaded member [9]. Currently, experimental tests are required by the design standard [9]. Since the

---

Abbreviations: A_e, column effective area obtained from testing; A_{es}, column effective area obtained from numerical simulation; A_g, gross area; A_n, net area; D_{max}, maximum displacement load; D, distortional mode; E, Young's modulus; F_u, material engineering tensile strength; f_y, true yield strength; f_{ey}, engineering yield strength; ISD, inward symmetric distortional mode; K_{ae}, axial compression stiffness obtained from testing; K_{as}, axial compression stiffness obtained from numerical simulation; K_{ag}, axial compression stiffness of non-perforated column; L, local mode; LD, local and distortional mode; LYS, engineering lower yield strength; M, initial geometric imperfection magnitude; OSD, outward symmetric distortional mode; P_u, column ultimate compression capacity obtained from testing; P_{us}, column ultimate compression capacity obtained from numerical simulation; P_{ug}, ultimate compression capacity of non-perforated column; SL, symmetric local mode; SLD, symmetric local and distortional mode; t, thickness; U_Z, out-of-plane displacement; UYS, engineering upper yield strength; σ, true stress; σ_e, proportional limit; σ_{eng}, engineering stress; σ_p, stress at ε_p; ε, true strain; ε_{eng}, engineering strain; ε_p, strain at the intersection of yielding platform and initial strain hardening portion; ε_y, true strain at f_y; ε_{F_u}, engineering strain at F_u; ε_f, engineering fractural strain.

* Corresponding author.
E-mail addresses: p.zhang@alumni.ubc.ca (P. Zhang), shahria.alam@ubc.ca (M.S. Alam).

http://dx.doi.org/10.1016/j.jcsr.2017.02.023

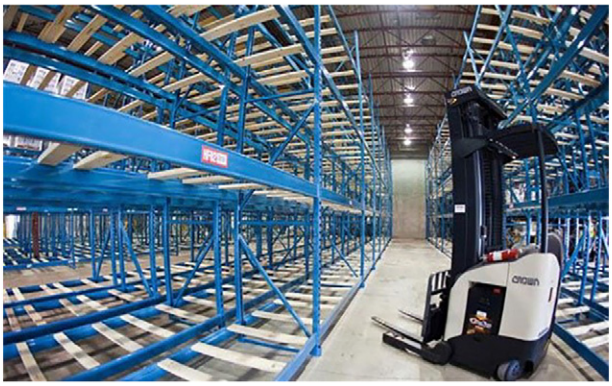


Fig. 1. Pallet-racking.

Fig. 2. An RCB under construction [1].

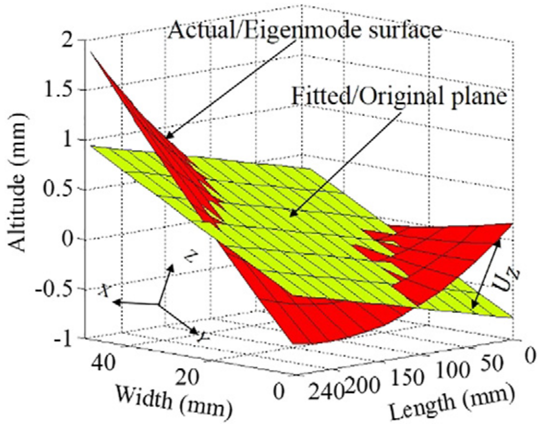


Fig. 3. Out-of-plane displacement U_Z.

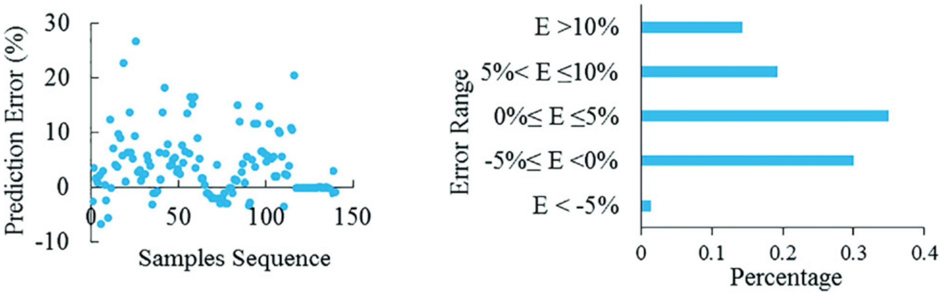
tests are costly, extensive researches have been devoted to the prediction of the SCUC through analytical solutions, but none of them can replace the experimental tests for two reasons [10–12]. The first reason is due to less available computational methods, e.g., the Generalized Beam Theory (GBT) and finite strip method cannot handle the elements with perforations. The second reason is because the IGI mode can hardly be restored in a numerical simulation; however, proper treatment of the IGI is a key point for an accurate numerical simulation. In this study, the past numerical simulation strategies concerning the IGI in the prediction of the pallet-rack stub column were reviewed, and they were divided into classical and non-classical strategies.

1.1. Classical strategy

The classical strategies are based on the eigenmode mapping technique. The technique is to define an element's eigenmode as it's initial state in a linear or nonlinear analysis. The classical strategies consist of Classical Strategy 1 (CS1) and Classical Strategy 2 (CS2). Since an element's eigenmodes can be numerous, to be on the conservative side, the most unfavorable eigenmode is pursued by the two strategies. The most unfavorable eigenmode is the eigenmode that provides the lowest SCUC. The CS2 selects the most unfavorable eigenmode from a series of eigenmodes, but the CS1 assumes that the first eigenmode is the most unfavorable one. Both strategies were successfully used by Bonada et al. [13] on the predictions of the pallet-rack columns with lengths prone to distortional buckling. The schemes of the CS1 and CS2 are presented in Appendices A and B.

The accuracy for the CS1 and CS2 depends on the determination of IGI Magnitude (M). In this study, M is defined as the maximum distance (U_Z) between the actual/eigenmode surface and the fitted/original plane, as illustrated in Fig. 3. The M can be determined by measurements or a researcher's experience. Most scientists preferred the CS1 [7,14–17] due to its convenience. When the experimental tests are available, the magnitude sensitivity analysis can be performed to seek a best-fit magnitude. The common IGI magnitudes suitable for the analysis were collected by Pastor et al. [18]. There is no evidence that the first eigenmode can always provide the lowest SCUCs. Hence, this assumption in CS1 imposes challenges.

For the CS1, 140 simulation cases were collected from literature and their prediction errors for the column capacity are shown in Fig. 4 [7,14,15,17,19]. It was found that almost 35% of the cases have an error larger than 5%, 14% of them have an error beyond 10%, and the maximum error is around 27%. The statistics reveal that the CS1 is not reliable because most of the IGI magnitudes were empirically determined, and that these magnitudes lack of a general applicability. On the other hand, higher eigenmodes should be investigated to consider the effects of the IGI mode uncertainty [16]. There is a lack of literature for the use of CS2 on the pallet-rack stub column's capacity prediction (as per author's recent research). In this study, the performance of the CS2 was studied, and the CS1 was applied for comparisons.



(a) Prediction errors (b) Statistics of prediction errors

Fig. 4. Simulation cases of the CS1.