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Finite strip elastic buckling solutions for thin-walled metal columns with perforation patterns

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ABSTRACT

Approximate finite strip eigen-buckling solutions are introduced for local, distortional, flexural, and flexural-torsional elastic buckling of a thin-walled metal column with perforation patterns. These methods are developed to support a calculation-based strength prediction approach for steel pallet rack columns employing the American Iron and Steel Institute's Direct Strength Method, however they are generally posed and could also be useful in structural studies of thin-walled thermal or acoustical members made of steel, aluminum, or other metals. The critical elastic global buckling load including perforations is calculated by reducing the finite strip buckling load of the cross-section without perforations using the weighted average of the net and gross cross-sectional moment of inertia along the length of the member for flexural (Euler) buckling, and for flexural-torsional buckling, using the weighted average of both the torsional warping and St. Venant torsional constants. For local buckling, a Rayleigh–Ritz energy solution leads to a reduced thickness stiffened element equation that simulates the influence of decreased longitudinal and transverse plate bending stiffness caused by perforation patterns. The cross-section with these reduced thicknesses is input into a finite strip analysis program to calculate the critical elastic local buckling load. Local buckling at a perforation is also treated with a net section finite strip analysis. For distortional buckling, a reduced thickness equation is derived for the web of an open cross-section to simulate the reduction in its transverse bending stiffness caused by perforation patterns. The approximate elastic buckling methods are validated with a database of 1282 thin shell finite element eigen-buckling models considering five common pallet rack cross-sections featuring web perforations that include 36 perforation dimension combinations and twelve perforation spacing combinations.

1. Introduction

Vertical steel pallet rack columns have perforation patterns punched continuously along their length to accommodate horizontal storage rack shelving (Fig. 1) and these perforations decrease a rack column's axial capacity. In the U.S., the Rack Manufacturer's Institute (RMI) predicts the strength decrease with the Q factor method [1], an empirical approach where stub column tests quantify decreased local buckling capacity from the perforations. The European Committee for Standardization (CEN) implements a similar test method to derive an effective cross-sectional area [2]. Both approaches treat local buckling, however they do not provide specific methods for addressing perforation patterns and their influence on distortional and global buckling limit states. A calculation-based method that considers all buckling limit states would improve the structural reliability of rack columns and reduce or eliminate the need for testing when new storage rack systems are introduced.

Efforts to improve rack column strength prediction are ongoing [4] with a focus on the American Iron and Steel Institute's (AISI) Direct Strength Method (DSM) [5,6]. Nominal column strength with the DSM is calculated as the minimum of local, distortional, and global buckling strength, i.e., $P_n = \min(P_{n\ell}, P_{nd}, P_{ne})$. Limit state strengths are obtained from design equations that accept cross-section and global slenderness parameters as inputs, i.e., $\lambda_c = (P_y/P_{cre})^{0.5}$, $\lambda_\ell = (P_{ne}/P_{cr\ell})^{0.5}$, and $\lambda_d = (P_y/P_{crd})^{0.5}$, where the column squash load $P_y = A_g F_y$, A_g is the gross column cross-sectional area, F_y is the steel yield stress, and the local distortional, and global critical elastic buckling loads are $P_{cr\ell}$, P_{crd}, and P_{cre} respectively. Elastic buckling loads are obtained from a signature curve generated with

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Fig. 1. Storage rack (a) assembly; (b) perforated rack column with shelf connection [3].

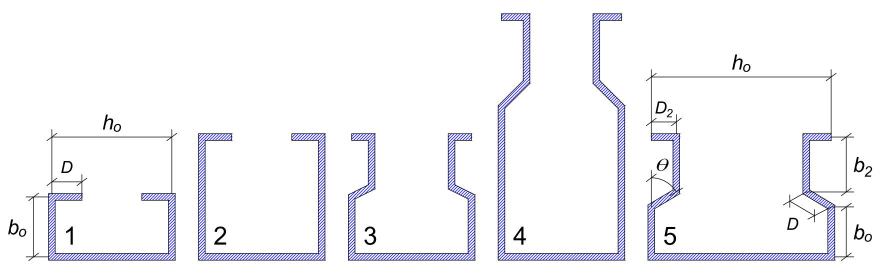

Fig. 2. Centerline cross-section dimension nomenclature.

finite strip eigen-buckling analysis or generalized beam theory software, e.g., CUFSM [7], CFS [8], THIN-WALL [9], or GBTUL [10].

Precedent for using the DSM to predict capacity of thin-walled members with perforations was established recently by a multi-year study [11] that demonstrated the DSM's viability both experimentally [12,13] and computationally [12] for cold-formed steel wall studs and floor joists with evenly spaced discrete perforations. The method is implemented in AISI S100-12 North American Specification for the Design of Cold-Formed Steel Structural Members, Appendix 1 [14]. Nominal column strengths are obtained using the same DSM equations for columns without perforations, however, P_{cre}, $P_{cr\ell}$, and P_{crd} are calculated including perforations with finite strip analysis and modifications to classical plate and member stability equations [15,16]. Inelastic buckling at a net section is treated with an equation transition to the net section capacity, P_{ynet}. It is hypothesized that this overall approach is applicable to any thin-walled metal column with perforation patterns if the critical elastic local, distortional, and global buckling loads are calculated considering the specific perforation layout.

In this manuscript, approximate finite strip methods are summarized and validated for cross-sectional and global elastic buckling loads of thin-walled columns with web perforation patterns. A thin-shell finite element eigen-buckling database constructed with over 1200 models shows how perforation quantity, spacing, and size affect buckling loads and mode shapes. Then finite strip eigen-buckling analysis methods are introduced for calculating $P_{cr\ell}$, P_{crd}, and P_{cre} considering perforation patterns. These methods were previously compared to the work of Casafont et al. [4,17]. Although the research motivation is cold-formed steel racks with web perforation patterns, mechanics underlying the methods are general, making them applicable to perforated hot-rolled steel rack columns, rack columns with flange perforation patterns, slit steel thermal studs [18], acoustic cold-formed steel decks [19], and even marine engineering applications such as ship decks [20].

2. Finite element parameter studies – thin-walled columns with perforation patterns

2.1. Elastic buckling database development

Finite element eigen-buckling analyses were conducted using the commercial software ABAQUS [21] to examine perforation pattern effects on elastic local, distortional, and global buckling loads and mode shapes, and to develop a database used later in the manuscript when validating the finite strip methods. The database includes cross-section types, thicknesses, perforation patterns, and unbraced column lengths common to cold-formed steel storage racks.

Five cross-section shapes were considered in this study (Fig. 2 and Table 1) with base metal thicknesses of 1.8 mm, 2.0 mm, and 2.5 mm. The shapes are consistent with other rack member studies [4,22]. Perforation dimension nomenclature is introduced in Fig. 3, and dimension ranges are provided in Tables 2 and 3. Two column lengths are evaluated, $2.5L_{crd,nh}$ and $4L_{crd,nh}$, where $L_{crd,nh}$ is the distortional buckling half-wavelength for an unperforated member calculated with CUFSM.