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Shape optimization of cold-formed steel columns with fabrication and geometric end-use constraints

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ABSTRACT

The objective of this paper is to present constrained optimization results for a cold-formed steel (CFS) cross-section shape with maximum axial capacity. In the authors' previous work unconstrained shape optimization was performed via stochastic search and gradient-based algorithms. Unconstrained shape optimizations produced a significant capacity increase, more than 140%, above standard CFS cross-sections, but many of the solutions are highly unconventional and have potential limitations both with respect to end use (e.g. attaching boards for walls and floors) and cost of manufacturing. Column capacity is determined using the Direct Strength Method (DSM) which requires inputs for the local, distortional and global critical buckling loads. These critical loads are obtained using the finite strip method, as implemented in the open source software CUFSM, which allows essentially any potential cross-section to be evaluated. To advance the applicability of the optimized results, end-use constraints and manufacturing constraints on the number of rollers employed in forming were both successfully incorporated in the shape optimization presented in this paper, resulting in optimized cross-sections that are more practical and economical with only marginally decreased capacity (usually less than 10%) from the earlier unconstrained optimized solutions. The constraints are implemented within a simulated annealing (SA) algorithm for the optimization. Optimized sections from multiple runs show uniformity, partially indicating the robustness of the final optimized shapes. The implemented constrained shape optimization provides a thorough search with high computational efficiency. The optimized cross-sections from this research provide promising potential shapes for the development of new commercial product families, and the member-level optimization methodology can also be integrated into building optimization in the future.

1. Introduction

Cold-formed steel (CFS) is widely used in many countries as both structural and non-structural members due to its high strength-to-weight ratio and low cost of material and manufacture [1]. Member cross-sections are created by bending steel sheets with roll-forming machines. Typical section depth ranges from approximately 75 to 300 mm (3–12 in.) and typical thicknesses ranges from 0.478 to 0.792 mm (0.0188–0.0312 in.) for non-structural members and from 0.879 to 3.154 mm (0.0346–0.1242 in.) for structural members [2]. By adjusting the number and location of rollers, it is possible to form almost any open cross-section. The recent push for lighter and greener buildings has spurred interest in identifying more efficient CFS cross-sections [3]. Although C- and Z-sections are typically employed in North American commercial practice (e.g. AISI Cold-Formed Steel Design Manual [4]) several new cross-sections have emerged in various stages of product development [1]. Here we look to identify new CFS cross-sections using shape optimization.

With low thickness and high slenderness, CFS members are subject to buckling failure, including local plate buckling, distortional buckling, and global (Euler) buckling [5]. In CFS column design optimization, an important objective is to maximize the axial capacity for a given length, coil width (i.e., cross-section perimeter), and sheet thickness. This design problem has been solved in past research using gradient-based optimizers, stochastic search optimizers, and combinations of these two. Gradient-based search algorithms, such as the steepest descent and trust-region methods, use exact or approximate estimations of first and/or second-order derivatives of the objective function with respect to the design variables [6]. These are not typically available analytically and thus must be estimated numerically, such as with finite differences, making the approach computationally costly. The advantage, however, is that the algorithm moves in a descent

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direction and convergence to a local minimum is guaranteed. Stochastic search algorithms, like simulated annealing (SA) and genetic algorithms (GA), do not require gradient information, and instead utilize random perturbations to carry out a wide search of the design space [7]. This provides a mechanism for the algorithm to avoid local minima; however, there is no guarantee that an optimum point is found, and thus the algorithm must be run multiple times to ensure robustness in the arrived solution.

The method used for determining nominal axial capacity, P_n, from design specifications may also have a significant impact on the formulation of the optimization problem. The design procedure utilizing the classical effective width method [8] requires reducing a plate under nonlinear longitudinal stress into a plate with effective width under constant stress, which is difficult or impossible to be implemented for complicated cross-sections. The Direct Strength Method (DSM, see Appendix 1 of [8]) only requires the user to provide the critical load in local (P_{crl}), distortional (P_{crd}), and global buckling (P_{cre}), and the load at yield (P_y). This can be coded in a general form amenable to simulation-based optimization. In this work, the authors use the open source finite strip method software CUFSM [9,10] to determine P_{crl}, P_{crd}, and P_{cre}.

Previous researchers on CFS member optimization have applied different combinations of strength evaluation criterion from design codes and optimization algorithms. The classic paper by Seaburg and Salmon [11] employs a gradient-based steepest descent method to explore the dimensions of hat sections using the effective width method of the AISI Specification [12]. Tran and Li [13] solved the optimization problem of a lipped channel beam using a trust-region method based on various failure modes from the British code BS 5950-5 [14] and Eurocode [15]. Tian and Lu [16] utilized sequential quadratic programming in cross-section dimension optimization of channel columns with and without lips according to BS 5950-5 [14]. As for heuristic methods, Adeli et al. published a series of papers on the development of a computational neural network model [17] and its application to the optimization of CFS beams with hat, I and Z sections [18] according to AISI ASD [19] and LRFD specifications [20], and space trusses with lipped channel sections [21] following the AISI ASD specification [19,22]. Lu [23] combined CUFSM with GA to optimize Z-section dimensions under the effective width design of EuroCode-3 [15]. Lee et al. [24,25] used genetic algorithms to search for optimized channel cross-section dimensions of cold-formed steel columns under axial compression and beams under uniformly distributed loads. Recently, Chamberlain Pravia and Kripka and Kripka and Martin [26,27] used SA to optimize the dimension of a C-section column following the effective width method in the AISI 2007 [28] specification. All of these works perform dimension optimization (i.e. adjusting sizes of depth, thickness, lip width etc.) of a predetermined cross-section and include the requirement on member capacity in constraints. Nearly all minimize the weight, with the exception of Lu [23] who maximizes load efficiency.

The first traceable effort of maximizing a CFS member's capacity by changing its shape appears to be Liu et al. [29]. They exploited Bayesian classification trees in CFS column optimization by maximizing P_n with the help of DSM and CUFSM. Kolcu et al. [30] considered Mindlin–Reissner finite strips and used sequential quadratic programming to maximize the critical load P_{cr}. The authors' previous publication [31] demonstrated that several novel, high strength cross-sections can be identified using stochastic search optimizers SA or GA for general search, which can be further improved by combining with a steepest descent method for refining the results locally. Gilbert et al. [32] proposed 'self-shape optimization' based on floating-point type GA and applied the algorithm in CFS columns [33] with CUFSM for buckling analysis. Similar to our previous work, Moharrami et al. [34] and Gargari et al. [35] used GA in their study, but considered boundary conditions other than simply–simply supports. Franco et al. [36] coded shape grammar to generate cross-sections, evaluated designs as columns and beams with DSM and CUFSM, and used genetic algorithms as the optimizer. Some manufacturing constraints are also coded into the shape grammar generator. The optimized cross-sections identified in Ref. [31] offer estimated strength increases over traditional C channels of 141% and 209% for short (4 ft) and long (16 ft) columns, respectively. They are also similar in shape to those reported in [32–35], further supporting that these cross-section designs offer maximized nominal strength P_n. Due to the lack of absolute benchmark problems, the authors used same steel sheet dimensions and material properties with Liu et al. [29] for better comparison.

While our previous results [31] suggest significant enhancements in strength can be achieved, the resulting shapes could be considered complex, and thus difficult or costly to manufacture and use in practice. This complexity was ultimately because the shape optimization problem was essentially unconstrained. It was formulated to maximize axial capacity P_n of a steel sheet of fixed thickness and width, the latter achieved by simply discretizing the cross-section by a fixed number of equal width finite strips. The only optimization constraint was to prevent overlap of finite strips, which is physically impossible, but the shape design space was otherwise unconstrained.

The goal of this work is to constrain the design space such that optimized cross-sections are more readily fabricated and useful in practice. This is addressed firstly by developing geometric constraints based on practical end-use limits [37]. These constraints are then related to the turn-angles of the finite strips to enable optimization. Fabrication cost is then considered by constraining the number of rollers from manufacturability (i.e. locations where the section may be folded) and reformulating the design variables to allow for variable finite strip widths [38].

These new formulations are solved using a SA algorithm previously developed in Ref. [31]. The resulting optimized cross-sections include singly symmetric 'Σ' like sections for short (0.61 m, (2 ft)) and intermediate length (1.22 m, (4 ft)) columns and point symmetric squashed 'S' like sections for long (4.88 m, (16 ft)) columns. These optimized shapes offer 50% to over 200% improvement in P_n over reference lipped C-sections, indicating that significant enhancements can be obtained through cross-section optimization without loss of manufacturability or geometric end-use requirements. The generalized optimization framework of constrained optimization of CFS columns in this paper can be integrated into system optimization of cold-formed steel buildings.

2. General formulation of constrained optimization problem

The design objective of this research is to maximize the capacity of a steel column, cold-formed from a fixed width coil of sheet steel, under uniform compression, subject to a series of geometric end-use and manufacturing constraints. The design variables, strength calculation, and optimization algorithm are described in this section, and the discussion of new constraints is left to Section 3.

2.1. Cross-section design descriptors

The steel sheet forming the cross-section is discretized into finite strips and locations where two adjacent strips meet (nodes) indicate possible locations of rollers that are used to create folds. The orientation and width of these strips define the cross-section design.