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COMPUTATIONAL MODELING OF COLD-FORMED STEEL

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ABSTRACT

The objective of this paper is to summarize recent research and experiences with computational modeling of cold-formed steel conducted within the author's research group at Johns Hopkins University. This admittedly biased view of computational modeling focuses primarily on the use of the semi-analytical finite strip method and collapse modeling using shell finite elements. Issues addressed include how to fully compare finite strip and finite element solutions, and the importance of imperfections, residual stresses, boundary conditions, element choice, element discretization, and solution controls in collapse modeling of cold-formed steel. The paper concludes with a discussion of areas worthy of future study that are within the domain of cold-formed steel modeling.

1 INTRODUCTION

Modeling cold-formed steel, particularly through collapse, presents a strongly nonlinear problem with both material and geometric nonlinearity. However, meaningful modeling requires more than a good nonlinear solution scheme and a robust element. Successful modeling requires in-depth understanding of the model inputs and their sensitivities, as well the limitations and strengths of the modeling tools themselves. This paper presents a brief introduction to the tools and current issues surrounding computational modeling in cold-formed steel, an introduction which is strongly biased by the research experiences within the author's research group. Thus, this paper does not attempt to provide a comprehensive survey of the computational modeling literature – my apologies to the many excellent researchers who contribute to this area and do not find themselves mentioned herein.

2 ELASTIC BUCKLING ANALYSIS

2.1 Tools

Computational modeling of the elastic buckling of cold-formed steel members is an important step in understanding the behavior (and even designing) cold-formed steel members. Three tools are in regular use in the author's research group for elastic buckling analysis: CUTWP [1], CUFSM [2], and ABAQUS [3]. The former two are freely available, open source programs distributed by the author, while the latter is a well known general purpose commercial finite element package. CUTWP provides global member stability solutions using expressions based on classical beam theory and Vlasov warping torsion [4]. CUTWP sees regular use in our efforts because it: (i) uses the same mechanics employed in codes and standards; (ii) readily allows for different global effective length factors (K_xL_x, K_yL_y, K_tL_t); and (iii) has been modified to read CUFSM input files. CUFSM, which provides an implementation of the semi-analytical finite strip method (FSM), appropriate for cold-formed steel members with (locally) pinned boundary conditions (see [5] for another example), is the workhorse of the authors research group. Basic understanding begins with interpretation of the CUFSM buckling analysis of a given member. ABAQUS, is a well known general purpose finite element method (FEM) package; for the purposes of this paper only models built from shell elements are considered for discussion.

2.2 CUFSM extensions

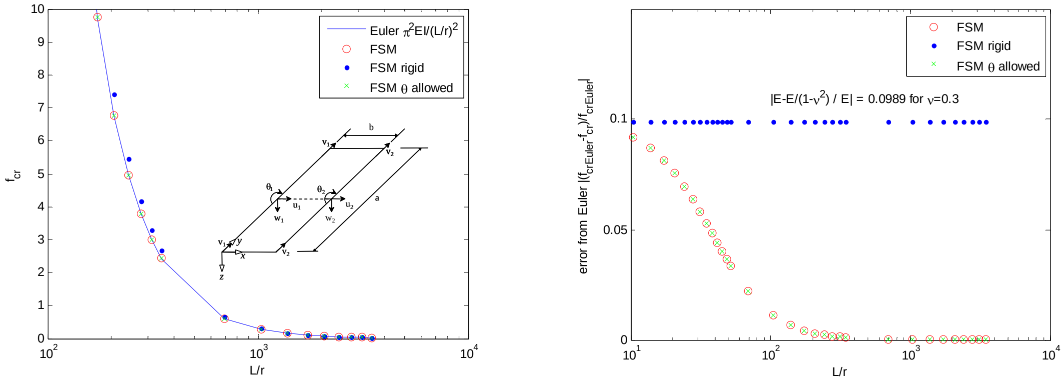
An important advance in computational modeling of cold-formed steel are the modal-based methods such as Generalized Beam Theory [6, 7] and the constrained Finite Strip Method [8]. These methods allow for discrete separation of local, distortional, and global deformations, at least for sharp corner models of cold-formed steel sections (see [9] for comparisons). The constrained Finite Strip Method (cFSM) has been fully implemented within CUFSM [2] and provides a unique means to explore decomposition and identification (including coupled instabilities) in the stability solutions of cold-formed steel members.

An additional extension to CUFSM which is currently underway is the expansion to other boundary conditions, most notably, fix-fix, following the approximate longitudinal shape functions of [10]. Expansion of the constrained Finite Strip Method to other boundary conditions, as well as to general purpose identification in shell finite element models [11] is planned or already underway. Less theoretical, but important from a practical standpoint, computational modeling in the author's research group is greatly aided by a number of practical in-house tools which extend CUFSM's capabilities, including: (i) automatic comparison of classical global buckling solutions to FSM, (ii) automatic conversion of FSM cross-sections to shell element meshes appropriate for ABAQUS, including the potential to include holes along the length, and (iii) automatic conversion of FSM buckling modes for the use as imperfection shapes in ABAQUS models. These tools greatly aid the computational modeling efforts of the group.

2.3 Global buckling and beam vs. plate theory

It is well known that the finite element method, finite strip method, and classical beam theory provide similar buckling loads for global stability problems. Perhaps less well known is how these solutions are provided mechanically. Consider a single finite strip in compression, undergoing flexural "Euler" buckling (Figure 1). Now consider three FSM models: (i) "FSM" with no modifications, (ii) "FSM rigid" where the cross-section has been forced to be rigid, i.e. w is allowed, but not u, v, θ, and (iii) "FSM θ allowed" where transverse bending (through θ) has been allowed, but in-plane u, v are still restricted. Casual examination of the buckling load (Figure 1a) appears to indicate that all solutions converge to the Euler solution, but closer inspection (Figure 1b) shows that the solution where the cross-section is rigid maintains a 10% error from the Euler solution for all lengths.

Shell finite elements, and finite strip methods built up from plate theory converge to beam theory global buckling loads, but require the presence of transverse bending. The θ associated with such bending is small, but non-negligible. Thus, the commonly held notion that global stability may be understood as rigid cross-section deformations is practically useful, but mechanically inaccurate. In fact, the error is exactly equal to E-E/(1-ν^2), the fundamental rigidity difference between beam and plate theory. At least for the author, this finding was first observed during the course of the development of cFSM and is discussed further in [12].

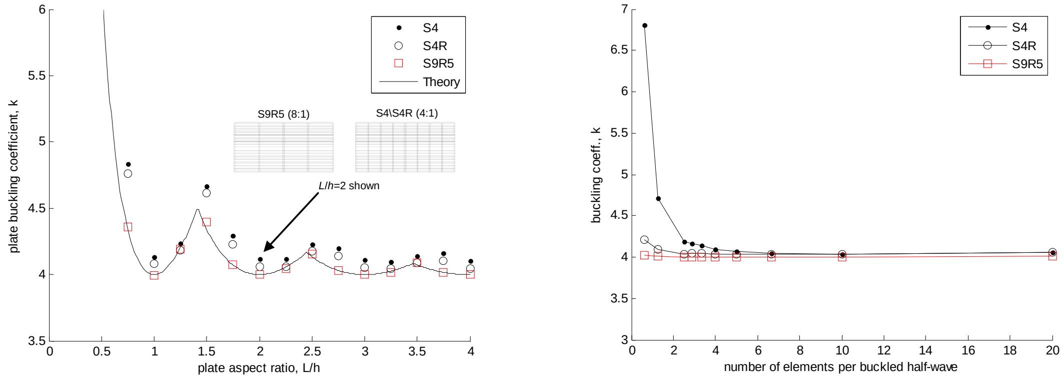


(a) stability solution (b) error

Figure 1: Global stability comparison for Euler buckling and a single finite strip

2.4 Local buckling and FEM sensitivity

The vast majority of finite element modeling performed in the author's research group is completed with an element that uses quadratic shape functions (the S9R5 in ABAQUS), as opposed to elements with linear shape functions (such as the S4R or S4 in ABAQUS). Use of shell elements with linear shape functions are far more typical in the literature, and the graphical user interface for ABAQUS does not easily support the element preferred by the author. So, why bother with the added complications? The origins of this decision may be found in [13], but recent studies continue to support this decision.



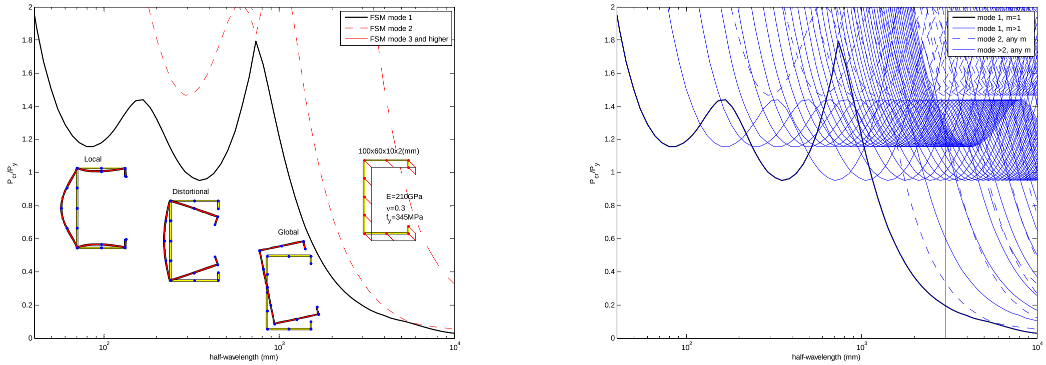
(a) varying physical plate length (b) varying number of elements along the length

Figure 2: Sensitivity of ABAQUS elements for local buckling of a simply supported plate in compression

For example, Figure 2 (see [14]) provides local buckling results for a simply supported plate in pure compression using different elements. The quadratic element, S9R5, provides solutions in excellent agreement with (Kirchoff) thin plate theory (Figure 2a) and is robust, allowing as little as one element per buckling half-wave without degrading the solution (Figure 2b). The S4 element locks when fewer than 5 elements are used per buckled half-wave, and while the S4R performs reasonably well, it provides a coarser approximation than the S9R5 even when the effort (number of nodes) is the same.

2.5 Comparing FSM to FEM

Comparisons between FEM and FSM solutions are invariably of interest, especially for the researcher. While the common approach is to physically vary the length in a finite element model (e.g. [13]), in an effort to mimic the finite strip approach, a more robust comparison is possible if the FSM results are understood in their entirety. Consider a typical FSM result, as given in Figure 3a, but now with higher modes added. For example at L=3000 the first global mode is flexural-torsional, the 2nd global mode is flexural. Now consider that in a given physical length L, many multiple (*m*) half-waves can exist. Simple translation of the *m*=1 curve of Figure 3a provides the multiple half-waves solution, inclusion of higher modes and these higher *m* gives a complete FSM result as shown in Figure 3b.



(a) higher modes (b) *m* > 1 half-waves and higher modes

Figure 3: FSM analysis considering higher modes and higher numbers of half-waves

Now, consider a typical FEM analysis completed at L=3000 (the vertical line of Figure 3b). The FEM results are usually provided in increasing eigenevalue order, which is equivalent to finding the intersections with the vertical line in Figure 3b: FEM mode 1 is global flexural-torsional with *m*=1 half-wave, FEM mode 2 is global flexural with *m*=1 half-wave, FEM mode 3 returns to global flexural-torsional, but with *m*=2 half-waves, the next FEM modes are all distortional buckling with *m* between 6 and 9 half-waves, followed by a large group of FEM modes with local buckling, then a group of FEM modes with FSM 2nd mode distortional buckling. This “grouping of modes” is consistent with what one finds in FEM buckling results – and provides a robust way to compare the two methods. If the FEM model has the same boundary conditions as the FSM model agreement is generally excellent; however, some differences will still be observed. In particular, FEM may provide a superposition of results with different *m* half-waves, for example global *m*=1 and local *m*=30 in the same FEM mode. Such a result is impossible in the semi-analytical FSM model [13].

3 COLLAPSE MODELING OF MEMBERS

3.1 Geometric Imperfections

The treatment of geometric imperfections is of significant importance in cold-formed steel members, as ultimate strength and post-buckling mechanisms are both imperfection sensitive. Selection of the magnitude and distribution of imperfections is strongly colored by the needs of the analyst: are imperfections included as a modeling convenience, or a physical reality? If imperfections are a modeling convenience (the most common approach) then the distribution is typically the first buckling mode, sometimes higher modes too, and the magnitude is either a function of the plate thickness (i.e., 0.1*t*) or the plate slenderness [15]. Magnitudes may be "fit" so that predicted strength matches a test (e.g., [16, 17]) or so that instabilities under study are appropriately triggered [18]. The author certainly uses the preceding approach, but prefers that the imperfections distribution, and particularly magnitude, is grounded in measured data.

The goal in modeling imperfections as a physical reality is to accurately assess the imperfection sensitivity to expected magnitudes, rather than perfectly capture the strength from a single test. The statistical summaries of [19] are limited, but provide magnitudes measured from actual cross-sections; values from the 25%, 50% and 75% CDF of type 1 and type 2 imperfections in [19] are in common use in my research group for imperfections associated with local and distortional buckling. A research project is currently underway to collect statistics on global imperfections (bow, camber, twist) in cold-formed steel members. Measurements are being taken at 6 manufacturing plants in the United States, the resulting data will provide important insights on these parameters.

Modeling imperfection distributions as buckling modes is convenient, but not grounded in physical reality. Collapse mechanisms do not typically resemble buckling mode shapes. Dents and other localized imperfections that are common in practice are generally ignored when mode shapes are used for imperfections. It is common for models to predict imperfection sensitivity that is not generally observed in tests; perhaps because of the choice of a buckling mode as an imperfection when the real imperfection does not take this shape. Current research in my group focuses on continuing the imperfection spectrum work in [19] to generate suites of imperfection distributions and magnitudes that are based on observed data, in much the same way earthquake input signals can be generated from a spectra. Complications include evolving from processes, to fields (as the imperfection is spatial), and providing sufficient input data to ground the model in reality.

3.2 Residual Stresses

Residual stresses are discussed in another paper in this conference, [20], so they are not the focus here. However, the modeling guidance provided by the author in [19] suffers from the fact that the recommended through thickness linear residual stress distribution is not consistent with the mechanics involved in the plastic bending of the section. Further, ignoring transverse residual stresses, and all residual strains (as in [19]) is inconsistent when implemented in the 3D yield criterions employed in collapse analysis. The distributions of [20] are recommended; if all residual stresses and strains that initiate from the manufacturing process are included then the notions of residual stresses and cold-work of forming become the same, and the initial conditions of the model more accurately reflect the real member.

3.3 Yield criteria

The von Mises yield criteria with isotropic hardening is rarely questioned when used. Indeed, in conventional models where residual stresses are ignored its use in cold-formed steel is universal. However, if initial stresses and strains are included in the model then even for static loading cases kinematic hardening is a necessity. Further, as blast and seismic loads become of greater interest, the hardening rules require reconsideration. Finally, it is common to use a 0.2% offset to determine the initiation of plasticity, modelers should be aware that results can be sensitive to this assumption, initiation of plasticity has an important influence on the formation of collapse mechanisms.

3.4 Boundary Conditions

Boundary conditions have an inordinate impact on cold-formed steel collapse modeling; with the issue of longitudinal warping restraint at the member ends the most commonly overlooked and important facet. It is worth noting that boundary conditions in cold-formed steel systems are never as clean as in the computational model, and are usually far more complicated than would exist in laboratory testing as well. The most common boundary conditions in use in our research group employ kinematic constraints such that member ends are forced to bend or twist about known points; i.e., typically reflecting idealization of the global behavior of the section. See [21] for further discussion.

3.5 Element selection

Section 2.4 provides an examination of the sensitivity of shell finite elements for elastic buckling, this sensitivity is accentuated in collapse modeling. The use of quadratic elements (e.g., S9R5) instead of linear elements allows much greater flexibility in building the mesh, particularly in models where the corner radius is included. In such models it is difficult not to have elements with large aspect ratios. During collapse it is common to have large strain demands in small regions (e.g., in the lip). The linear strain gradient in a quadratic element is superior to the step changes in strain across meshes of linear elements.

The modeler should also be aware of the influence of the number of integration points through the thickness of the element. The default value in ABAQUS is 5; obviously sufficient in the elastic range, but as yielding occurs, this implies that when the face yields 1/5 of the section through the thickness yielded – as plate bending stiffness is proportional to t^3 a 1/5 reduction results in significant reduction in stiffness. Increased number of integration points can improve the consistency of the model and decrease sensitivity to the initiation of yielding, and is mandatory if the more advanced residual stresses of [20] are included.

3.6 Solution schemes

Space is too limited to provide an extensive discussion of model sensitivity to solution schemes, but displacement control, arc-length (work control), and artifical damping are the available schemes. Displacement control is simplest and preferred when snap-back is not so profound as to cause lack of model convergence. Otherwise, the arc-length methods, such as Riks, are preferred by the author, but their sensitivity can be significant in even common models. The artificial damping models are efficient in providing a solution in the post-collapse regime, whether or not they provide the right solution depends on the nature of the problem.

4 DISCUSSION

In the hope that this paper can be a potential vehicle for discussion and change within our own research community some effort is expended discussing shortcomings, and opportunities in computational modeling of cold-formed steel. Focusing on collapse modeling, shortcomings include: (i) model results which are more sensitive than experimental results - too sensitive to solution controls, too sensitive to imperfection distribution and magnitude, and too sensitive to boundary conditions, (ii) solvers which over-predict the potential for elastic stability when compared with testing, and (iii) significant challenges in the accurate modeling of as-built conditions. The list is longer, but these represent major issues.

Numerous opportunities exits in cold-formed steel modeling, the largest of which is the evolution of research and design from members to systems. This evolution creates challenges for the modeler: most notably, reliable material models for non-metallic materials such as wood, gypsum board, and concrete, and the modeling of connections including bolts, screws, and welds. In many instances the cold-formed steel modeling community is slow to take advantage of advances in related fields. For example, considerable work has been completed on ductile fracture, but this important mode of failure is completely absent from state-of-the-art cold-formed steel modeling. Further, advances in the modeling associated with metal-forming, even though these models imply much with respect to initial imperfections, residual stresses and strains remain unutilized. Advances in implicit and explicit dynamics, multi-physics and/or multi-scale modeling, stochastic finite elements, (to name a few) could all impact aspects of our understanding under a variety of relevant loadings, but remain essentially ignored by our research community.

5 CONCLUSIONS

Computational modeling of cold-formed steel requires sophisticated mechanics to provide accurate solutions. For elastic buckling it is important to understand the capabilities and limitations of the theoretical model employed. Collapse modeling generally requires the use of material and geometric nonlinear finite element analysis. Solution sensitivities abound in these models: solvers, element choice and discretization, boundary conditions, material models, initial imperfections, initial residual stresses and strains all impact the solution. The modeler must take care when considering these issues and presenting their results. Finally, despite the known shortcomings, significant opportunities exist. Computational modeling has a strong role to play in the future of cold-formed steel research and design.

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7 REFERENCES

[1]Sarawit, A., *CUTWP: Cornell University Thin-walled Section Properties*. p. December 2006.

[2]Schafer, B.W. and S. Adany. *Buckling analysis of cold-formed steel members using CUFSM: Conventional and constrained finite strip methods*. in *Eighteenth International Specialty Conference on Cold-Formed Steel Structures*. 2006. Orlando, FL, United States: University of Missouri-Rolla, Rolla, MO, 65409-1060, United States.

[3]Simulia, *ABAQUS*. 2008.

[4]Timoshenko, S., *Theory of elastic stability*. 2d ed. Engineering societies monographs;. 1961, New York: McGraw-Hill. 541 p. illus. 24 cm.

[5]Papangelis, J.P. and G.J. Hancock, *Computer analysis of thin-walled structural members.* Computers and Structures, 1995. **56**(1): p. 157-176.

[6]Silvestre, N. and D. Camotim, *First-order generalised beam theory for arbitrary orthotropic materials.* Thin-Walled Structures, 2002. **40**(9): p. 755-789.

[7]Silvestre, N. and D. Camotim, *Second-order generalised beam theory for arbitrary orthotropic materials.* Thin-Walled Structures, 2002. **40**(9): p. 791-820.

[8]Adany, S. and B.W. Schafer, *A full modal decomposition of thin-walled, single-branched open cross-section members via the constrained finite strip method.* Journal of Constructional Steel Research, 2008. **64**(1): p. 12-29.

[9]Ádány, S., et al., *GBT and cFSM: Two modal approaches to the buckling analysis of unbranched thin-walled members.* International Journal of Advanced Steel Construction, 2008 (Accepted).

[10]Bradford, M.A. and M. Azhari, *Buckling of plates with different end conditions using the finite strip method.* Computers and Structures, 1995. **56**(1): p. 75-83.

[11]Ádány, S., A. Joó, and B.W. Schafer, *Approximate identification of the buckling modes of thin-walled columns by using the modal base functions of the constrained finite strip method*, in *International Colloquium on Stability and Ductility of Steel Structures*, D. Camotim, N. Silvestre, and P.B. Dinis, Editors. 2006: Lisbon, Portugal. p. 197-204.

[12]Ádány, S., *Flexural buckling of thin-walled columns: discussion on the definition and calculation*, in *International Colloquium on Stability and Ductility of Steel Structures*, D. Camotim, N. Silvestre, and P.B. Dinis, Editors. 2006, IST Press: Lisbon, Portugal. p. 249-258.

[13]Schafer, B.W., *Cold-formed steel behavior and design : analytical and numerical modeling of elements and members with longitudinal stiffeners*. 1997, Cornell University. p. xxiv, 454 leaves.

[14]Moen, C.D., Schafer, B.W., *Direct Strength Design for Cold-Formed Steel Members With Perforations, Progress Report No. 1*. 2006, American Iron and Steel Institute.

[15]Dawson, R.G. and A.C. Walker, *Post- buckling of geometrically imperfect plates.* 1972. **98**(ST1): p. 75-94.

[16]Gardner, L. and D.A. Nethercot, *Numerical modeling of stainless steel structural components - A consistent approach.* Journal of Structural Engineering, 2004. **130**(10): p. 1586-1601.

[17]Ashraf, M., L. Gardner, and D.A. Nethercot, *Finite element modelling of structural stainless steel cross-sections.* Thin-Walled Structures, 2007. **44**(10): p. 1048-1062.

[18]Borges Dinis, P., D. Camotim, and N. Silvestre, *FEM-based analysis of the local-plate/distortional mode interaction in cold-formed steel lipped channel columns.* Computers and Structures, 2007. **85**(19-20): p. 1461-1474.

[19]Schafer, B.W. and T. Pekoz, *Computational modeling of cold-formed steel: Characterizing geometric imperfections and residual stresses.* Journal of Constructional Steel Research, 1998. **47**(3): p. 193-210.

[20]Moen, C. and B.W. Schafer, *A general prediction method for residual stresses and strains in cold-formed steel members*, in *Fifth International Conference on Coupled Instabilities in Metal Structures*. 2008: Sydney, Australia.

[21]Dinis, P.B. and D. Camotim. *On the use of shell finite element analysis to assess the local buckling and post-buckling behaviour of cold-formed steel thin-walled members.* in *Third European Conference on Computational Mechanics Solids, Structures and Coupled Problems in Engineering*. 2006. Lisbon, Portugal.