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Stochastically simulated mode interactions of thin-walled cold-formed steel members using modal identification

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ABSTRACT

The purpose of this paper is to investigate the impact of the geometric imperfection on the interaction of buckling modes for thin-walled cold-formed steel members with a quantitative modal identification approach. Previous studies showed that the interaction of buckling modes varies during the loading process and how buckling interacts depends not only on the section itself but also on the geometric imperfections in the member. This interaction could change the failure modes of the member and its strength accordingly. This paper integrates a modal identification approach based on constrained finite strip method to track this interaction out of the shell finite element model for nonlinear collapse analyses. The geometric imperfections are included in the computational shell finite element model using the traditional modal approach with stochastically simulated magnitudes. The simulations are performed on five specially selected cold-formed steel sections that are deemed to be local-dominant, distortional-dominant, local-distortional interacted, P_{cr}-equal interacted, and P_n-equal interacted. The deformations of the analyses are categorized into the fundamental deformation modes commonly available to cold-formed members: local, distortional, and global. Sensitivity of imperfection is studied by tracing the variation of mode interaction, in particular, for the failure mode. Peak load and associated mode participations are investigated. In addition, a statistical study of the impact of imperfections on the potential failure mode at peak is provided. The potential correlation of the member strength with mode participation is explored, which will shed light on the coupled instability of cold-formed steel member, in particular on investigating the impact of mode participations to member strength.

1. Introduction

Due to high cross-sectional slenderness, a variety of buckling behaviors usually governs the strength of thin-walled members. These buckling behaviors, as commonly acknowledged, can be generally categorized as: local (local-plate), distortional, and global (Euler) buckling. The different post-buckling strengths and potential interaction between these buckling modes require the analysis and design with appropriate separation and identification of these buckling modes. In current design specifications, such as AISI-S100 [1], the design procedure requires calculating the design strengths of these three modes separately with consideration of potential interaction (e.g., global-local interaction has been explicitly included in the Direct Strength Method).

Recent advances in computational methods have enabled the analyses on mode separation and identification for member stability, noticeably, Generalized Beam Theory (GBT) [2,3] and the constrained Finite Strip Method (cFSM) [4–10]. Both methods can provide a formal means to separate the buckling modes into the fundamental mode classes such as, global, distortional, local, shear and transverse extension, in particular for elastic buckling analysis. Extension of GBT has enabled mode separation for nonlinear analysis with material plasticity [11,12]. While the extension of cFSM has focused on applying the modal identification concept in cFSM towards the shell finite element method to take advantage of its versatility in computational modeling and analysis [13,14]. This extension provides a means of formal modal identification similar to cFSM (or GBT), which overcomes the barrier of identifying modes requiring a laborious and completely subjective procedure employing visual investigation.

In experimental observations of thin-walled cold-formed steel member [15], the failure mode and final collapse mechanisms have significant contributions from other modes (e.g., distortional). It is well known that the geometric imperfections impact the strengths of thin-walled member greatly and appropriate consideration in computational model is necessary [16–18]. Advanced analysis methods have been proposed [19–22] and much more is still needed in the field of computationally modeling thin-walled members [23]. Previous studies utilizing the modal identification method for shell finite element method [13,14] showed that how buckling modes interact depends not

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only on the section itself but also on the geometric imperfections in the member. This mode interaction could change the failure modes of the member and its strength accordingly.

Hence, in this paper, the impacts of geometric imperfections on the mode interactions and strengths of thin-walled cold-formed steel members (in particular, columns) have been investigated by stochastically simulating the geometric imperfections in shell finite element method. Then the mode interactions are studied through the modal identification of the shell finite element model for nonlinear collapse analyses. The geometric imperfections are included in the computational shell finite element model using the traditional modal approach with stochastically simulated magnitudes. The simulations are performed on five specially selected cold-formed steel sections that are deemed to be local-dominated, distortional-dominated, and local-distortional interacted (three types). Therefore, how modes interact at failure is traced and studied.

2. Modal identification for shell finite element method

The modal identification for shell finite element method is originated from the constrained Finite Strip Method (*c*FSM) by separating the original displacement field into the four categorized and reduced buckling mode classes: G, D, L, and ST (denoting the Global, Distortional, Local, and Shear and Transverse extension modes, respectively). The separation is based on their corresponding mechanical assumptions, as has been typical of the *c*FSM literature [4–6,8–10,24]. Constraint matrices are defined through the application of the mechanical assumptions for each mode class and the full matrices of all modes (R) span the original full deformation space, which represent a transformation of the solution from the original nodal degrees of freedom to a basis where G, D, L, and ST deformations are separated. In fact, columns of R are referred as 'base vectors'. These vectors are the nodal representations of mode deformations. In cFSM, transformations of bases are possible [8,24,25].

Due to the discrepancy of the degree of freedom of displacement vectors between cFSM and shell FEM, appropriate transformation of the base vectors in cFSM to shell FEM's displacement field is necessary and can be fulfilled through an interpretation using the cFSM shape functions (note, since cFSM is based on semi-analytical FSM. The shape functions are those utilized by semi-analytical FSM.) Therefore, the basis R is expanded consistent with the shell FEM displacement field (R_{FE}). See details in [13].

Once the basis is constructed for shell finite element, modal identification can be performed on any general displacement vector from shell finite element analysis through a simple minimization procedure to assign participation coefficients on each base vector. For instance, the nonlinear collapse analysis problem, in an FEM context, can be expressed as:

$$(K_e + K_g + K_p)D = F \tag{1}$$

where, K_e is the conventional elastic stiffness matrix, K_g is the geometric stiffness matrix depending upon the current forces applied on the structure, K_p is the plastic reduction matrix to account for yielding, D is the displacement vector, F is the consistent nodal forces applied on the structure. Note, for the collapse analysis of thin-walled members, the second-order effects and plasticity require an iterative equilibrium path tracing techniques, such as the arc-length method (the modified Riks method [26] in ABAQUS). The minimization is performed on the displacement vector D as a linear least square problem:

$$\min(D - R_{FE}C)^T(D - R_{FE}C) \tag{2}$$

where C is the contribution coefficients (for modes of G, D, L, and ST). Then the summation of the contributions in a particular class (e.g., L) is typical to form the predicted modal participations.

For collapse analysis, the identification procedure can be performed on D to categorize the buckling modes of each step during the collapse analysis by using the generalized base functions. More details about the theoretical background of modal identification for shell finite element method can be found in [13].

3. FEM modeling for nonlinear collapse analysis

To predict the ultimate strength of thin-walled structures using shell finite element modeling and to investigate the collapse behavior, the computational model shall include the necessary material and geometric nonlinearity along with other input parameters that the simulation will be highly sensitive to. These model inputs include geometric imperfections, residual stresses, plastic strain, yield criteria, material model, boundary conditions, and also the fundamental mechanics, particularly with regard to element selection and solution schemes [17,27]. Details about the modeling parameters are following the studies the author has done in [13] and a brief summary is provided herein with expanded details on the geometric imperfection using stochastic simulations. Note, all the analyses performed in this paper utilize the commercial finite element package ABAQUS [26].

- Element: the S4 is a 4-node linear element (fully integrated) from the ABAQUS library of elements
- Mesh: fine mesh and the element aspect ratio is controlled between ½ to 2 to avoid element distortion under large deformations
- Boundary conditions: local-plate simply supported conditions, which imply warping fixity at the member ends
- Loading: the end shortening (loading) is applied at the end to simulate column member
- Material: homogeneous and isotropic and modeled as elastic-perfectly plastic (von Mises yield criteria) with Young's modulus $E = 210{,}000$ MPa, Poisson's ratio $\nu = 0.3$, and a yield stress of 345 MPa
- Solution scheme: the arc-length method (the modified Riks method [26] in ABAQUS)

3.1. Imperfections: stochastic simulation

With the complex instability nature of thin-walled members, geometric imperfections have been shown to have a significant impact on their ultimate strength and post-buckling mechanisms. Careful treatment of geometric imperfection shall specify both the imperfection distribution and magnitude. Generally speaking, there are two kinds of approaches available to simulate the imperfection field in computational modeling. First one, if measured imperfection field is available, is that the computational modeling of thin-walled members can be simulated by closely tying it with measure data. Great advances have been made, in particular for cold-formed steel member, in full field imperfection measurement [28] and simulations [29]. Second one, which is a commonly used approach, is to use a portion of the thickness of the members as the magnitude and the buckling mode shapes as the distribution [18]. The distribution encompasses the distribution of both with the cross-section and along the longitudinal direction of the member.

A variety of approaches can fulfill this task and has been studied in [18]. In this study, the traditional modal approach is employed. Only the cross-sectional geometric imperfections following the mode shapes of local and distortional (L and D in Fig. 1a) are modeled and global imperfections such as camber, bow, and twist are not included. Particularly, the distribution of the imperfection within the cross section is seeded from the local and distortional buckling mode shapes generated from a CUFSM analysis [9], and the longitudinal distribution follows a sinusoidal function with a half-wave length associated with each mode shapes. In addition, the magnitude is a function of the plate thickness. Stochastic simulation is performed on the measured magnitude summarized in [17]. To simulate, the probability density functions of local and distortional imperfection magnitudes are taken as a lognormal distribution as shown in Fig. 1a. The mean and standard deviation for