



## **CUFSM Elastic Buckling Analysis Software Module for Quantifying Hole Effects in Thin-Walled Structural Members**

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### **Abstract**

A new hole effects calculator for finite strip eigen-buckling analysis in CUFSM is introduced. The calculator allows users to input varying hole sizes and locations along the length of a structural member, and to obtain the influence of this hole configuration on critical elastic local, distortional, and global buckling loads and moments. The use of the hole effects calculator is demonstrated with examples for a cold-formed steel joist and stud, and the elastic buckling results are verified with thin shell finite element eigen-buckling analyses.

### **1. Introduction**

This paper introduces and verifies a new hole effect calculator in CUFSM, a widely used finite strip elastic buckling solver supporting thin-walled cold-formed steel structural member design (Li and Schafer 2010). Discrete punched holes are placed in cold-formed steel studs and joists at regular intervals to accommodate utilities in floors and ceiling. Storage rack columns have perforation patterns to allow vertical shelf adjustment. The presence of holes in thin-walled members almost always influence elastic buckling (Moen and Schafer 2009a, Moen and Schafer 2009b) and reduce load-carrying capacity (Moen and Schafer 2008), and these reductions are accounted for in cold-formed steel design by calculating cross-sectional and global slenderness considering critical elastic local, distortional, and global buckling loads (moments) including the influence of holes (Moen and Schafer 2011, Moen et al. 2013, AISI 2016). The addition of a hole effect calculator to CUFSM provides a convenient method for approximating this influence on elastic buckling for engineers.

An introduction to the calculator is provided in the next sections. The CUFSM hole effect calculator is designed with three regions as shown in Fig.1, from left to the right: holes and member geometry input; net section viewer and selection; and global/distortional/local buckling analysis and results viewer. These three regions are described in detail, followed by perforated stud and joist finite strip elastic buckling examples, the results of which are verified with thin-shell finite element eigen-buckling analyses.

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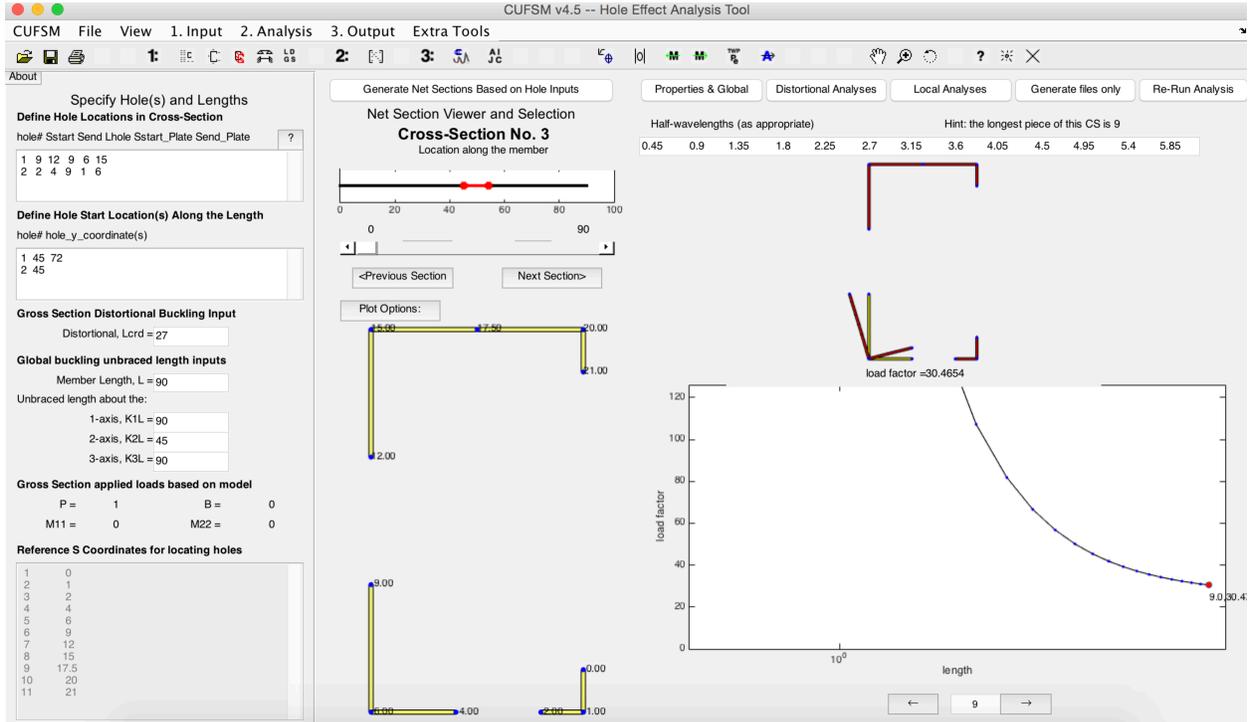


Figure 1: Overview of the CUFSM hole effect calculator interface

## 2. CUFSM Hole Effect Calculator – Hole Geometry Input Region

### 2.1 Holes and Member Geometry Input

The hole effect analysis tool imports the gross cross-section geometry, material properties and reference stress from the main pre-processor. The holes and member geometry input panel accepts rectangular hole size and location from the user as shown in Table 1. The variables in Table 1 are shown in Fig. 2. The  $s$  coordinate stands for the line length around the cross-section; 'Sstart' and 'Send' are the  $s$  coordinates defining the starting and ending point of the hole; 'length of hole' refers to the hole length along the member; and 'Sstart\_Plate' and 'Send\_Plate' stand for the starting and ending  $s$  coordinates of the plate (or element) the hole belongs to. For example, Hole Number 1 in Table 1 begins at 9 in. from the tip of the stiffening lip ( $s=0$  in Fig. 2) and ends at 12 in. from the lip, and the hole width or depth is therefore 3 in. Sstart\_Plate of 6 in. and Send\_Plate of 15 in. locates the hole in the web element which is needed for distortional buckling reduced thickness calculations. Currently the nomenclature and inputs are only applicable to single-branch cross-sections (e.g., C-section, Z-section, hat sections). Multiple branch cross-sections (i.e., an I-section) and lip-reinforced holes are planned as future updates.

Table 1: Nomenclature definitions for hole location in the cross-section

Hole Number	Sstart	Send	Length of Hole	Sstart_Plate	Send_Plate
1	9	12	9	6	15
2	...	...	...	...	...

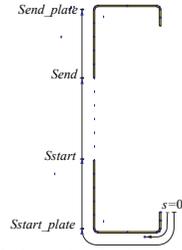


Figure 2: Variables defining the hole location in the cross-section

The hole start location, i.e., the  $y$  coordinate along the member length, is defined as shown in Table 2 and Fig. 3. Hole Number 1 (9 in. long, 3 in. deep as defined in Table 1) is placed at two locations starting at 45 in. and 72 in. from the end of the stud. The user inputs allow multiple holes to occur in the same net cross-section as shown in Fig. 3.

Table 2: Hole start location(s) along the member length

Hole Number	Hole $y$ coordinates	
1	45	72
2	...	

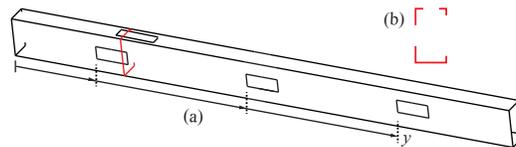


Figure 3: Hole geometry: (a)  $y$  coordinates of the hole start locations; and (b) net section containing two holes

### 2.2 Gross Section Distortional Buckling Input

The user is required to input the critical distortional buckling half-wave length of the member without holes found by a finite strip elastic buckling analysis on the gross cross-section. The distortional buckling load (or moment) including the influence of holes is calculated with this half-wavelength (Moen and Schafer 2009b).

### 2.3 Global Buckling Unbraced Length Inputs

The user inputs the member length necessary for determining the geometry of the member with holes. In addition, unbraced lengths about strong, weak and torsional axes, i.e., the  $KL$ 's, are required for global buckling calculations.

### 2.4 Global Section Applied Loads Based on Model

The global section applied loads (moments) are calculated from the reference stress applied before entering the hole effect calculator and reported for the user. The reference stress cannot be modified from the hole effects calculator screen.

### 2.5 The $s$ Coordinates for Locating Holes

The  $s$  coordinates of all the discretization nodes are calculated for the user to assist them in defining hole locations within the cross-section (see Section 2.1).

### 3. CUFSM Hole Effect Calculator – Net Section Viewer and Selection

The net section viewer and selection module is designed to define net cross-sections where many holes exist. The number of net cross-sections does not necessarily equals the number of hole types. For example, in Fig. 3, there are 2 hole types and 4 cross-section types including the gross section. All the cross-section types are determined using the data in *'Holes and Member Geometry Input'* panel by pressing the *'Generate Net Sections Based on Hole Inputs'* button. The location of a specific cross-section along the member and the net cross-section itself are shown in the upper and lower image box in the *'Net Section Viewer and Selection'* panel. Matlab *'.mat'* files of each net cross-section are created and saved for advanced users.

### 4. CUFSM Hole Effect Calculator – Buckling Analysis Module and Result Viewer

Elastic buckling analyses are activated for global, distortional, and local modes by pressing the buttons along the top of the hole effect calculator panel, i.e., Properties & Global, Distortional Analyses, and Local Analyses.

#### 4.1 Global Buckling Analyses

For global buckling including the influence of holes, weighted average or smeared section properties are calculated from net and gross cross-sections (Moen and Schafer 2009b) and then sent to the embedded open-source Matlab program CUTWP (Sarawit 2006). Euler buckling from an axial load or uniform moment, reduced by the presence of holes, is calculated, see  $P_e$  in Fig. 4 for the case of a column (click *Me* button for a beam). The finite strip cross-section reference stress is not used in the global buckling calculation.

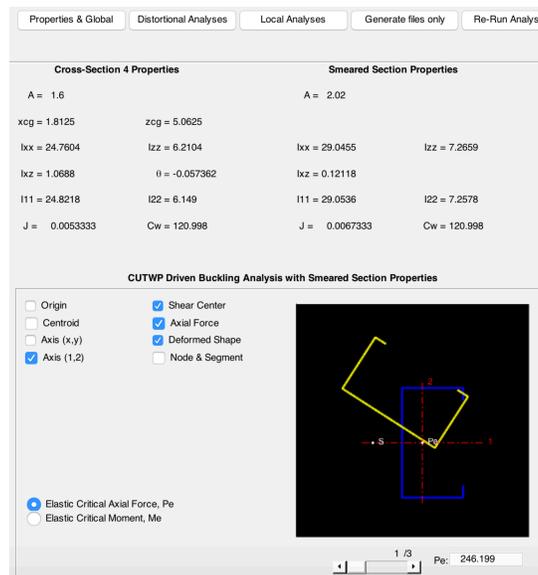


Figure 4: Global buckling including hole effects with the open-source code CUTWP

#### 4.2 Distortional Buckling Analyses

Distortional buckling including the influence of holes is computed based on the input of the buckling half-wavelength of gross section,  $L_{crd}$ , in the *'Holes and Member Geometry Input'*

panel, and the cross-section element with the hole(s) is modeled with a reduced thickness (Moen and Schafer 2009b):

$$t_r = \left( 1 - \frac{L_h}{L_{crd}} \right)^{1/3} t \quad (1)$$

The hole length,  $L_h$ , is obtained from user inputs (see Section 2.1 and Table 1) and the element base metal thickness is  $t$ . The distortional buckling mode shape and critical elastic buckling load (or moment) at  $L_{crd}$  with the reduced element thickness  $t_r$  is provided as shown as in Fig. 5.

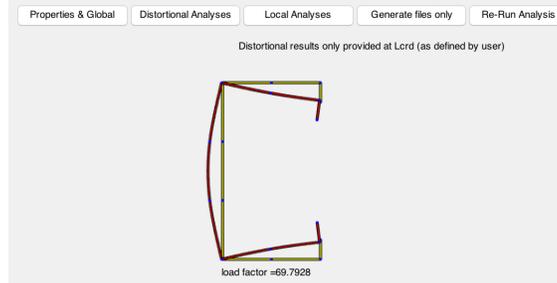


Figure 5: Distortional buckling result considering a reduced web thickness to simulate hole effects

#### 4.3 Local Buckling Analyses

Hole effects on local buckling are examined cross-section by cross-section. A signature curve is calculated for each net cross-section, providing a critical elastic buckling load (or moment) for the unstiffened strips between holes as shown in Fig. 6. The buckling half-wavelength at the hole is defined at the minimum of the signature curve. If this half-wavelength is less than the length of the hole or holes in the cross-section, then use the buckling load at the hole is found at the minimum of the curve. If the hole is shorter than the buckling half-wavelength (defined at the minimum of the signature curve), then follow the signature curve up and take the buckling load at the length of the hole. More examples discussing the calculation of local buckling at a hole are available in Moen and Schafer (2010a) and Moen and Schafer (2010b).

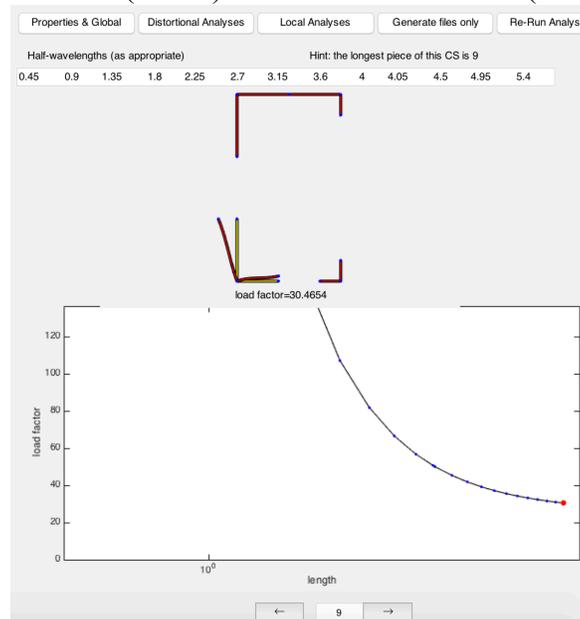


Figure 6: Local buckling module generates 'signature curve' of unstiffened strips at a net cross-section

## 5. CUFSM Hole Effect Calculator Example – 550S162-33 stud with punched web holes

### 5.1 Member and hole geometry definitions and input

The CUFSM hole effect calculator is used to calculate the critical elastic buckling loads for a cold-formed steel structural stud with a 550S162-33 lipped C-section and standard punched holes as shown in Figure 7. The member is assumed pinned-pinned at its ends for flexure about the  $x$ -axis and  $z$ -axis, and fixed against twisting at its ends about the  $y$ -axis (Figure 7). The C-section flanges are assumed to be unbraced along the member length, making distortional buckling a viable limit state, resulting in unbraced lengths of  $L_x=96$  in.,  $L_z=96$  in., and  $L_t=96$  in. and  $K_x=K_y=K_t=1.0$ .

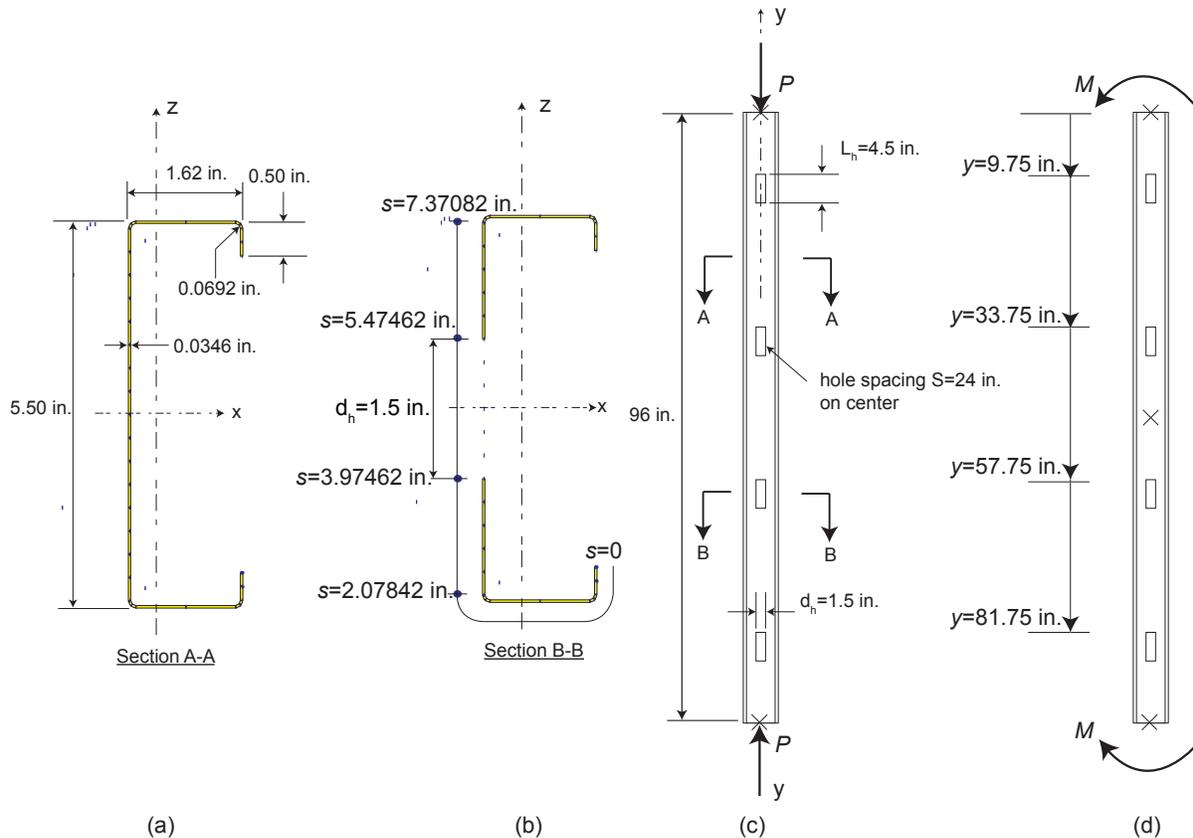


Figure 7: CUFSM hole effect calculator example - 550S162-33 (a) gross cross-section; (b) net cross-section; (c) stud boundary conditions and loading; (d) joist boundary conditions and load

The gross cross-section geometry and reference stress are input using the main CUFSM pre-processor before entering the hole effect calculator screen (Fig. 8). The  $s$  coordinates of the hole edges and the plate edges where the hole resides are determined as shown in Fig.7b. The  $y$  coordinates of the hole starting sections are defined in Fig.7d. The member length,  $s$  and  $y$  coordinates are all entered into the corresponding input boxes to define the geometry of the members with holes. The unbraced lengths of  $L_x=96$  in.,  $L_z=96$  in., and  $L_t=96$  in are also entered for global buckling calculation. For the distortional half-wave length, CUFSM is run on the gross-section to identify  $L_{crd} = 19.6$  in., see Moen and Schafer (2010b) to see how the constrained finite strip method is used to treat the indistinct distortional buckling minimum.

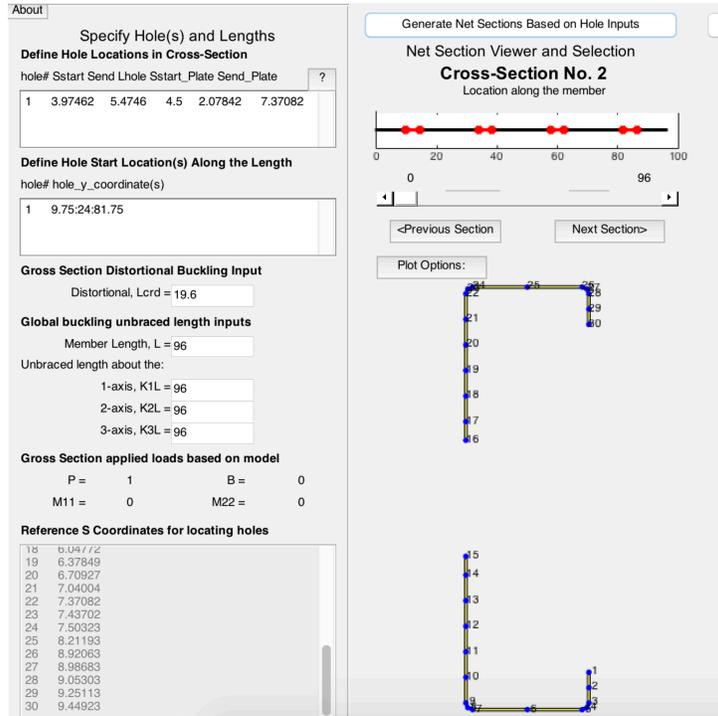


Figure 8: Holes and member geometry input for 550S162-33 stud with punchouts

### 5.2 Global Buckling Results - 550S162-33 stud with punched web holes

Using the tool to perform global buckling analysis, it is found that global buckling mode is weak axis flexural buckling and the buckling load is  $P_{cre} = 3.52$  kips, as shown in Fig. 9, which is a 1.4% reduction from  $P_{cre} = 3.57$  kips for the stud without holes. The stud with holes is also analyzed with a thin-shell finite element eigen-buckling analysis in ABAQUS (Simulia 2012), resulting in  $P_{cre} = 3.32$  kips with a weak axis flexural buckling mode which is consistent with the CUFSM result. The FEA result is 6.0% lower than the hole effect calculator because the hole effect calculator assumes a rigid cross-section while FEA accounts for cross-section distortion even in global buckling, see Moen and Schafer (2009b) for more details.

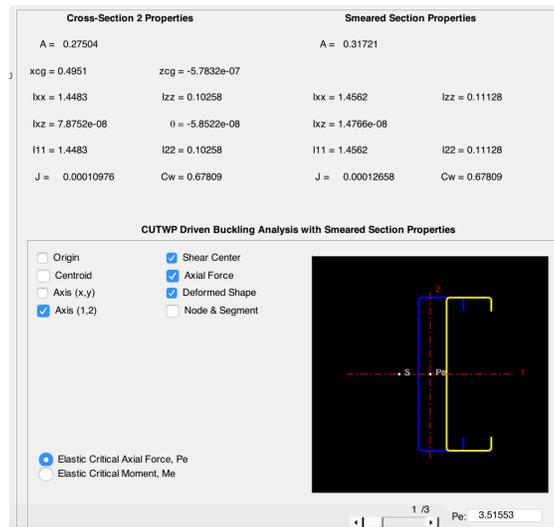


Figure 9: Stud column global buckling result from the CUFSM hole effects calculator tool

### 5.3 Distortional Buckling Results - 550S162-33 stud with punched web holes

The distortional buckling load of the net cross-section is calculated to be  $P_{crdh}=4.48$  kips as shown in Fig. 10a, a 10.8 % reduction from the same stud without holes ( $P_{crdnh}=5.02$  kips). Thin-shell finite element eigen-buckling analysis predicts  $P_{crdh}= 4.16$  kips, which is 7.7% lower than that calculated by the hole effect calculator.

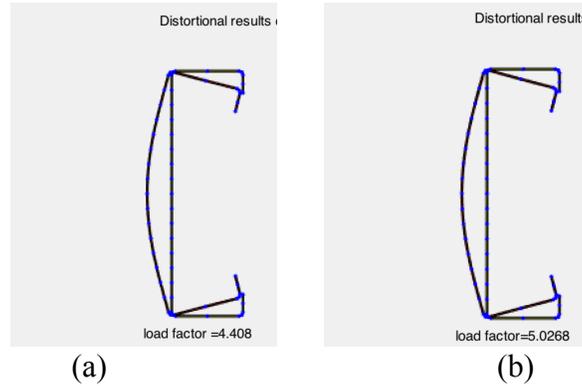


Figure 10: Column stud distortional buckling results for (a) net cross-section and (b) gross cross-section

### 5.3 Local Buckling Results - 550S162-33 stud with punched web holes

For the net section, the CUFSM hole effect calculator finds a local buckling load at the hole of  $P_{crth}=2.23$  kips at the unstiffened strip corresponding to critical half-wave length of  $L_{crth}=3.97$  in., as shown in Fig. 11 which is less than the hole length. For the gross section, the local buckling load is the minimum on the signature curve in Fig. 11,  $P_{crtnh}=2.02$  kips at a half-wavelength  $L_{crtnh}=4.25$  in. The buckling load is predicted as the lower of the gross and net section results, i.e.,  $P_{cr}=\min(P_{crtnh}, P_{crth})=2.02$  kips. Thin-shell finite element eigen-buckling analysis predicts results consistent with CUFSM ( $P_{crtnh}=2.04$  kips  $P_{crth}=2.26$  kips) with no-hole and hole local modes identified visually with criteria defined in Moen (2009).

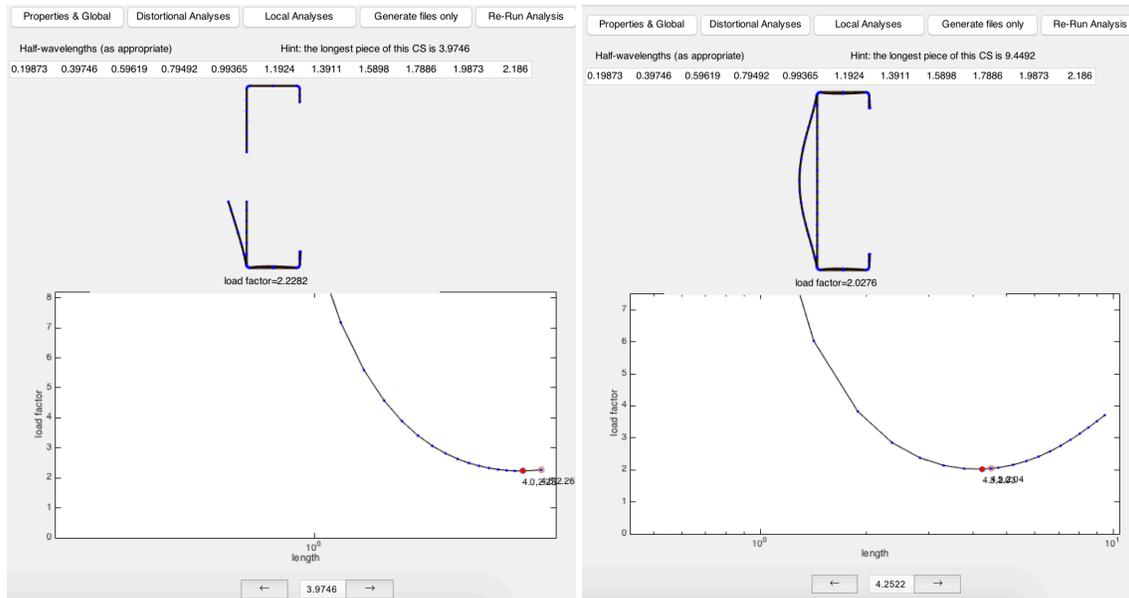


Figure 11: Column stud local buckling results: (a) gross cross-section; (b) net cross-section

## 6. CUFSM Hole Effect Calculator Example – 550S162-33 joist with punched web holes

### 6.1 Member and hole geometry definitions and input

The geometry input is identical with the previous example of a stud column except the reference stress is now calculated with a moment  $M_{11}=1$  kip·in. Coincidentally, the distortional buckling length equals that of the previous column example,  $L_{crd} = 19.6$  in.

### 6.1 Global Buckling Results - 550S162-33 joist with punched web holes

From the CUTWP window, the critical elastic buckling moment is found to be  $M_{cre} = 8.96$  kip·in, as shown in Fig. 12 which is a 1.32% reduction from a joist without holes calculated with CUTWP ( $M_{cre}=9.08$  kips). The lateral-torsional buckling result is within 3% of the shell finite element eigen-buckling solution considering the joist with holes ( $M_{cre}=8.96$  kips·in).

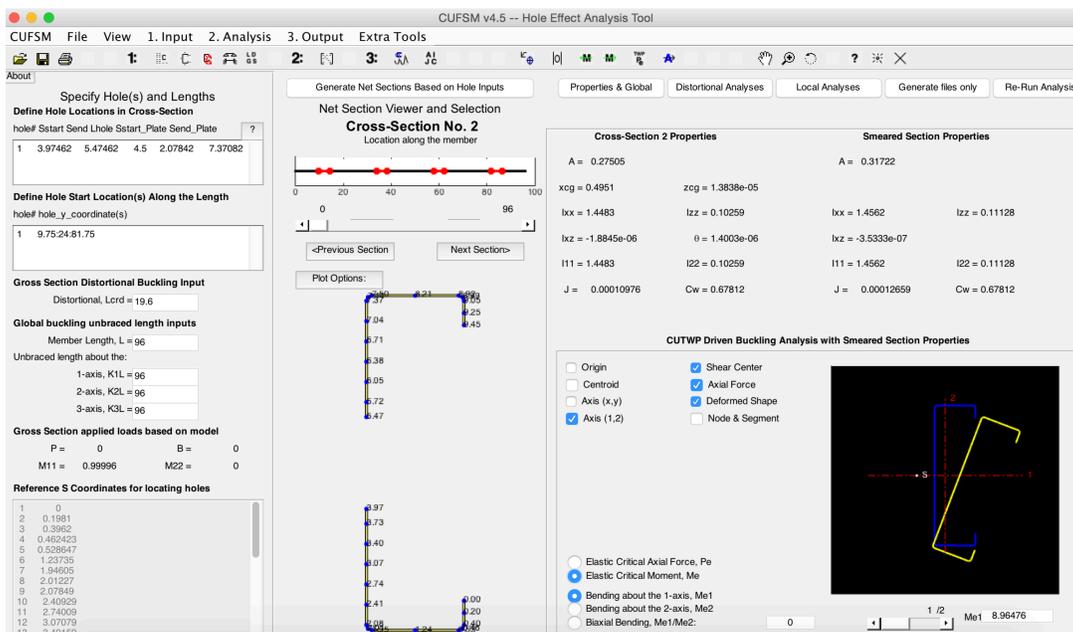


Figure 12: Joist example input and global buckling result considering the influence of holes

### 6.2 Distortional Buckling Results - 550S162-33 joist with punched web holes

The distortional buckling moment considering the influence of holes is calculated as  $M_{crdh}=20.9$  kip·in, which is a 16.4% reduction from a joist without holes ( $M_{crdnh}=25.0$  kip·in). The buckling moment from the CUFSM hole effect calculator is consistent with shell finite element eigen-buckling analysis ( $M_{crdh}=19.0$  kip·in) with the distortional hole mode identified visually.

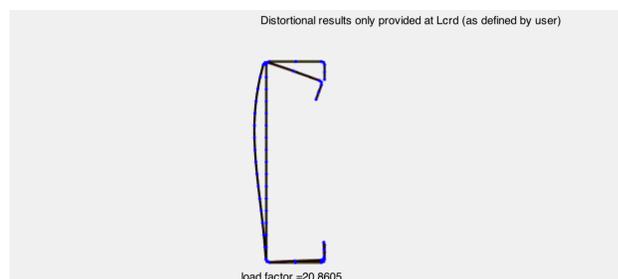


Figure 13: Joist distortional buckling result considering the influence of holes

### 6.3 Local Buckling Results - 550S162-33 joist with punched web holes

The local buckling moment at the hole is predicted as  $M_{cr(th)}=9.58$  kip·in. as shown in Fig. 14 (the minimum of the signature curve since  $L_{cr(th)}=L_h=4.0$  in.), and  $M_{cr(nh)}=17.63$  kip·in. Therefore  $M_{cr}=\min(M_{cr(th)}, M_{cr(nh)})=\min(9.58, 17.63)=9.58$  kip·in. which means local buckling will initiate at the hole for this cross-section, not between holes. Thin shell finite element eigen-buckling analysis predicts  $M_{cr(th)}=11.14$  kip·in. and  $M_{cr(nh)}=18.77$  kip·in. again verifying the CUFSM hole effect calculator.

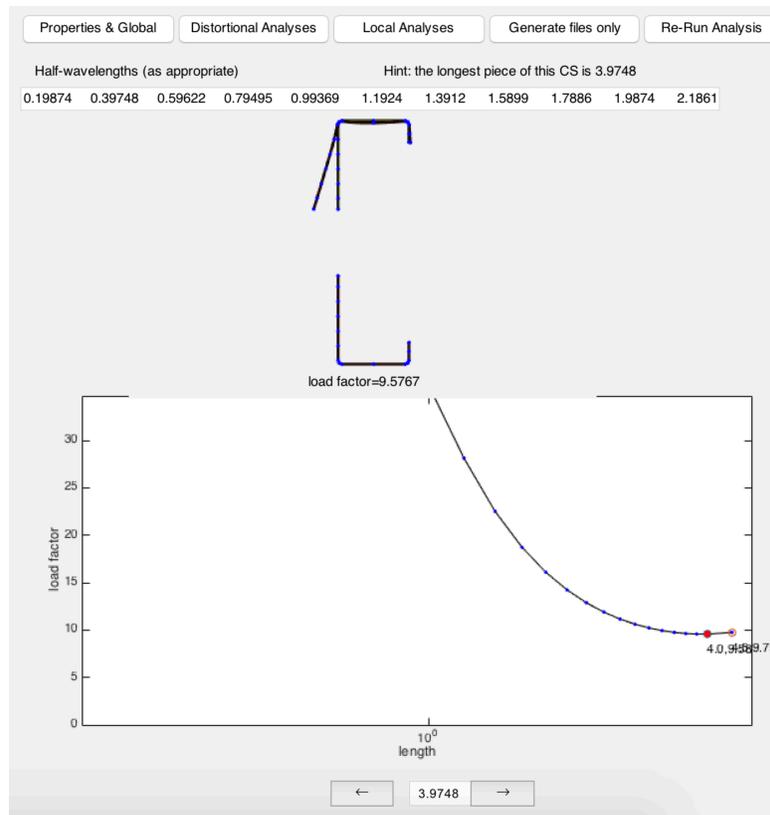


Figure 14: Joist local buckling results - net section

## 7. Conclusion

A new hole effects calculator for finite strip eigen-buckling analysis in CUFSM is introduced. The calculator allows users to input varying hole sizes and locations along the length of a structural member, and to obtain the influence of this hole configuration on critical elastic local, distortional, and global buckling loads and moments. The use of the hole effects calculator is demonstrated with examples for a cold-formed steel joist and stud, and the elastic buckling results are verified with thin shell finite element eigen-buckling analyses.

## Acknowledgments

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