

Capability of “Direct Strength Method” for welded steel sections with non-slender components

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ABSTRACT: In this investigation, a modern process of designing named “Direct Strength Method” (DSM) for the columns with welded steel sections formed of the sheet with non-slender components under uniform compression into two statues, with and without effect of residual stress based on AISC regulations has been expressed and evalouted. A set of theoretical and software studies have been conducted on the welded non-slender sections of box and H shaped with the conventional steel sheets with the constant thickness of 8 (mm) and yield stress of 2400 (Mpa) in order to reach the ultimate strength of the aforementioned columns. Subsequently, using DSM for final predicting such sections like these needs numerical stability analysis and it is also required to determine the behavior of elastic buckling of the member in a range of actions and reactions related to local and general buckling modes. Hence it is mandatory for the sections to be analyzed through CUFSM software based on the finite strip method (FSM) in order for simulating the mentioned behavior. So as to complete the basic information, the effect of initial imperfections and defects on the applied sections and the behavior of post-buckling strength has been surveyed through using non-linear analysis of ABAQUS software based on finite element method (FEM) with the assumption of effect of above statuses. Eventually, the accuracy and precision of DSM equations have been compared to the final amounts obtained from AISC regulations for columns with non-slender sections.

Keywords: Direct Strength Method, Welded non-Slender Sections, Post-Buckling Strength, Linear and Non-linear Analysis, Residual Stress, AISC Regulations.

INTRODUCTION

DSM method as a set of equations was presented for cold-formed steel members in the AISI regulations for the first time in the North America (1). Subsequently, after conducting wide researchers, it was developed in Australia and New Zealand as a method for designing cold-formed steel members such that it could be used as a method for designing compressive, bending, shear, beam columns and perforated cold-formed steel members. In the recent years, it was intensively attempted to use this method as a manner to design compressive steel members based on a rational analysis throughout using elastic buckling solutions related to the corresponding member directly. Briefly, it could be said regarding the columns that the start of DSM method was a survey for determining distortional buckling of thin-walled members at university of Sydney specially Hancock who has conducted numerous researches relevant to this field and concluded that the compressive strength obtained at the distortional elastic mode of the section is proportional to the slenderness for different kinds of sections (2).

Development of DSM after Hancock’s work regarding distortional buckling was perfected in a wider range of various cold-formed sections by Schafer in 2000 (3) including numerous tests and experiments through considering distortional and local buckling modes and also general bending and torsional-bending buckling modes which manual and numerical solutions of FSM for elastic buckling of the sections were calculated for 187 columns with the available features which finally, DSM equations were indicated in the corresponding regulations based on AISI characteristics by applying the effective width method for compressive cold-formed members (4).

Development of DSM equations based on Winter's relation as the curve of design strength has been done through various tests by Schafer and Pekoz which finally led to creation the direct strength method for designing compressive members considering the below notion (5).

In fact, the definition of DSM is related to using self-dimensions of the section with the effective design stress ρF_y instead of using the effective width of the elements with yield fracture stress in the effective width method.

$$(1) \quad A_g \cdot P_{ne} = P_n = \rho \cdot P_y = (\rho \cdot A_g) \cdot F_y = A_g \cdot (\rho F_y)$$

$$\rho = 1/\lambda (1 - 0.22/\lambda), \quad \lambda > 0.673 \quad (2)$$

Where, ρ is the effective stress factor or the limited stress coefficient.

This notion is applied on the whole of the section as a limited stress which can be named for each of various buckling modes under different pressure as the limited buckling step of the corresponding mode which its conclusion is direct strength method (DSM). Actually, DSM presents equations with the aforementioned notion for cold-formed members in the following modes through considering various actions and reactions relevant to buckling modes and with replacing P_{ne} in columns and M_{ne} in beams instead of P_y and M_y , respectively.

1- Local buckling mode

In this mode, the elements forming the section were only rotated and bent at their junction and the storage after buckling was high at the local mode and happened at the minimum wavelength.

DSM relations for compressive members at the local mode:

$$\left\{ \begin{array}{l} \lambda_l \leq 0.776 \\ \lambda_l > 0.776 \end{array} \right. \quad P_{nl} = \begin{cases} P_{ne} \\ (1 - 0.15(P_{crl}/P_{ne})^{0.4}) * (P_{crl}/P_{ne})^{0.4} * P_{ne} \end{cases}$$

$$c = \sqrt{(P_{ne}/P_{crl})} \quad \lambda$$

Where, P_{nl} is the ultimate strength of the section under local mode and P_{crl} is the critical local strength of the section from the CUFSM output and P_{ne} is the strength of the section at the elastic state.

2- Distortional buckling mode

In this mode, the junction points of the web and flange changed and the elements have revolution movement addition to the rotation. After that, the storage after buckling at the distortional mode is average and occurred at the medium wavelength.

DSM relations for compressive members at the distortional mode:

$$\left\{ \begin{array}{l} \lambda_d \leq 0.561 \\ \lambda_d > 0.561 \end{array} \right. \quad P_{nd} = \begin{cases} (1 - 0.25(P_{crd}/P_{ne})^{0.6}) * (P_{crd}/P_{ne})^{0.6} * P_{ne} \\ P_{ne} \end{cases} \quad (4)$$

$$d = \sqrt{(P_{ne}/P_{crd})} \quad \lambda$$

Where, P_{nd} is the ultimate strength of the section under distortional mode and P_{crd} is the critical distortional strength of the section from the CUFSM output and P_{ne} is the strength of the section at the elastic state.

3- General buckling mode

Under this mode, rotation or revolution or a combination of both occurred at the whole of the section without bending the elements of the section and also the storage after buckling is less and had longer wavelength in this mode.

DSM relations for compressive members at the general mode:

$$\left\{ \begin{array}{l} P_{ne} = (0.658/\lambda_c^2) * P_y \\ P_{nc} = (0.877/\lambda_c^2) * P_y \\ c = \sqrt{(P_y/P_{cre})} \end{array} \right. \quad \begin{array}{l} \lambda_c \leq 1.5 \\ \lambda_c > 1.5 \\ \lambda \end{array} \quad (5)$$

$$P_y = A_g \cdot F_y$$

In this study, it has been attempted to adopted analysis of CUFSM and ABAQUS software programs and with the help of the effect of local and general actions– reactions and the concept of post-buckling storage related to the sections on the ultimate strength of compressive members in the above statues, can use the advantages created from DSM for analyzing non-slender built-up welded H and box shaped sections. In addition, the revised design formulas for the mentioned sections have been presented. Eventually, it has been compared and concluded based on AISC regulations.

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2 - Investigation procedure

In accordance with the definition, slender sections are the ones which usually made of several slim elements. Generally, columns with the mentioned sections buckle in the local buckling mode and general buckling mode such as lateral, torsional and lateral-torsional. In spite of being lower the stress of local buckling in comparison to the general buckling stress and available actions – reactions between two modes, the ultimate nominal strength of the columns decrease. Consequently, it made the determination of elastic local buckling stress under uniform pressure have particular significance and it leads to create the storage after buckling. In this event, the opposite of this subject has occurred for non-slender sections (compressed or uncompressed). Accordingly, a set of theoretical and software studies is conducted on the welded non-slender sections in shape of box and H with the convectional steel sheets with a constant thickness of 8 millimeters and the yield stress of 240 Mpa. In addition, the geometry of the sections is defined through AISC regulations as follows:

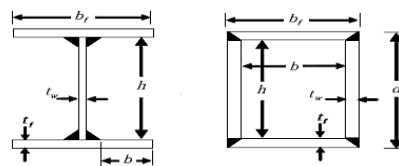


Figure 1. The geometry of welded sections of box and H shaped

The criterion for choosing the sections is such that it should , the ratio of the width to the thickness of the components making the section has to be located at the regulation non-slenderness limitation as follows (6):

1- Elements with two depended edges under uniform pressure:

$$h/t_w \text{ or } b/t_f < 1.4\sqrt{(E/F_y)} \tag{6}$$

2- Elements with one depended edge under uniform pressure:

$$\left\{ \begin{array}{l} b/t_f < 0.95\sqrt{(K_c \cdot E/F_L)} \\ , \quad F_L = 0.7F_y \quad K_c = 4/\sqrt{h/t} \quad (0.35 \leq K_c \leq 0.76) \end{array} \right. \tag{7}$$

Other characteristics of the conventional soft steel have been considered from AISC regulations as follows:

$$\left\{ \begin{array}{l} 0.3 \\ G = 769230.7 \text{ kg/cm}^2 \end{array} \right. \quad = \nu \quad E = 2 \cdot 10^6 \text{ kg/cm}^2$$

According to the abovementioned inquiries, the characteristics of the surveyed sample sections have been presented on table 1.

Table1. Characteristics of sections

Sections	b_f (cm)	d (cm)	b/t	h/t
B 10x5	10	5	10.5	10.5
H 10x10	10	10	5.75	10.5

In order to model the behavior of the sample sections with definition the geometry the welded sections made of sheet and the features of corresponding materials in CUFSM software, the geometric characteristics of the sections could be obtained directly. The diagrams of load factor–wavelength of all sections are determined through conducting the analyses in the compressive loading state uniformly. The curves, obtained from elastic analysis of CUFSM for the sections mentioned on table 1, have been show in figure 2. In accordance with the mentioned issue, the values of general and local elastic buckling stress(F_{cro}) have been shown on table 2 briefly.

Table 2. The values of stress related to general and local elastic buckling

Sections	F_{crit} (kg/cm ²)	F_{cro} (kg/cm ²)
B 10x5	59222	1072
H 10x10	30458	1248

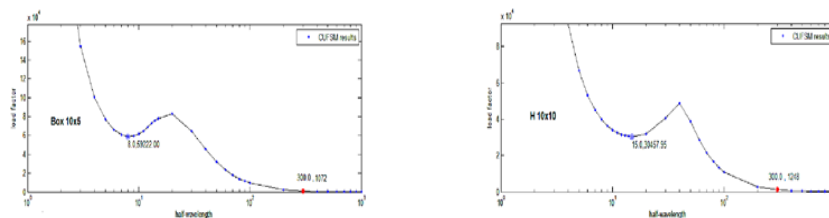


Figure 2. Curves related to elastic analysis of CUFSM

The minimum point on the diagram shows the value of F_{crit} related to the sections which equals P_{crit}/A_g for a section under uniform pressure. The horizontal axis of the graph (wavelength) indicates number of half-sine waves equal $m=L/b$ and the vertical axis (stress factor) presents the domain of half wave or the amount of elastic buckling stress of the member in the range of the wavelength relevant to the corresponding point with double hinged bottom.

Linear and non-linear analysis of ABAQUS

To complete the basic data obtained from elastic analysis of CUFSM and reach the ultimate load of selected sample sections, it is mandatory to survey the non-linear analysis of welded non-slender sections in the non-linear range by ABAQUS software. For this purpose the effect of initial defects and imperfections, sections as a combination of all deformations resulted from linear buckling modes with applying small coefficients as a primary geometric model of the section, has been applied in non-linear buckling analysis. In fact, geometric local imperfections and defects present the displacements gained from local buckling of slim components related to the sections in various buckling modes in terms of eigenvalue. In accordance with the conducted study works and with considering that the most common method for applying the effect of initial imperfections and defects on various sections is the same as elastic buckling analysis, the maximum domain of displacements of eigenvalue is applied in a percentage of the thickness related to section as the effect of local initial imperfections and defects in three first modes of the local elastic buckling obtained from linear analysis which are 0.001t, 0.005t, 0.01t in order.

General parameters of simulation with ABAQUS:

1. Simulation of the geometry, dimensions and geometry specifications of the columns sections has been matched to the aforementioned matters.
2. Von Mises stresses have been used for the application in the theory of plastic sections.
3. All columns have been defined as two-dimensional shell elements (Shell, S4R) . In fact, S4R element indicates 6 degrees of freedom in each node with direct bilinear interpolation, concurrent with applying the effect of membrane strains considered as reduced integration.
4. The length of all columns is 3 meters and their supports are modeled double hinged support. Schematic model of the support conditions in a column with H shaped section has been shown in figure 3.

5. Loading of the columns is vertically at longitudinal direction of the column which has been allowed to displace at the loading direction. This loading is applied as the uniform pressure on the cross section at the free bottom in the vertical direction. Figure 3 shows the schematic model of the loading.

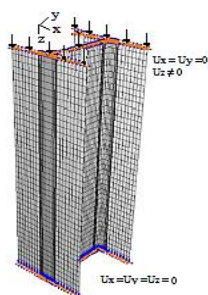


Figure 3. Schematic model of the support conditions and the loading of the column

6. Meshing relevant to elements of the total sections has been used in the size of 0.1 small dimension of the section regularly.
7. Figure 4 indicates an illustration of regular meshing elements related to box and H shaped sections surveyed in the analysis.

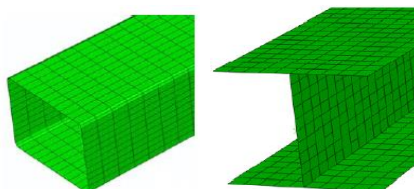


Figure 4. Meshing the elements of the sections

8. Amount and distribution of residual stress for the sections mentioned on table 1, considered such ideal linear form that have been show in figure 5.

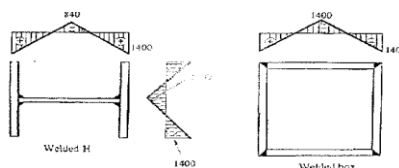


Figure 5. Distribution of residual stress in sections of box and H shaped

Simulation of linear analysis with ABACUS

Elastic linear analysis of all columns for the effect of initial imperfections and defects values is done through using Buckle order in Linear Perturbation state which the specific first mode of local buckling at Buckle step is considered as the initial imperfections and defects for all sections and it is saved for non-linear analysis of buckling by applying corresponding coefficients.

Simulation of non-linear analysis with ABACUS

In the non-linear simulation of the sample columns without any impact of residual stress, we use Static Riks order at General state associated with applying large deformations in the analysis procedure which is done after linear buckle step. It is needed to note that to create the aforementioned conditions the Nelgeom icon has to be on. In the non-linear simulation of the sample columns with effect of residual stress, often it will be done in from of thermal elasto-plastic .therefore thermal conduction will be defined in the face of thermal gradient variation in compression member. non-linear analyze is done in order to apply this effect after Buckle linear step with associated general static order on columns that amount and distribution of residual stress base on figure 5 will be analyze before compressing member loading . After general static step, non-linear buckling analyze with static riks order will be continued in general state and the section will be loaded in external uniform pressure and along the different loading evaluation,

deformation and final load of column will be gained from non-linear buckling analyze.

DSM equation with and without effect of residual stress

The revised equation of DSM for residual stress state with assumption has been introduced below:

$$\beta = 0.25 \left\{ \begin{array}{l} \frac{P_{ne}}{1/\lambda_l * (\alpha - \beta/\lambda_l) * P_{ne}} \\ \text{or} \\ P_{ne} \end{array} \right. \left\{ \begin{array}{l} \lambda_l \leq \lambda_{lim} \\ \lambda_l \geq \lambda_{lim} \end{array} \right. \quad \begin{array}{l} P_{nl} = \\ = (P_{ne}/P_{crl})^{1/n} \lambda_l \\ \\ \\ P_{nl} = \\ (P_{crl}/P_{ne})^{1/n} * (1 - \beta * (P_{crl}/P_{ne})^{1/n}) * P_{ne} \\ \\ \\ P_{nl} = \end{array} \quad (9)$$

The revised equation of DSM for residual stress state with assumption has been introduced below:

$$\left\{ \begin{array}{l} P_{ne} \\ \beta / \lambda_l^2 * P_{ne} \\ \beta = (\lambda_{lim})^{1/n} \end{array} \right. \left\{ \begin{array}{l} \lambda_l \leq \lambda_{lim} \\ \lambda_l \geq \lambda_{lim} \end{array} \right. \quad \begin{array}{l} P_{nl} = \\ = (P_{ne}/P_{crl})^{1/n} \lambda_l \end{array} \quad (9)$$

$$\left\{ \begin{array}{l} P_{ne} \\ P_{nl} = \\ \beta * (P_{crl}/P_{ne})^{2/n} * P_{ne} \end{array} \right. \left\{ \begin{array}{l} \lambda_l \leq \lambda_{lim} \\ \lambda_l \geq \lambda_{lim} \end{array} \right.$$

In the above equation, P_{ne} is the minimum general strength of the column in the bending or torsional or torsional-bending elastic modes based on the AISC regulations.

P_{crl} is the elastic local buckling obtained from CUFSM analysis and P_{nl} is the ultimate nominal strength of the column with local buckling mode and λ_l is the slenderness relevant to the local buckling of the section and λ_{lim} is the slenderness limited to the boundary of elastic and inelastic buckling in action-reaction with the general buckling mode.

In order to determine n, the degree of post- buckling strength the sample sections, the concept of inelastic buckling of columns is used which could be written for the motioned no-linear zone as follows:

$$\left\{ \begin{array}{l} f_{pb} = \pi^2 E_t / \lambda^n \\ f_{pb} = f_u - f_p \quad \longrightarrow \quad (f_u - f_p) = \pi^2 E_t / \lambda^n \\ \lambda^n = \pi^2 E_t / (f_u - f_p) \quad \longrightarrow \quad n = \log(\pi^2 E_t / (f_u - f_p)) / \log \lambda \end{array} \right. \quad (10)$$

The ratio of Fu/F_{ne} obtained from the analysis is the same as the limited slenderness factor which equals:

$$\lambda_{lim} = F_u / F_{ne} \quad \lambda$$

Where, f_{pb} is the amount of stored strength of local post- buckling, f_u is the ultimate strength of the section related to non-linear analysis and f_p is the primary local buckling stress with considering the initial imperfections.

The P-Δ curves related to non-linear analysis of the buckling with and without residual stress for sample sections have been drawn in figures 6 and 7.

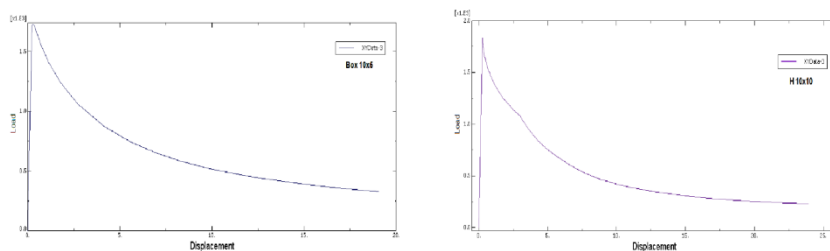


Figure 6. P-Δ curves relevant to the non-linear analysis of the buckling with residual stress

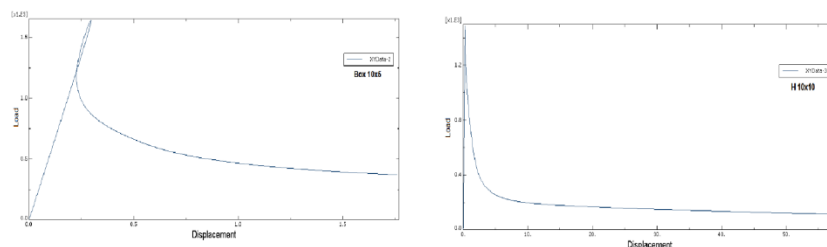


Figure 7. P-Δ curves relevant to the non-linear analysis of the buckling without residual stress

The summary of the results at the state of with and without residual stress has been presented on tables 3 and 4.

Table 3. the results summarized from non-linear analysis with residual stress

مقاطع نمونه	Fp (kg/cm ²)	Fu (kg/cm ²)	n	λ _l	Fcro (kg/cm ²)	λ _c	Fne (kg/cm ²)	λ _{lim}
B 10x5	1990	1990	∞	1	1072	1.53	900	2.21
H 10x10	1850	1850	∞	1	1248	1.38	1078	1.71

Table 4. the results summarized from non-linear analysis without residual stress

مقاطع نمونه	Fp (kg/cm ²)	Fu (kg/cm ²)	n	λ _l	Fcro (kg/cm ²)	λ _c	Fne (kg/cm ²)	λ _{lim}
B 10x5	1700	1700	∞	1	1072	1.53	900	1.89
H 10x10	1490	1490	∞	1	1248	1.38	1078	1.38

DISCUSSION AND CONCLUSION

According to above graphs and tables , we can express that firstly , in this kind of sections, non post-buckling strength didn't make and absolutely be $F_p = F_u$. in accurate way , $(1/n)$ proportion lead to being zero and amount of slenderness related to local buckling section being equal to 1. Secondly , according to 5 equations and results of table 1 , furthermore in residual stress and washout's statue , slenderness limited to the boundary of elastic and inelastic buckling going to larger than 1. It means that $\lambda > \lambda_{lim}$

Verisimilitude of the results obtained from DSM relations and AISC regulations

According to AISC regulations, non-slender sections (compressed and uncompressed) , defiantly, has general buckling mode that caused to determination of ultimate strength of them and local buckling never made in.

Up to above words and context of DSM that based on determine of local buckling elastic stress and considering local and general mode action-reactions, Finlay, in equations relate to DSM fore welded non-slender sections always $P_{nl} = P_{ne}$ and the results accuracy are In accordance with Euler diagrams of AISC.

Allowable strength design method (ASD) has been used so as to compare and estimate the percentage of error between the ultimate strength obtained from the proposed DSM relations and AISC regulations which the allowable strength design of criterion sections under the uniform pressure in the state of residual stress has been determined through definition of safety factor and it has been indicated on table 6 briefly.

According to table (6), the comparison -between the results obtained from AISC and the proposed DSM relations- shows that the percentage of the error was averagely 5 percent which expresses a proper agreement. Furthermore, in residual stress state and with the assumption of $Q=1$, the suggested curve of DSM presents bigger and conservative amounts compared to the Euler curve AISC whereas for $Q<1$, the proposed DSM values in compare to the AISC regulation values express in 2 below forms :

- 1- For 0.695 and 0.81 up to 1 slenderness, proposed DSM values are so close to AISC values.
- 2- For bigger than 1 slenderness, proposed DSM values are little bigger and Conservative than AISC values.

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