MINISTRY OF EDUCATION AND TRAINING
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BEHAVIOR OF COLD-FORMED STEEL MEMBERS SUBJECTED TO BENDING ABOUT ASYMMETRICAL AXIS

SUMMARY OF DOCTORAL THESIS IN ENGINEERING

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INTRODUCTION

1. Rationale of the topic

The Direct Strength Method (DSM), proposed by Schafer and Peköz, offers a new and effective approach to designing flexural members made of cold-formed steel (CFS). This method determines bending strength using the elastic critical stresses of the entire cross-section.

Since current DSM design formulas are based on experimental and simulation data for members bending about the symmetrical axis, applying DSM to members bending about the asymmetrical axis often results in overly conservative strength estimates.

Apparently, the application of current DSM design methods to CFS members bending about asymmetrical axes exposes limitations that must be addressed. Therefore, the study on the "***Behavior of cold-formed steel members subjected to bending about asymmetrical axis***" is both necessary and practically significant.

2. Research purpose

To propose modifications to the DSM formula for more accurate prediction of the ultimate strength of cold-formed steel channel members subjected to bending about the asymmetrical axis.

3. Research objectives and tasks

a) To develop an analytical method to determine the buckling coefficient of the entire cross-section.
b) To propose an analytical formula to determine the critical stress of cold-formed steel channel members bending about the asymmetrical axis with the web in compression.

c) To propose modifications to improve the accuracy of the DSM formula in predicting the strength of cold-formed steel members bending about the asymmetrical axis.

4. Research subjects and scope

Subject of study: The strength of cold-formed steel members based on the Direct Strength Method (DSM).

Scope of research:

Hot-rolled carbon steel and high-strength cold-formed steel

Channel sections

Bending about the asymmetrical axis, with the web in compression

5. Research methodology

Data collection

Simulation method

Analysis and synthesis method

6. Scientific and practical significance

The findings of this research may be referred to when updating the current cold-formed steel structure design standards.

7. Contributions of the study

a) Development of the Restraining Stiffness Method (RSM) capable of determining the local critical stress of open-section members constructed from flat steel plates.

b) Proposal of an analytical formula to calculate the critical stress of cold-formed steel channel members bending about the asymmetrical axis with the web in compression.

c) Introduction of a linear relationship between DSM formula parameters and the cross-section aspect ratio (*B*/*H*) when applied to cold-formed steel channel members bending about the asymmetrical axis with compressed webs.

8. Structure of the thesis

In addition to the required sections including the Introduction, List of Abbreviations, Tables, Figures, Conclusion and Recommendations, References, and Appendices, the main structure of the thesis consists of four chapters.

THESIS CONTENT

CHAPTER 1. COLD-FORMED FLEXURAL MEMBER BENT ABOUT ASYMMETRICAL AXIS: OVERVIEW

1.1. Introduction to cold-formed structures

This section provides an overview of the definition, materials, and typical cross-sections of cold-formed steel structures. It also presents various cold-forming methods, compares the advantages and disadvantages of cold-formed versus hot-rolled steel structures, and outlines their applications and historical development.

1.2. Design standards of cold-formed structures

An overview of international design standards for cold-formed steel structures is presented. Based on this review, the American standard AISI S100 is selected for use in this thesis.

1.3. Cold-formed structure design approaches

1.3.1. Effective Width Method (EWM)

Presentation of the fundamental principles of the EWM.

1.3.2. Direct Strength Method (DSM)

Presentation of the fundamental principles of the DSM.

1.3.3. Numerical methods

Numerical methods can be used to solve problems related to cold-formed steel structures; however, they are often complex and therefore more suitable for research purposes.

1.3.4. Method selected in the thesis

The Direct Strength Method (DSM) is adopted in this study owing to its simplicity, practicality, and suitability for application in the design of cold-formed steel structures.

1.4. Importance and applications of asymmetrical-axis bending

Statistical data are used to emphasize the significance of bending about the asymmetrical axis in cold-formed steel members, as commonly encountered in practical applications such as purlins and biaxially loaded columns.

1.5. Direct Strength Method: Problems of ultimate flexural strength about the asymmetrical axis

Many researchers have observed that when using the Direct Strength Method (DSM) to determine the bending strength about the asymmetrical axis, the results tend to be overly conservative. This section summarizes existing studies on this issue. Several conclusions have been drawn, including the assertion that there is a need for further research to improve the current DSM equations for cold-formed channel section steel members subjected to bending about the asymmetrical axis, in order to achieve more accurate strength predictions.

1.6. Local buckling stress of channel cross-sections bent about the asymmetrical axis having the web in compression

1.6.1. The role of the local and distortional buckling stress of the entire cross-section in DSM

The critical stresses associated with local buckling and distortional buckling are of great importance in the Direct Strength Method (DSM), as they serve as key input parameters for the strength prediction equations.

1.6.2. Methods to determine the local buckling stress of the entire cross-section by AISI S100

According to the AISI S100 standard, there are two methods used to determine the critical stress due to local buckling of the full cross-section: the analytical solution and numerical solution. While the analytical approach is simple and easy to apply, it tends to offer low accuracy and therefore requires further improvement.

1.6.3. Improvements of the analytical solution to determine the assembly buckling stress of the investigated section

The buckling problem of the entire cross-section can be addressed by analyzing the buckling behavior of a single plate (using methods such as Timoshenko's or Bleich's approach with the coefficient of restraint) or by solving simultaneously for the entire cross-section, which includes Bulson's exact method, energy methods, numerical methods, and others. Each method has its own limitations. Currently, there is no comprehensive analytical solution applicable to members subjected to complex loading conditions. Therefore, this thesis aims to explore an analytical approach to address the local buckling problem of the studied members.

Some analytical expressions for calculating the buckling coefficients of the channel section profiles investigated in this thesis have been developed; however, their accuracy remains limited due to the incomplete consideration of various influencing parameters. Consequently, further improvements are necessary.

1.7. Thesis objectives and deployment

Based on the above discussion, this thesis intends:

To develop an analytical method for solving the elastic buckling problem of the entire cross-section.

To establish formulas for predicting the elastic critical moment of channel cross-section.

To improve the bending strength calculation formulas according to the DSM for application to channel cross-section members.

CHAPTER 2. THEORETICAL BACKGROUND

2.1. DSM ultimate strength calibration process

2.1.1. Calibration process of current DSM equations

This procedure was used by Schafer and Peköz to develop the original DSM formulation, based on the results of 574 bending test specimens.

2.1.2. Modified DSM equations proposed by Oey and Papangelis

The second procedure, conducted by Oey and Papangelis, was also used to develop DSM expressions, but based on 33 numerical simulation data sets of cold-formed C-section steel members subjected to bending about the weak axis, with the web in compression. The authors employed elastic buckling analysis using the finite strip method (FSM) to calculate the local buckling moment, and nonlinear finite element analysis (NLFEA) to determine the ultimate strength. A two-stage nonlinear Ramberg-Osgood stress–strain curve was adopted. Geometric imperfections were incorporated into the model using the first local buckling mode. The coefficients in the existing DSM equations were proposed to be modified, and the reliability of these proposed modifications was evaluated.

2.2. Elastic buckling moment of the whole cross-section

2.2.1. Coefficient of Restraint Method

Bleich introduced a method in which the cross-section is divided into individual plate elements, each influenced by adjacent plates through a coefficient of restraint, and the buckling behavior is analyzed using the single-plate buckling analysis.

2.2.2. Method to consider cross-section as a whole

Bulson proposed a method for solving the local buckling problem of a plate assembly simultaneously; however, it is limited to the case of simple uniform compression.

2.2.3. Rectangular plates subjected to linearly compressive stresses having unloaded edges generally supported

Kang proposed an exact analytical method to solve the buckling problem of rectangular plates under linearly distributed compressive stress and general boundary conditions, utilizing a polynomial series function.

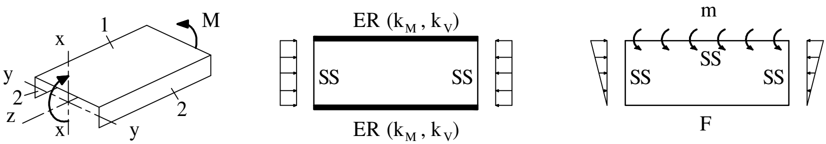
2.3. Summary

This chapter has presented the strength theories based on the Direct Strength Method (DSM), the existing analytical methods for determining the elastic critical stress due to local buckling of the entire cross-section, and recent research on the stability of thin plates with general boundary conditions under non-uniform compressive stress.

CHAPTER 3. CALIBRATION OF CLOSED-FORM FORMULAE FOR ELASTIC LOCAL BUCKLING COEFFICIENT OF COLD-FORMED MEMBERS BENT ABOUT ASYMMETRICAL AXIS HAVING THE WEB IN COMPRESSION

This chapter develops the Restraining Stiffness Method (RSM) to address the elastic local buckling behavior of entire cross-sections. The method is then employed to derive an analytical expression for the local buckling coefficient of cold-formed channel cross-section members subjected to bending about the asymmetrical axis, with the web in compression.

3.1. Restraining Stiffness Method to solve the buckling problem of the entire cross-section



a) Cross-section b) Buckling plate c) Restraining plate

Fig. 3.1 Calculation model of RSM

The RSM uses the following assumptions:

The initial state for solving the buckling problem is the equilibrium state of the loaded members;

The plate assembly is consecutive;

The cross-section is open. The outermost boundary conditions are known;

The cross-section is formed by right angles. Rounded corners are neglected;

The material behaves within the elastic range.

3.1.1. Rectangular plates subjected to linearly compressive stresses having unloaded edges generally supported

The study of Kang on the buckling problem of rectangular plates subjected to linearly compressive stresses having unloaded edges generally supported is presented in matrix form and is utilized in this section.

The deflection function is expressed as power series as follows:

$$w \quad \sin m \qquad \overset{i}{\underset{i\ \ 0}{}} \quad {}_{m,i} \quad C_m^* \tag{3.1}$$

Thus

$$w \quad K_{m,w} C_m^* \sin m \tag{3.2}$$

$$K_{m,} \; C_m^* \sin m \tag{3.3}$$

$$M_y \quad K_{m,M} C_m^* \sin m \tag{3.4}$$

$$V_{yT} \quad K_{m,VT} C_m^* \sin m \tag{3.5}$$

The system of equilibrium equations is

$$K_m^* C_m^* \quad P \tag{3.6}$$

where K^*_m is the 4x4 stiffness matrix, formed by four 1x4 sub-stiffness matrices K_{m0}, K_{m1}, K_{m2}, and K_{m3}, each of them can be $K_{m,w}$, $K_{m,\theta}$, $K_{m,M}$, or $K_{m,VT}$ in Eqs. (3.2) to (3.5). When i approaches infinity, the stiffness matrix K^*_m in Eq. (3.6) approaches a definite matrix.

3.1.2. Rotational stiffness on one longitudinal edge of a plate subjected to linearly distributed stress on transverse edges

Let the edge $y = 0$ subjected to a moment of $M_0 \sin m$ and compute the corresponding rotation angle θ, the rotational stiffness of the plate along this edge can then be calculated as follows

$$k_M \quad \frac{D}{bC_{m,1}} \quad 1u \tag{3.7}$$

3.1.3. *Translational stiffness*

A restraining plate can be idealized as a simply supported beam subjected to a sinusoidal load. The translational stiffness provided by the restraining plate to the adjoining plate is determined by dividing the applied load q by the corresponding deflection w

$$k_V \quad \frac{m^2 \quad ^2}{a^2} \; N_{cr,m} \quad N \tag{3.8}$$

The cross-section to determine the translational stiffness consists of the restraining plate itself and a half of the width of each adjoining plate. The total axial force N in the restraining body is obtained by summing the axial forces N_i contributed by each individual component of the combined section.

3.1.4. *Determination of the critical stress on the buckling plate*

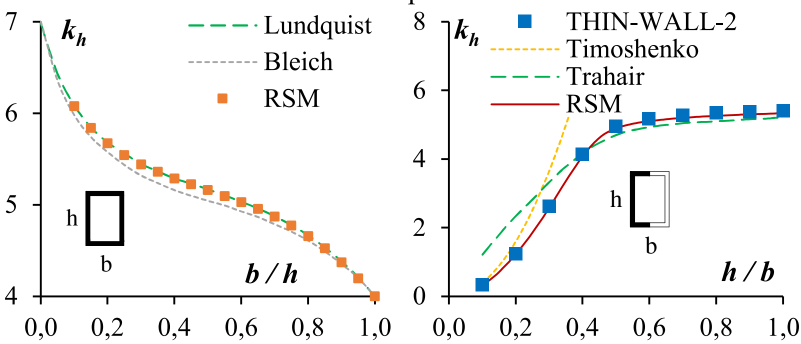
The boundary stiffness of the buckling plate is determined through an iterative procedure, starting from the outermost plate and progressing inward toward the buckling plate. This process results in a polynomial eigenvalue problem. The solution method presented here is a trial-and-error method, based on the condition that the determinant of the matrix K^*_m equals zero.

3.1.5. *Method validation*

A comparison show that the RSM results consistent with other existing methods over all existing charts, with a small error margin of approximately 2%. Furthermore, the RSM results also agree well with those obtained from other numerical methods.

3.1.6. Negative stiffness

This study proposes the application of negative stiffness. The restraining plate weakens the buckling plate by providing negative stiffness through the common edge. As a result, the critical stress of the restraining plate increases while that of the buckling plate decreases until the two values are equal.



a) Tube in compression b) Tube in *y*-axis bending

Fig. 3.2 RSM validation

3.2. Using RSM to calibrate buckling coefficient formulae

This section proposed a set of equations to calculate the buckling coefficient of channel cross-section members subjected to bending about the asymmetrical axis with the web in compression. These equations result from a parametric study and regression on the data obtained by RSM. The following assumptions are used:

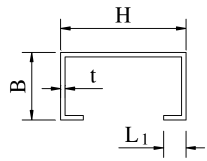
The channel section is subjected to bending about the asymmetrical axis, with the web in compression.

The material behaves within the elastic range.

The member experiences local buckling in compressed web.

3.2.1. Sampling plans

The geometric parameters vary within the range of: $H = 200$ mm, $B = 15 \sim 500$ mm, $L_1 = 0 \sim 90$ mm, $t = 0{,}7 \sim 3{,}2$ mm, to generate 1576 models.



3.2.2. Modeling and method

The calculation model of the channel section flexural member is a simply supported beam subjected to concentrated end moments.

3.2.3. Results and discussions

All studied cross-sections exhibit local buckling of the web as the governing buckling mode.

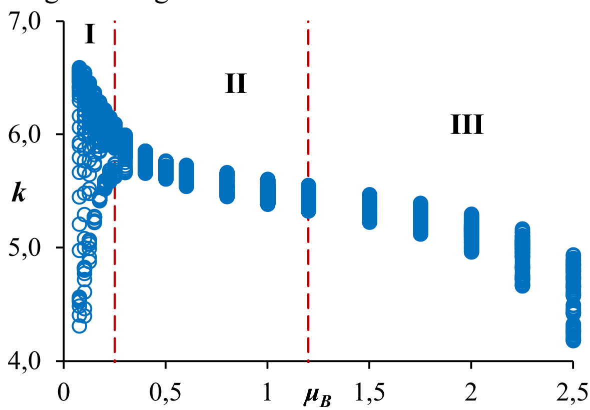


Fig. 3.3 Buckling coefficient with respect to *B*/*H* ratio

Fig. 3.3 presents the buckling coefficients calculated by the RSM. The variation of the buckling coefficient with respect to the flange width (μ_B) in Fig. 3.3 exhibits a explicit trend and can be divided into three distinct regions.

3.2.4. Buckling coefficient formulas calibration

Based on Fig. 3.3, the elastic critical stress at the mid-plane of a thin-walled channel section member subjected to bending about the asymmetrical axis with the web in compression is proposed to be determined by the following equation:

$$_{cr} \quad k^{*} \frac{^{2}E}{12 \;\; 1 \qquad ^{2}} \;\; \frac{t}{H} \;\; ^{2} \qquad (3.9)$$

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$$k^{*} \quad C \; C_{R} k \qquad (3.10)$$

$$C_{R} \quad 1 \quad 0{,}18 \;\; _{R} \quad 34{,}6 \;\; _{R}^{2} \qquad (3.11)$$

$$C \quad \begin{matrix} 1{,}04 \quad 0{,}04 \;\; _{0{,}3} & _{B} \;\; 0{,}5 \\ 1{,}0 & _{B} \;\; 0{,}5 \end{matrix} \qquad (3.12)$$

Table 3.1 Expressions of core buckling coefficient *k*

$0{,}075 \quad _{B} \quad _{B0}$	$_{B0} \quad _{B} \;\; 1{,}2$	$1{,}2 \quad _{B}$
$k_{0} \quad \frac{_{B} \quad 0{,}075}{_{B0} \quad 0{,}075} \;\; \begin{matrix} 5{,}45 \;\; _{B0}^{\;\;0{,}05} \\ k_{0} \end{matrix}$ where $k_{0} \quad 7{,}2 \quad \frac{0{,}1}{_{L}} \quad 0{,}97 \;\; _{t} \quad 4{,}2$	$5{,}45 \;\; _{B}^{\;\;0{,}05}$	$5{,}73 \quad 0{,}95 \;\; _{b}$ $0{,}98 \;\; _{b}^{2}$ $0{,}36 \quad 0{,}2 \;\; _{L} \quad _{b}^{3}$ where $_{b} \quad _{B} \quad 0{,}5$

Note

$$_{B0} \quad 0{,}21 \quad 0{,}34 \;\; _{L}^{0{,}4} \quad 0{,}06 \;\; _{t} \quad 0{,}08$$

$$_{B} \;\; \frac{B}{H} \qquad _{t} \;\; \frac{t}{H} \;\; 100 \qquad _{L} \;\; \frac{L_{1}}{H}$$

Scope of application

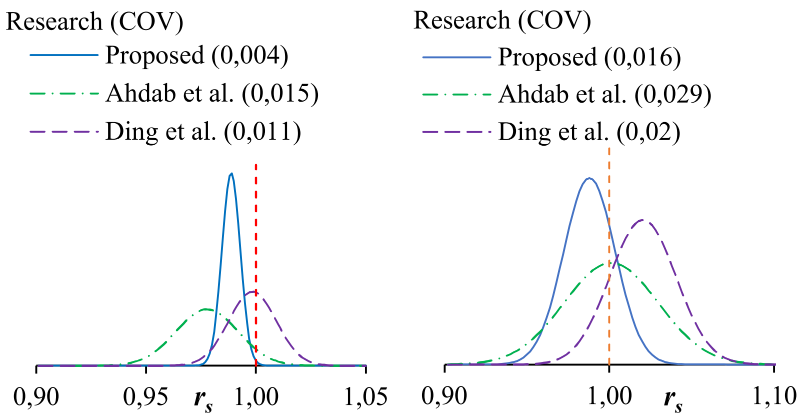
$$0{,}075 \quad _{B} \quad 2{,}5 \qquad 0{,}35 \quad _{t} \quad 1{,}6 \qquad 0 \quad _{L} \quad 0{,}45$$

3.2.5. Reliability of the proposed formulas

The proposed formula in this thesis has been compared with the formulas developed by Ahdab and Ding, and it demonstrates higher accuracy, as shown in Table 3.2. The proposed formula also shows the best agreement with the simulation results from THIN-WALL-2 and CUFSM (see Fig. 3.4).

Table 3.2 Accuracies of proposed expressions over expanded cross-section set

Stage	Proposed		Ahdab et al.		Ding et al.	
	ε_{min}	ε_{max}	ε_{min}	ε_{max}	ε_{min}	ε_{max}
Stage 1	-18,4	5,7	-7,3	36,4	-30,1	13,4
Stage 2	-5,0	5,6	-6,5	9,9	-23,8	6,8
	(-1,8)	(4)	(-1,9)	(9,9)	(0,7)	(6,8)
Stage 3	-0,7	4,2	-20,2	18,2	-	-
Total	-18,4	5,7	-20,2	36,4	-30,1	13,4



a) Over THIN-WALL-2 results b) Over CUFSM results

Fig. 3.4 The distribution density of similarity over existing data

3.3. Summary

The validation results show that the RSM yields an error of approximately 2%, demonstrating its accuracy and potential for practical applications. The proposed formula in this thesis for calculating the critical stress of cold-formed channel section members subjected to bending about the asymmetrical axis, with the web in compression, exhibits higher accuracy compared to previously proposed formulas in the literature.

CHAPTER 4. PROPOSAL TO IMPROVE THE DSM STRENGTH PREDICTION FOR COLD-FORMED CHANNEL MEMBERS BENT ABOUT THE ASYMMETRICAL AXIS HAVING THE WEB IN COMPRESSION

This chapter conducts a study and proposes a modified formula to improve the accuracy of strength prediction for cold-formed channel cross-section steel members subjected to bending about the asymmetrical axis, with the web in compression.

4.1. Ultimate strength determination using NLFEA

The GMNIA method (Geometrically and Materially Nonlinear Analysis with Imperfections Included) in ABAQUS is used to determine the ultimate strength of thin-walled members in this thesis.

4.1.1. Material model

The materials used include hot-rolled carbon steel (using a bilinear plus nonlinear hardening model) and cold-formed steel (using a two-stage Ramberg–Osgood model).

4.1.2. Geometric imperfection

The first buckling mode was used to represent the distribution of geometric imperfections along the length of the beam and factored by the maximum geometric imperfection of 0,66t.

4.1.3. Modeling

A simply supported beam model is employed to investigate the strength of channel cross-section members subjected to pure bending about the asymmetrical axis.

4.1.4. Element type and meshing

Models are meshed into S4R elements with seed size of H/40.

4.1.5. Sampling plan

The parameters vary within the range of: H = 100 ~ 400 mm, t = 0,8 ~ 3,2 mm, B/H = 0,2 ~ 2,5, L_1/H = 0,04 ~ 0,18, F_y = 250 ~ 550 MPa. Totally 1440 models are created.

4.1.6. Current DSM equation assessment by EWM

The flexural strength of the studied cross-sections was calculated using the EWM method. A difference of up to 2,6 times was observed between the results of the EWM and DSM methods, indicating that the DSM method requires improvements to enhance its accuracy.

4.2. Modeling validation

Before officially developing the strength database, the modeling procedure using Python needs to be validated against existing studies to ensure its accuracy.

4.2.1. Comparison with Oey and Papangelis's results

The similarity between the simulation results of this thesis and those of Oey and Papangelis has an average value of 1,014 and a COV of 0,011, indicating that the model used in this study is consistent with the one used in the research by Oey and Papangelis.

4.2.2. Comparison with experimental results

The numerical strength predictions in this study show strong agreement with the experimental results obtained by Yu, Fan, and Winter, confirming the reliability of the proposed model and its suitability for further applications.

4.3. Simulation results of the extensive sample set

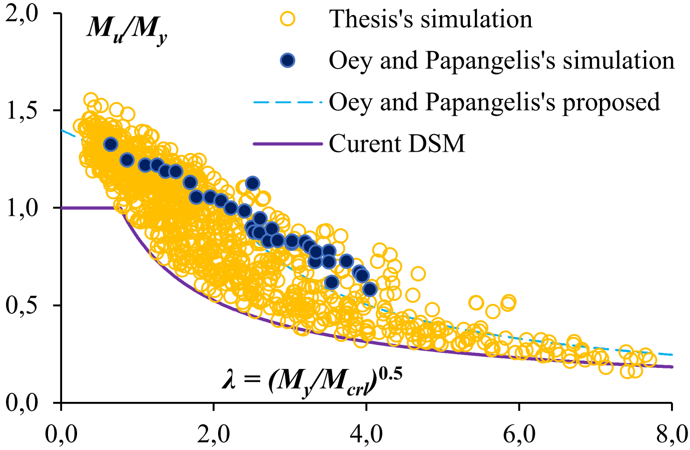


Fig. 4.1 ABAQUS strength simulation results

Fig. 4.1 illustrates the strength simulation results obtained from ABAQUS. As the range of variation in the input geometric parameters is expanded, the current DSM curve is observed to fall below nearly all newly generated data points, leading to an excessively conservative safety factor. This observation underscores the necessity for refining the existing DSM formulation to improve its predictive accuracy.

4.4. Formula proposal for predicting the ultimate strength of members bent about the asymmetrical axis with the web in compression

4.4.1. Discussions on simulation results

The strength data are grouped by the *B*/*H* ratio. When *B*/*H* is small, the data points deviate significantly from the current DSM curve. As *B*/*H* increases, the strength decreases, and the data points gradually approach the DSM curve, converging at *B*/*H* = 2,5. The "power" form of the current DSM formulation continues to be observed across all *B*/*H* ratios. Thus, the new strength equations in the form of the current DSM expression can be proposed.

4.4.2. Proposal for strength prediction

Newly proposed strength equations are based on the current DSM formula, considering inelastic flexural reserve capacity with some modifications

$$\text{For} \quad {}_0 \quad M_u \quad 1 \quad / {}_0 \; M_p \quad / {}_0 \; M_y$$

$$\text{For} \quad {}_0 \quad M_u \quad C \quad \frac{M_{cr}}{M_y}^{0,4} \quad \frac{M_{cr}}{M_y}^{0,4} \quad M_y \qquad (4.1)$$

where the key coefficients λ_0, C, and ψ are the functions of the aspect ratio *B*/*H*, determined by

$$\begin{aligned} {}_0 \quad & 1{,}77 \quad 0{,}4\,B/H \\ C \quad & 1{,}55 \quad 0{,}22\,B/H \qquad (4.2) \\ & 0{,}065\,B/H \end{aligned}$$

The graphical results are shown in the figure below.

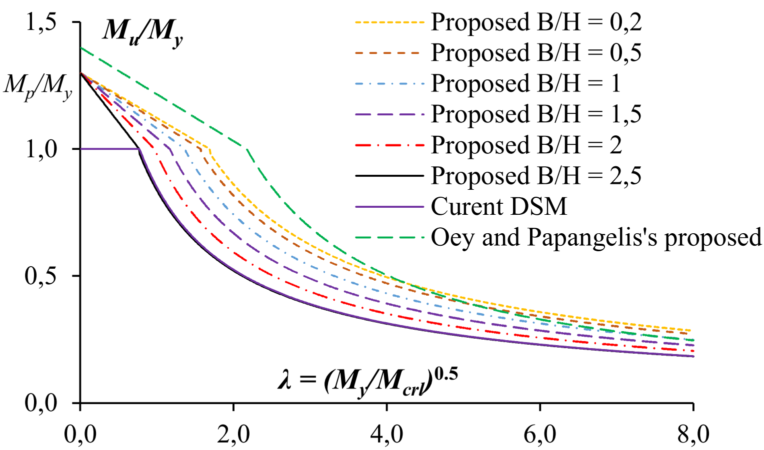


Fig. 4.2 Proposed strength curves presented by *B/H*

The evaluation of the proposed DSM are presented in Fig. 4.3.

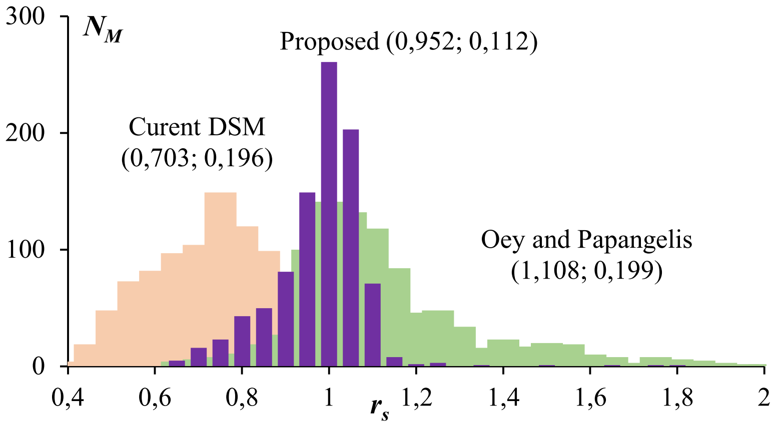


Fig. 4.3 Similarity distribution of the DSM equations

4.5. Proposed equation validation

The proposed strength formula was validated against experimental results from Winter, Yu and Laboube, and Fan et al. The results indicate that the proposed formula in this thesis demonstrates high accuracy, with an average similarity of 0,947. In contrast, the current DSM formula tends to be overly conservative, with an average similarity of 0,695, while the formula proposed by Oey and Papangelis tends to be unconservative, showing an average similarity of 1,101

Notably, the proposed strength formula in this thesis predicts more accurately than the other two formulas for high section ratios (B/H = 1,0), but it does not outperform them at low B/H ratios.

4.6. Reliability analysis

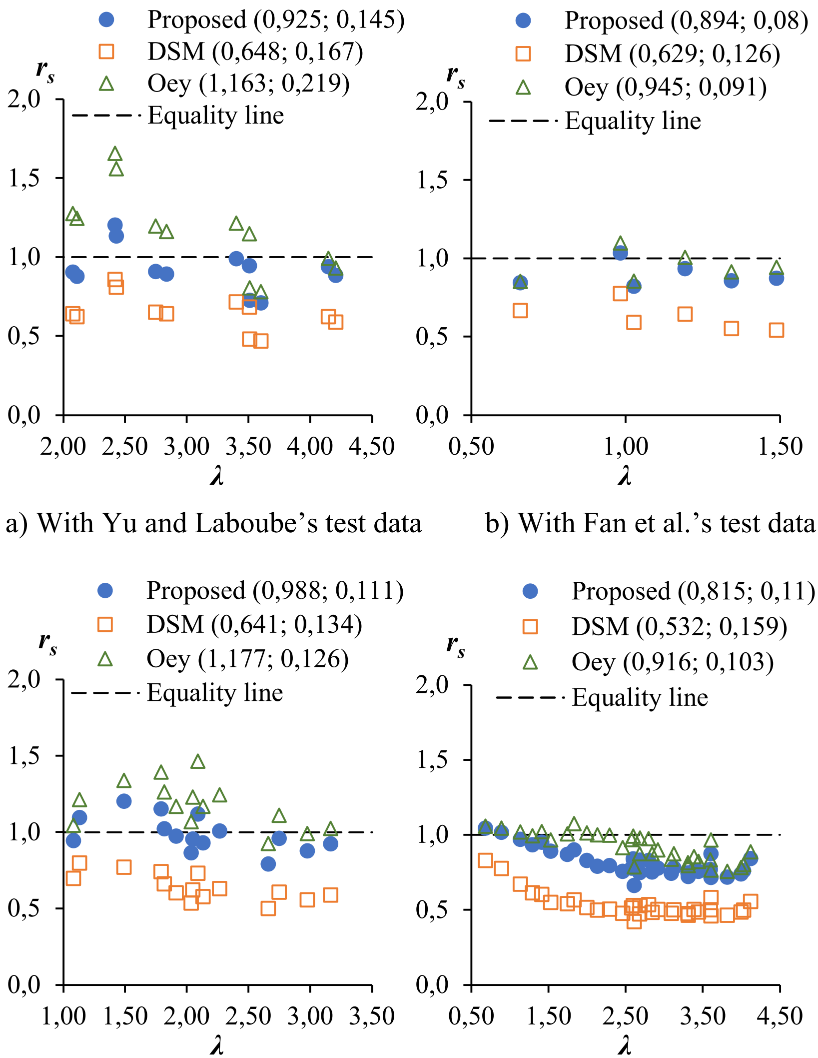
The reliability index, determined according to the AISI S100 standard corresponding to a safety factor of 0,9, is 2,55, which exceeds the target reliability index, thereby confirming the reliability of the proposed formulas..

4.7. Application example

Examples have been presented to illustrate the application of the proposed strength formulas.

4.8. Summary

CHAPTER 4 proposes a new DSM expression for calculating the strength of thin-walled C-section members subjected to bending about the asymmetrical axis with a compression web. The proposed formula is more general and accurate than both the current DSM formula and the formula proposed by Oey and Papangelis.



a) With Yu and Laboube's test data b) With Fan et al.'s test data

c) With Winter's test data d) With Oey's simulation data

Fig. 4.4 Validation against experimental and simulation results

CONCLUSIONS AND PROPOSALS

Conclusions

Recognizing the limitations of the DSM strength prediction formula in the AISI S100 standard when applied to cold-formed channel sections subjected to bending about the asymmetrical axis with a compression web, this thesis has conducted research to propose improvements to enhance the formula's accuracy. A method for determining the buckling coefficient of the entire cross-section (the Restraining Stiffness Method - RSM) was developed in CHAPTER 3, combined with a closed-form formula to calculate the critical moment of the whole section, which is one of the essential input values for the DSM strength calculation. The RSM method was developed based on Bleich's Coefficient of Restraint method, with three main improvements: (i) using a generalized power series for the deflection instead of specific functions; (ii) incorporating the translational stiffness (k_V); and (iii) introducing the concept of a "Restraining Body" which may include multiple plates, and employing an iterative procedure to calculate the stiffnesses. Thanks to these improvements, the RSM method has been extended to members with complex cross-sectional shapes and load conditions, including channel cross-section members subjected to bending.

The critical moment of the entire cross-section was calculated using the practical formula proposed in CHAPTER 3. Finite element analysis in ABAQUS was employed to compute the strength of 1,440 sections made from hot-rolled carbon steel and cold-formed steel. Consequently, the relationship between strength and critical moment was evaluated, and adjustments to the current DSM formula were proposed to improve its accuracy when applied to channel cross-section members subjected to bending about the asymmetrical axis with a compression web. The proposed DSM formula was validated against various experimental and simulation data.

Throughout the research process, the thesis has achieved the following results:

New contributions of the thesis

1. Development of a new analytical method (RSM) to address the problem of local elastic buckling of the entire cross-section. The RSM method can be applied to open cross-sections composed of continuously folded steel plates with very small errors (approximately 2%), paving the way for the application of analytical methods to complex cross-sections under generalized loading conditions in practice.

2. Development of a practical formula to determine the buckling coefficient for cold-formed C-shaped steel members subjected to bending about the asymmetrical axis with the web in compression. Compared to previously proposed formulas, the advantages include: a simpler form; higher accuracy (maximum error reduced by about 50%); wider range of applicability; consideration of more influencing factors; and reduced dependence on specialized software.

3. Proposal of the new DSM strength formula to be applicable to cold-formed C-shaped steel members subjected to bending about the asymmetrical axis with the web in compression. The improved formula establishes a relationship between strength and the cross-sectional aspect ratio B/H, thereby achieving significantly higher

accuracy (an increase of 1,36 times) compared to the current DSM formula.

Future research directions of the thesis

Extend the proposed DSM formula to other cross-sections and material types, including alloys.

Extend the proposed DSM formula to cold-formed steel channel members subjected to bending about the asymmetrical axis with the web in tension. The strength development in this loading case differs from that with the web in compression, as distortional buckling becomes the dominant failure mode.

Proposals

The research presented in this thesis, along with numerous other studies, has highlighted existing limitations of the current DSM formula when applied to members subjected to bending about the asymmetrical axis. Therefore, the standards committee may consider the thesis's proposals to improve the accuracy of the current DSM formula.

The proposed strength formula in this thesis for channel sections under asymmetrical axis bending has been validated against experimental data as well as a large number of simulation results, providing sufficient reliability for structural engineers and designers to apply it in practice for cold-formed steel structures.

LIST OF PUBLICATIONS RELATED TO THE THESIS

1. Vu, H.H., Q.A. Vu, and C.H. Pham, *Enhanced strength prediction of cold-formed lipped channels bent about asymmetrical axis*, Journal of Constructional Steel Research, 2025,Vol. 236. Elsevier B.V. ISSN 0143-974X. **SCIE Q1**. DOI: https://doi.org/10.1016/j.jcsr.2025.109941
2. Vu, H.H., Q.A. Vu, and C.H. Pham, *Approximate formula for local buckling in thin-walled channels bent about the asymmetrical axis*, Journal of Constructional Steel Research, 2025,Vol. 232. Elsevier B.V. ISSN 0143-974X. **SCIE Q1**. DOI: https://doi.org/10.1016/j.jcsr.2025.109647
3. Vu, H.H., Q.A. Vu, and C.H. Pham, *Local buckling coefficients for thin-walled lipped channels under bending about asymmetrical axis.* Results in Engineering, 2025. Vol. 26. Elsevier B.V. ISSN 2590-1230. **ESCI Q1**. DOI: https://doi.org/10.1016/j.rineng.2025.104935
4. Vu, H.H., Q.A. Vu, and C.H. Pham, *Global Buckling Strength of Girts with Inner Flange in Compression.* Civil Engineering Journal, 2024. Vol. 10. Salehan Institute of Higher Education. ISSN 2676-6957. **Scopus Q1**. DOI: https://doi.org/10.28991/CEJ-2024-010-11-05
5. Vu, H.H., Q.A. Vu, and C.H. Pham, *Convergence study on asymmetrically flexural problem of cold-formed channel sections.* International Journal for Computational Civil and Structural Engineering, 2024. Vol. 20. ASV Publishing House. ISSN 2587-9618. **Scopus Q3**. DOI: https://doi.org/10.22337/2587-9618-2024-20-4-23-30
6. Vu, H.H., Q.A. Vu, and C.H. Pham. *Evaluation of the software's reliability in solving the buckling problem of the cold-formed plain c-section member bending about its asymmetrical axis*. in *Structural Health Monitoring & Engineering Structures Conference, Da Nang, Vietnam, Lecture Notes in Civil*

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7. Vu, H.H., Q.A. Vu, and C.H. Pham. *Calculation Guide of Cold-Formed Channel Girts by AISI S100 Using DSM Analytical Solution*. in *Proceedings of the 7th International Conference on Geotechnics, Civil Engineering and Structures, CIGOS 2024*. 2024. Ho Chi Minh City, Vietnam. Springer Nature. ISSN 2366-2557. **Scopus**. https://doi.org/10.1007/978-981-97-1972-3_20
8. Vu, H.H., Q.A. Vu, and C.H. Pham. *Behavior of Cold-Formed Channels with a V-shape Web Stiffener Bending About the Asymmetrical Axis*. in *7th International Conference on Geotechnics, Civil Engineering and Structures, CIGOS 2024*. 2024. Ho Chi Minh City, Vietnam. Springer Nature. ISSN 2366-2557. **Scopus**. https://doi.org/10.1007/978-981-97-1972-3_18
9. Vu, H.H. *Accurate model for simply supported plates*. In *XXVII International Scientific Conference on Advance in Civil Engineering "Construction the Formation of Living Environment" (FORM-2024)*. 2024. E3S Web of Conferences. ISSN 2267-1242. **Scopus**. https://doi.org/10.1051/e3sconf/202453303002
10. Hoàng V.H. *Kiểm tra độ bền uốn kết hợp của thép tạo hình nguội theo tiêu chuẩn AISI S100 (AISI S100 to check cold-formed flexural members for biaxial bending strength)*. Tạp chí xây dựng. 2024. Số 4. ISSN 2734-9888.
11. Hoàng, V.H., N.T.T. Hương. *Độ bền của cấu kiện chữ C tạo hình nguội chịu uốn quanh trục không đối xứng theo các phương pháp của Tiêu chuẩn AISI S100 (Ultimate strength of flexural cold-formed channel members subjected to asymmetrical axis bending using AISI S100 methods)*. Tạp chí xây dựng. 2025. Số 11. ISSN 2734-9888.