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CONVERGENCE STUDY ON ASYMMETRICALLY FLEXURAL PROBLEM OF COLD-FORMED CHANNEL SECTIONS

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Abstract: Current Direct Strength Method equations computing flexural strength of cold-form members were reported to be over-conservative when applied to members bent about the asymmetrical axis. Finite Element Analysis was used to develop new equations. However, the convergence study, which ensures the accuracy of the Finite Element Analysis result, has not been presented clearly. Thus, this paper performed a convergence study on the strength problem of channel-section asymmetrically flexural members having the web in compression. 33 cold-form channel cross-sections utilized in Oey and Papagelis' study were modeled into ABAQUS to calculate the elastic buckling moment and the ultimate strength. Two factors affected the accuracy of the models, i.e., the mesh size, being 5 mm, $D/20$, $D/40$, and $D/60$, and the member length, ranging from 0.3D to 7D, where D is the cross-section height, were examined. The investigation shows that the seeding method considering the local buckling of the web is the most justifiable. Therefore, the seed size being 1/40 the cross-section height is suggested. This seed size is proven to produce results with reasonable accuracy. To avoid the end effect as well as the influence of incorrect half-wavelength, it is recommended that the member length should be chosen as greater than or equal to two times the cross-section height, and the lengthier the better.

Keywords: Convergence study, cold-formed, thin-walled, channel section, asymmetrical axis, Finite Element Analysis, Finite Element Method

ИССЛЕДОВАНИЕ СХОДИМОСТИ РЕШЕНИЯ ЗАДАЧИ НЕСИММЕТРИЧНОГО ИЗГИБА ХОЛОГНУТЫХ ШВЕЛЛЕРОВ

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Аннотация: Используемые в настоящее время уравнения метода прямой оценки прочности для оценки несущей способности подверженных изгибу конструкций из холодногнутых профилей являются слишком консервативными применительно к конструкциям, изогнутым вокруг асимметричной оси. Для построения новых уравнений было использовано моделирование методом конечных элементов. Однако исследование сходимости решения, которое бы обеспечивало необходимую точность результатов расчета по методу конечных элементов, ранее не было представлено в явном виде. Таким образом, в данной работе было проведено исследование сходимости решения задачи о несущей способности при несимметричном изгибе швеллеров со сжатой стенкой. В ABAQUS были смоделированы 33 поперечных сечения холодно гнутых швеллеров, рассмотренные ранее в исследовании Оэя и Папагелиса. Вычислялись момент потери устойчивости в упругой постановке и прочность сечений. На точность моделей влияли два фактора: размер сетки разбиения (5 мм, D/20, D/40 и D/60) и длина конструктивного элемента (от 0,3D до 7D, где D - высота сечения). Исследование показало, что наиболее оправданным является шаг разбиения, позволяющей учесть местную потерю устойчивости стенки швеллера. Поэтому предлагается использовать размер сетки разбиения, равный 1/40 высоты стенки. Доказано, что такой размер ячейки сетки разбиения позволяет получить результаты с достаточной точностью. Чтобы избежать краевых эффектов, а также влияния неправильной длины полуволны, рекомендуется выбирать длину элемента больше или равной двукратной высоте поперечного сечения, при этом чем больше длина, тем лучше.

Ключевые слова: Исследование сходимости, холодно гнутые профили, тонкостенные профили, швеллер, ось симметрии, конечно-элементный анализ, метод конечных элементов

1 INTRODUCTION

The ultimate strength problem of cold-form members bent about the asymmetrical axis using the Direct Strength Method (DSM) is under investigation due to the finding that the current DSM analytical equations for the flexural member listed in relevant codes, i.e., AISI S100 [1] and AS/NZS 4600:2018 [2] are over-conservative for this type of member. Finite Element Analysis (FEA) is the primary tool for calibrating the newly efficient equations.

A convergence study is an important step in ensuring the accuracy of the Finite Element Analysis result. Some studies have been carried out on many types of problems. For example, a mesh convergence study was conducted by Hemesh Patil and P. V. Jeyakarthikeyan (2018) [3] using ANSYS on the hub of the automotive clutch disc assembly. Abdulsalam (2021) [4] has investigated the meshing sensitivity of Abaqus/CAE software to the problem of compact tension specimens. The resultant stresses and strains were discussed. Aron (2024) [5] analyzed displacement versus force, stress-strain relationship, maximum force, and stress for a series of mesh sizes of a rectangular hollow steel column using ABAQUS. On the problem of cold-formed steel channels bent about the asymmetrical axis, Oey and Papangelis (2021) [6] has utilized a mesh size comprising 97 nodes along the cross-section and extruding at 5 mm increments along the longitudinal length of the member. A finer element sizes were employed at the corners of the channel sections. The method produced the largest mesh size of 12 x 5 mm. To avoid the end effect on the instability of the web, the length of the member was chosen as 5 times the section height. However, no details about the convergence study were provided.

To more effectively deal with the mesh convergence problem in Abaqus/CAE, D. H. Vu (2022) [7] has introduced a method that uses the integrated Python script to refine automatically the mesh and update the system.

The literature review shows that the convergence problem of channel cross-section cold-formed members bent about the asymmetrical axis with the compressive web using Finite Element Analysis has not been discussed clearly. Therefore, it will be presented in this paper. Python scripts are a great help to solve a series of analogous problems with varying parameters.

2 MATERIALS AND METHODS

ABAQUS/CEA 2020 was selected to solve FEA problems in this study. Its reliability has been validated against the buckling problem of the cold-formed plain C-section member bending about its asymmetrical axis [8].

The full 3D shape of plain channel cross-section simply-supported beams subjected to bending about the asymmetrical axis having the web in compression was modeled into the software as a shell (see Fig. 1). The shell was then meshed into S4R elements [9, 10]. S4R is a 4-node, quadrilateral, stress/displacement shell element with reduced integration and a large-strain formulation. The mesh density is a factor causing the error of the FEA result and therefore was taken into account for the study.

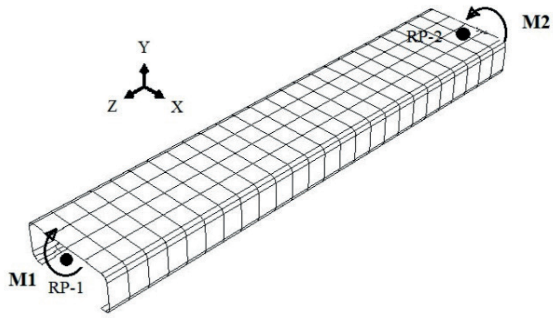


Figure 1. Model in ABAQUS

Member sections are 33 cross-sections utilized in Oey and Papangelis's study [6]. Thus, the modeling in this study can be verified in Section 3.1 by the results from that paper.

ABAQUS's "Rigid Body" constraint combined with "Reference Point" was used to facilitate the assignment of loads and support conditions at the member ends. Research shows that the function is useful but also results in some errors because it prevents the edges of plate elements from deforming freely [11]. "Rigid Body"'s end effect and the influence of member length is the second subject to be investigated.

To model a simple beam, one end reference point was assigned a boundary condition eliminating the transition in all three directions (Pinned type, $U_1 = U_2 = U_3 = 0$), the remaining point in *x*- and *y*- directions (ZASYMM type, $U_1 = U_2 = UR_3 = 0$). All three rotational restraints were free. The loads are a pair of opposite-sign concentrated moments applied on reference points in the cross-section's symmetrical plane (*y*0*z* plane) which causes the web to be compressed. The magnitude of moments is 1 kN.m for the buckling problem. The value of the critical moment archived from the buckling problem was then assigned to reference points in the same process to simulate the load of the ultimate strength problem.

The Ramberg-Osgood material model was used which best describes the behavior of high-strength steel [6, 12]. The grades of steel are G450, G500, and G550 [13] associated with each cross-sectional as outlined in [6]. The elastic modulus *E* and the Poisson ratio *v* are 200000 MPa and 0.3, respectively.

Four seed sizes were investigated in this study. The first is a fixed size of 5 mm. This seed size was used by Oey and Papagelis [6] to mesh the longitudinal edge of the member. In their study, Oey and Papagelis recognized that the buckling of the web dominates the behavior of channel members bent about the asymmetrical axis when the web is in compression. This phenomenon can also be seen in Fig. 5. Thus, seed sizes related to the web width, represented by the cross-section height *D*, were considered. They are relative seed sizes of *D*/20, *D*/40, and *D*/60.

A "Buckle" step of the "Linear Perturbation" category was derived from the original one to solve the buckling problem in the elastic range of materials. As for the ultimate strength, the "Static, Risk" step dealing with non-linear analysis was added. Appropriate values of parameters of the above steps were carefully selected to ensure the convergence of problems.

Geometry imperfection [14] was also taken into account in the ultimate strength problem. The imperfection surface adopted the first local buckling mode [15] of the web with the largest magnitude of 0.66*t* [6, 16], where *t* is the thickness of the cross-section.

3 RESULTS

3.1 Model's input validation

First, the correctness of the modeling process was checked by comparison to the result obtained by Oey and Papangelis [6]. The member length is taken as five times the cross-section height according to [6].

The term "Similarity" is defined in this paper to describe how close one value is to another. It is designated as the ratio between two numbers. The similarity being equal to unity means that two values are equal and close to unity means that one value is in good accuracy compared to the other.

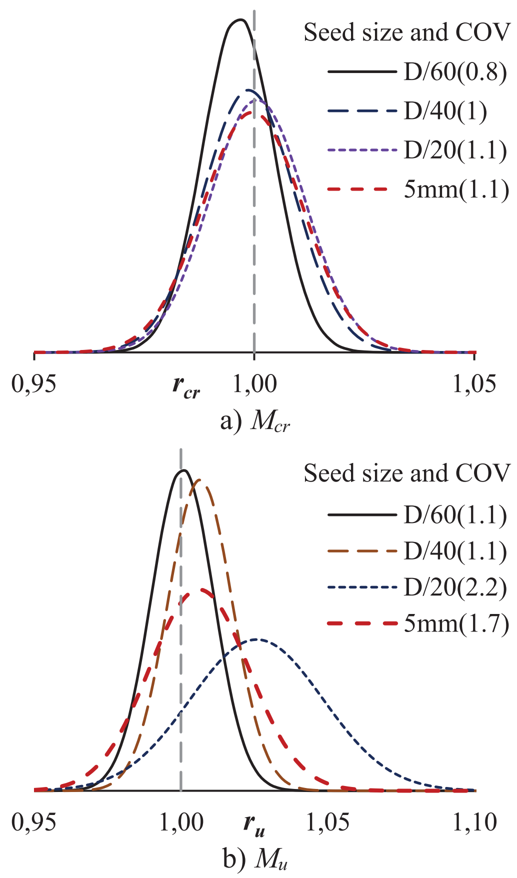


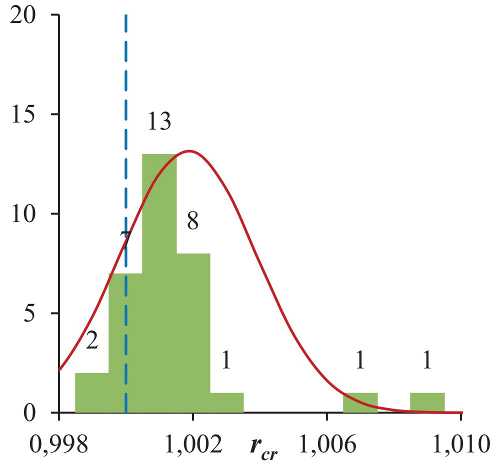
Figure 2. Normal distribution of similarities to Oey's research

The critical moments M_{cr} and ultimate strengths M_u of 33 cross-sections were determined using ABAQUS for four seeding methods. The similarities between these moments and the result of Oey and Papangelis were computed, where r_{cr} and r_u. represent the ratio between two buckling moments and that of two ultimate strengths, respectively. The probability density function (PDF) for each case of seeding was built in a process detailed in Section 3.2. Finally, these functions were summarized and plotted in Fig. 2.

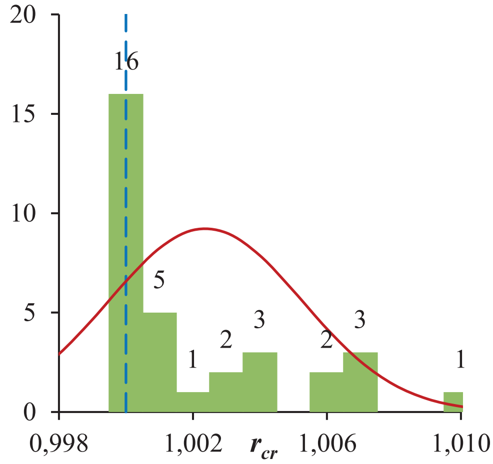
The outcome shows that the buckling moments and the ultimate moments archived from models in this study are nearly identical to those calculated by Oey and Papangelis. The means of similarities are very close to 1. The biggest is 1.026 belonging to the $D/20$ seed size case in calculating M_u. The other means are within 1% of unity. The corresponding coefficient of variance COV is also small, about 1 to 2 percent. It means that the models are reliable. Then the next phase was carried out and presented in the next sections.

3.2 Mesh density assessment

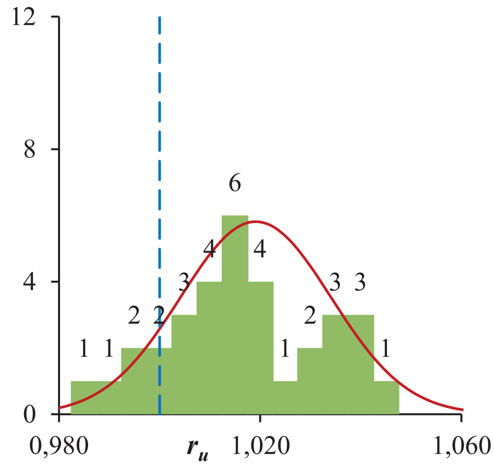
The convergence study is to compare the results of one mesh density to those of the next finer density until the difference between the two adjacent densities is acceptable. Three seed sizes, $D/20$, $D/40$, and $D/60$, were based on the governing buckling mode of the cross-section. i.e., the local buckling of the web. They establish a series of similar seeding methods. The mesh size of 5 mm is of intermediate accuracy and does not have a solid base. Thus, it is not important and excluded from the study. The remaining three seed sizes form two pairs for comparison, $D/20$ to $D/40$, and $D40$ to $D/60$. Thus, the similarities between the coarser and the finer ($D/20$ over $D/40$, $D/40$ over $D/60$) in a pair will be calculated (it is different from Section 3.1 where all the values are compared to the Oey and Papangelis's). Intervals were determined and the number of similarities inside each interval was counted and shown as column diagrams in Fig. 3. The mean value μ, the standard deviation σ, and the coefficient of variation COV were computed and listed in Table 1. The associated probability density functions (PDF) are also shown in Fig. 3.



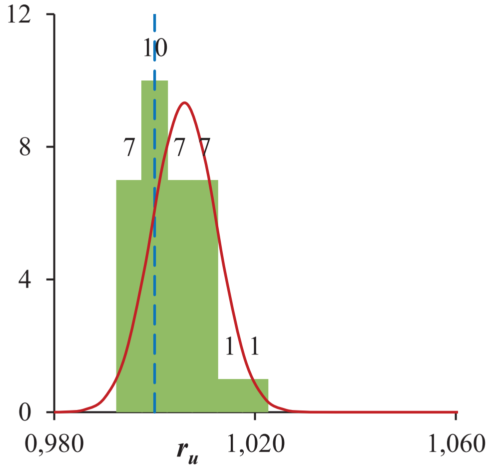
a) Similarities of M_{cr} ($D/20$ to $D/40$)



b) Similarities of M_{cr} ($D/40$ to $D/60$)



c) Similarities of M_u ($D/20$ to $D/40$)



d) Similarities of M_u (D/40 to D/60)

Figure 3. Probability density of ratio between values in a pair of mesh sizes

Fig. 3a, Fig. 3b and Table 1 show that the effectiveness of meshing methods of *D*/20 and *D*/40 are analogous. The mean values are the same and very close to unity. The COVs are both small. The maximum error rate is only 1%. Thus, both mesh sizes, *D*/20 and *D*/40, are suitable for the buckling moment determination.

Table 1. Statistical values in Fig. 3

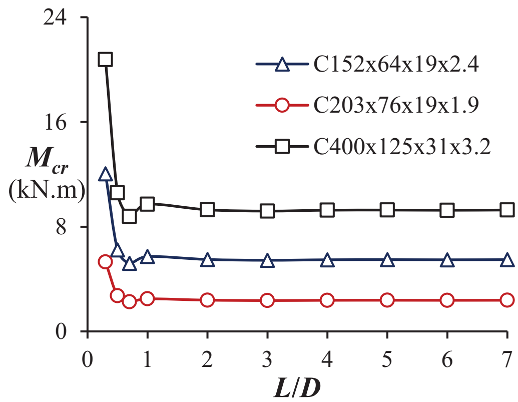
Item	M_{cr}		M_u	
Seedzise	*D*/20	*D*/40	D/20	D/40
μ	1.002	1.002	1.019	1.006
σ	0.0020 2	0.0028 8	0.0149 7	0.0064 1
COV (%)	0.20	0.29	1.47	0.64
ε_{max} (%)	1.0	1.0	4.7	2.3

For the ultimate moment, there is a big difference between Fig. 3c, and Fig. 3d. The values in Fig. 3d associated with the seed size of D/40 is more compact, which means that it is more reliable than seed size D/20 (Fig. 3c). The mean value of seed size D/40 is closer to unity than that of seed size *D*/20. The COV and the maximum error of seed size *D*/40 are a half smaller than those of seed size *D*/20. As for the seed size *D*/40, its mean value of 1.006, the COV of only 0.64%, and the maximum error of 2.3% are all within the expected range. Therefore, the seed size of *D*/40 is suitable for the current problem.

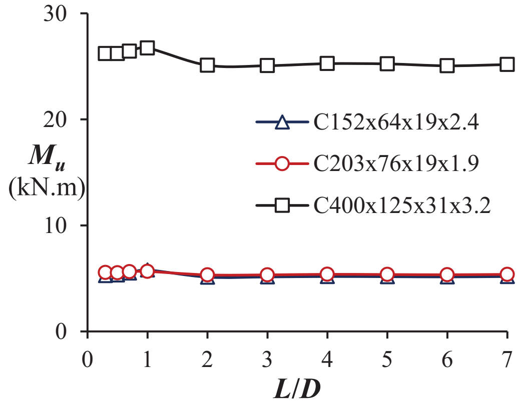
3.3 Member's end effect discussion

Three channel cross-sections of C152x64x19x2.4, C203x76x19x1.9, and C400x125x31x3.2 with a series of member length to cross-section height ratios (length/height ratio for short) including 0.3, 0.5, 0.7, 1, 2, 3, 4, 5, 6, and 7 were modeled in ABAQUS using the seed size of *D*/40. The elastic buckling moments and the ultimate strengths were determined and plotted against the *L*/*D* ratios in Fig. 4.

It can be observed that the trends of curves concerning three cross-sections are the same for both critical buckling moment and ultimate strength. In the small length/height ratio range, i.e., *L*/*D* < 1, the end constraint causes a large effect on the buckling moment while having little impact on the ultimate strength. The end effect fades after the member length exceeds two times the cross-section height for both critical buckling moment and ultimate strength with maximum differences to the values of *L*/*D* = 7 being 0.88% for the former and 1.1% for the latter.



a) M_{cr}



b) M_u

Figure 4. The moments with respect to L/D ratio

Therefore, it can be concluded that the length/height ratio greater than or equal to 2 gives sufficient accuracy.

The effect of the member length on the buckling moment can be easily seen from the buckle shapes in Fig. 5. The number of half-waves is always a whole number. Thus, different member lengths result in different half-wavelengths, as seen in Fig. 5c and Fig. 5d. As the member length increases, this effect reduces. Especially, when the member length is less than and equal to *D*, only one half-wave is observed (see Fig. 5a and Fig. 5b). The half-wavelength is equal to the member length. It explains the large change in the early stage of the critical moment curve. Since the ultimate moment is related to the buckling moment through the imperfection, its value can be seen to have a certain variation over the short member length range.

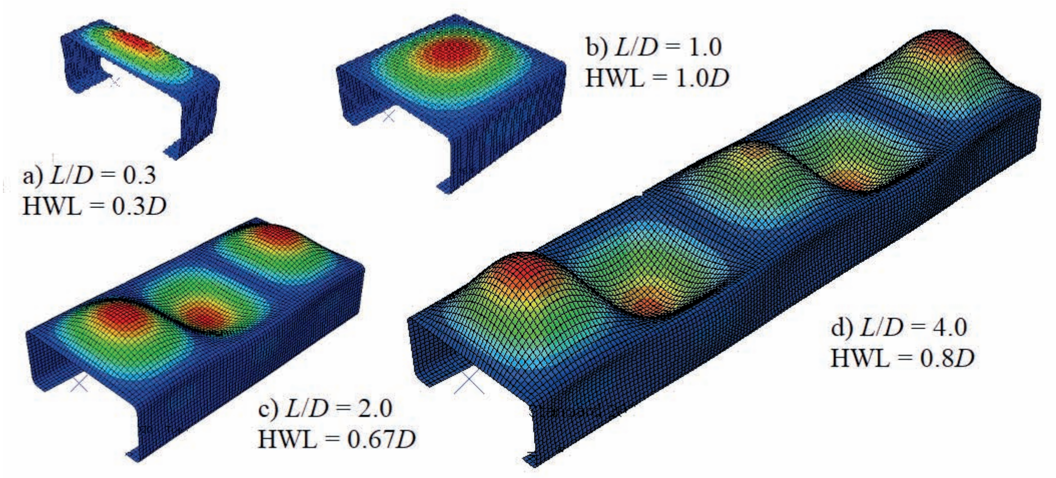


Figure 5. The half-wavelength with respect to L/D ratio

4 CONCLUSION

Convergence of the FEA elastic buckling and non-linear strength problems of cold-form channel cross-section members bent about the asymmetrical axis having the web in compression was investigated. The meshing method and reasonable member length were discussed.

The mesh size of *D*/40 is recommended for the current problem. Compared to Oey and Papagelis's meshing solution, the mesh size of 1/40 of the web depth is simpler. The method is more justifiable because it allows for the dominated buckling mode of the cross-section, i.e., the local buckling of the web. The method also gives a high accuracy with a mean similarity of 1.006 and COV of 0.64% compared to the next meshing step.

Another factor affecting the accuracy of the current problem is the member length. The lower bound of the member length to cross-section height ratio to eliminate the end effect is 2. It shows that the ratio of 5 utilized in Oey and Papagelis's study is conservative. Lower values may be considered to reduce the number of elements and thus the calculation time.

REFERENCES

1. AISI, AISI S100-16 North American Specification for the Design of Cold-Formed Steel Structural Members, 2016 Edition. 2016, American Iron and Steel Institute.
2. AS/NZS 4600:2018 Cold-formed steel structures. 2018, Australian/New Zealand Standard.
3. **Patil, H. and P.V. Jeyakarthikeyan,** Mesh Convergence Study and Estimation of Discretization Error of Hub in Clutch Disc with Integration of ANSYS, in 2nd International Conference on Advances in Mechanical Engineering (ICAME 2018).

2018, IOP Publishing Ltd: Kattankulathur, India.
4. **Abdulsalam, H.,** Mesh Sensitivity Assessment on 2D and 3D Elastic Finite Element Analysis on a Compact Tension Specimen Geometry Using Abaqus/CAE Software, in 4th International Conference/Training Workshop on Energy for Sustainable Development in Africa 11th - ICTWESDA 2020. 2021, IOP Publishing Ltd: University of Nigeria, Nsukka, Enugu State, Nigeria.
5. **Aron, M.A.H.,** The Mesh Convergence Analysis of a Rectangular Hollow Steel Column Using ABAQUS, in Department of Civil Engineering. 2024, Rajshahi University of Engineering & Technology: Bangladesh.
6. **Oey, O. and J. Papangelis**, Behavior of cold-formed steel channels bent about the minor axis. Thin-Walled Structures, 2021. Vol. 164.
7. **Vu, D.H.**, Developing Python scripting for mesh convergence in ABAQUS, in Journal of Science and Technique. A Section on Special Construction Engineering. 2022: Hanoi, Vietnam.
8. **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. 2023. International Journal of Civil Engineering, Springer.
9. SIMULIA. http://130.149.89.49:2080/v2016 /index.html. 2016 [cited 2024 Aug, 9th].
10. SIMULIA, Abaqus/CAE User's Manual. 2011, Providence, RI, USA: Dassault Systèmes Simulia Corp.
11. **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.
12. **Gardner, L. and X. Yun,** Description of stress-strain curves for cold-formed steels. Construction and Building Materials, 2018. Vol. 189: p. 527–538.
13. **Australia, S.,** AS 1397:2021 Continuous hot-dip metallic coated steel sheet and strip - Coatings of zinc and zinc alloyed with aluminum and magnesium. 2021, Standards Australia.
14. **Schafer, B.W., Z. Li, and C.D. Moen**, Computational modeling of cold-formed steel. Thin-Walled Structures, 2010. Vol. 48(Issues 10–11): p. 752-762.
15. **Yu, C. and B.W. Schafer**, Simulation of cold-formed steel beams in local and distortional buckling with applications to the direct strength method. Journal of Constructional Steel Research, 2007. Volume 63(Issue 5): p. 581-59.
16. **Schafer, B.W. and T. Pekoz**, Computational modeling of cold-formed steel: characterizing geometric imperfections and residual stresses. Journal of Constructional Steel Research, 1998. Vol. 47(3): p. 193–210.

СПИСОК ЛИТЕРАТУРЫ

1. AISI, AISI S100-16 North American Specification for the Design of Cold-Formed Steel Structural Members, 2016 Edition. 2016, American Iron and Steel Institute.
2. AS/NZS 4600:2018 Cold-formed steel structures. 2018, Australian/New Zealand Standard.
3. **Patil, H. and P.V. Jeyakarthikeyan,** Mesh Convergence Study and Estimation of Discretization Error of Hub in Clutch Disc with Integration of ANSYS, in 2nd International Conference on Advances in Mechanical Engineering (ICAME 2018). 2018, IOP Publishing Ltd: Kattankulathur, India.
4. **Abdulsalam, H.,** Mesh Sensitivity Assessment on 2D and 3D Elastic Finite Element Analysis on a Compact Tension Specimen Geometry Using Abaqus/CAE Software, in 4th

International Conference/Training Workshop on Energy for Sustainable Development in Africa 11th - ICTWESDA 2020. 2021, IOP Publishing Ltd: University of Nigeria, Nsukka, Enugu State, Nigeria.
5. **Aron, M.A.H.,** The Mesh Convergence Analysis of a Rectangular Hollow Steel Column Using ABAQUS, in Department of Civil Engineering. 2024, Rajshahi University of Engineering & Technology: Bangladesh.
6. **Oey, O. and J. Papangelis**, Behavior of cold-formed steel channels bent about the minor axis. Thin-Walled Structures, 2021. Vol. 164.
7. **Vu, D.H.**, Developing Python scripting for mesh convergence in ABAQUS, in Journal of Science and Technique. A Section on Special Construction Engineering. 2022: Hanoi, Vietnam.
8. **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. 2023. International Journal of Civil Engineering, Springer.
9. SIMULIA. http://130.149.89.49:2080/v2016/index.html. 2016 [cited 2024 Aug, 9th].
10. SIMULIA, Abaqus/CAE User's Manual. 2011, Providence, RI, USA: Dassault Systèmes Simulia Corp.
11. **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.
12. **Gardner, L. and X. Yun,** Description of stress-strain curves for cold-formed steels. Construction and Building Materials, 2018. Vol. 189: p. 527–538.
13. **Australia, S.,** AS 1397:2021 Continuous hot-dip metallic coated steel sheet and strip - Coatings of zinc and zinc alloyed with aluminum and magnesium. 2021, Standards Australia.
14. **Schafer, B.W., Z. Li, and C.D. Moen**, Computational modeling of cold-formed steel. Thin-Walled Structures, 2010. Vol. 48(Issues 10–11): p. 752-762.
15. **Yu, C. and B.W. Schafer**, Simulation of cold-formed steel beams in local and distortional buckling with applications to the direct strength method. Journal of Constructional Steel Research, 2007. Volume 63(Issue 5): p. 581-59.
16. **Schafer, B.W. and T. Pekoz**, Computational modeling of cold-formed steel: characterizing geometric imperfections and residual stresses. Journal of Constructional Steel Research, 1998. Vol. 47(3): p. 193–210.

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