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APPLYING OPTIMIZATION TECHNIQUES ON COLD-FORMED C-CHANNEL SECTION UNDER BENDING

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There are no standard dimensions or shapes for cold-formed sections (CFS), making it difficult for a designer to choose the optimal section dimensions in order to obtain the most cost-effective section. A great number of researchers have utilized various optimization strategies in order to obtain the optimal section dimensions. Multi-objective optimization of CFS C-channel beams using a non-dominated sorting genetic algorithm II was performed using a Microsoft Excel macro to determine the optimal cross-section dimensions. The beam was optimized according to its flexural capacity and cross-sectional area. The flexural capacity was computed utilizing the effective width method (EWM) in accordance with the Egyptian code. The constraints were selected so that the optimal dimensions derived from optimization would be production and construction-friendly. A Pareto optimal solution was obtained for 91 sections. The Pareto curve demonstrates that the solution possesses both diversity and convergence in the objective space. The solution demonstrates that there is no optimal solution between 1 and 1.5 millimeters in thickness. The solutions were validated by conducting a comprehensive parametric analysis of the change in section dimensions and the corresponding local buckling capacity. In addition, performing a single-objective optimization based on section flexural capacity at various thicknesses The parametric analysis and single optimization indicate that increasing the dimensions of the elements, excluding the lip depth, will increase the section's carrying capacity. However, this increase will depend on the coil's wall thickness. The increase is more rapid in thicker coils than in thinner ones.

Key words: cold-formed sections, single optimization, multi-objective optimization, genetic algorithms , effective width method, C-channel beams.

1. Introduction

Optimizing the design of CFSs can result in more cost-effective and efficient solutions. However, because of the complicated behavior of CFS parts, getting optimal design solutions might be a difficult challenge. Three structural unsTab.modes are likely to occur in CFS compression members: local, distortional, and flexural/flexural-torsional buckling. CFS members' cross-sectional optimization approaches can be characterized as follows: shape optimization, without regard for starting constraints on its shape or size optimization, and cross section relative dimensions with a specified shape optimization. One of the optimization techniques is the single optimization problem, and it is classified as: the minimization problem, in which CFS is applied to reach the minimum area of the cross section taking into consideration the serviceability and design constraints, is classified as a maximization problem, in which CFS is applied to obtain the maximum capacity of the section while satisfying the design, construction, and fabrication constraints. However, these two problems can be solved together as multi-objective optimization to get a number of helpful solutions (Pareto solutions). There are two paths for optimization framework. The first path is stochastic search (heuristic methods), examples for this method are genetic algorithms and particle swarm optimization. The other path is formal mathematical programming (former methods), examples of this method are sequential quadratic programming and Lagrange multiplier. Numerous aspects of evolutionary algorithms or heuristic methods make them ideal for solving real-world optimization problems to a desired level of satisfaction.

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A number of researchers have made comparisons between different design methods used for designing CFS. They have also conducted parametric studies before applying optimization to the studied CFS in their research. Tran and Li [1] applied optimization to a C-lipped channel beam and the aim was to minimize the coil width. Researchers also did a parametric study on the beam to check the influence of dimension changes on the studied section capacity. Moreover, they have used the British code and the European code to estimate the section local buckling capacity. They found that the section thickness has a small impact on the distortional buckling moment capacity. On the other hand, the distortional buckling affects the other section dimensions. In addition to that, they found that the optimum section is controlled by the moment of distortional buckling. Lu [2] used Eurocode-3 to investigate the capacity of Z and Σ shapes of cold-formed steel purlins. They conducted parametric analysis on these purlins to determine the effect of dimensions on the behavior of cold-formed purlins Z-shape and also to determine the effect of the position and size of web stiffener on the behaviour of purlins Σ-shape. They also performed optimization on these two cross sections used as purlins using genetic algorithms. The design of CFS follows the effective width design of Eurocode-3. The optimization objective is to make purlin load efficiency maximized while adhering to the geometric limits imposed by Eurocode-3. The cross-sectional dimensions that satisfy the highest capacity requirements were presented in the form of optimum design curves for various load levels.

Ye *et al.* [3] had compared the capacity of C-channel cold-formed beams estimated using Eurocode-3, which follows the EWM in cold-formed steel design, to that calculated utilizing the direct strength approach introduced by the American requirements. They applied size optimization and heuristic methods by establishing a novel practical framework to optimize a cold-formed steel C-channel beam with intermediate stiffeners. They determined that the most ideal cross section was the lipped channel section by one stiffener positioned at the web in the compression zone. They also discovered that the direct strength approach overestimates an unsupported beam's capacity by 36%. Numerous academics have proposed employing optimization techniques for cold-formed steel cross sections selection and design Leng *et al.* [4] used formal optimization tools to create nonconforming cold-formed steel cross sections. They sought to maximize cold-formed steel column compressive strength. The optimized sections' final capacities are confirmed to be double that of typical cold-formed steel lipped channels. Optimal shapes, on the other hand, were completely impractical. Madeir *et al.* [5] optimized cold-formed steel columns using a bi-objective approach to make the local-global buckling strength and the distortional buckling strength maximized. For symmetric and antisymmetric cross section configurations, trade-off Pareto optimum fronts are produced individually. They discovered that while variation in optimal local-global strength is inversely related to variation in ideal distortional strength, symmetrical shapes outperform anti-symmetrical designs when distortional strength maximization is desired. However, when maximizing local-global strength is required, anti-symmetrical structures take precedence over symmetrical shapes.

Lee *et al.* [6, 7] optimized the geometry of cold-formed steel channel beams and columns when subjected to a uniformly distributed load and a compressive axial load, respectively. They optimized using a genetic algorithm, and throughout the optimization process, they included penalties in the objective function for breaking the American specifications' limitations. They sought to decrease the cross section's cross-sectional dimensions. Their numerical results are provided as optimum design curves for a range of load levels. Seaburg and Salmon [8] investigated the size of hat sections utilizing American standards using a gradient-based optimization methodology. They seek to determine the lightest possible cold-formed segment that will support a particular loading situation. American requirements are used to determine the minimum thickness that is permissible for a section whose other dimensions are regarded to be temporary. This defines the design's minimal weight for the specified set of dimensions. Both direct and gradient searches were investigated, with the latter proving to be more efficient. Tian and Lu [9] modified the dimensions of channel columns with and without lips to meet British code requirements and compared the performance of intuitively determined cross sections to cross sections discovered using sequential quadratic programming. They seek to determine the smallest possible size of the column's cross section under various boundary circumstances. The objective function was the cross-sectional area, whereas the constraint functions were the column's capacity in all failure types. Their numerical results were shown as optimal design curves for different types of boundary conditions.

Liu *et al.* [10] optimized the shape of cold-formed steel columns to carry the maximum critical load using a Baysian classification tree. The objective was to maximize buckling loads at the local, global, and distortional levels. On the other hand, the angle of the turn between adjacent parts was optimized. Constraint functions ensured that the folds remained within the dimensions of the steel sheet and that the cross section remained free of crossings. They had established a variety of cross-sectional shapes and their maximum carrying capacities. However, employing Baysian classification trees to limit the solution space needs expert knowledge that is not always accessible El Hady *et al.* [11]. Adeli and Karim [12] reported that the local weight minima for cold-formed hats, Z cross sections, and I-formed beams met American standards. Additionally, they determined the optimal design for hat-shaped beams and lipped channel sections on a global scale. Magnucki and Paczos [13] determine the cold-formed channel beams with open or closed drop flange profiles. Closed drop flange channel beams outperform open drop flange or conventional lip beams, according to the researchers. They described two C-sections using inertia moments and warping functions. The optimization objective function represented the weight of the beam. Global and local buckling, strength, and geometric constraints are all constraints.

Moharrami *et al.* [14] used evolutionary algorithms to optimize the morphologies of open CFS cross sections for compression. The set coil width and plate thickness remained unchanged throughout the optimization process. The objective function was defined as the minimization of the failure load determined in each of the three modes of failure subjected to a constraint function consisting of a vector of turn angles at a set of places along the coil width. The compressive strength was determined using both the Finite Strip and direct strength methods. Ma *et al.* [15] used the evolutionary algorithm toolkit in MATLAB to optimize cold-produced compression and bending elements according to Eurocode-3. They began with a simple lipped C-shape and optimized the design from there, but the approach also allows for the incorporation of double fold (return) lips, slanted lips, and triangular web stiffeners. The cross sections are optimized in terms of structural capacity, with the goal of maximizing capacity. They got two commercially accessible cross sections: one designed for compression at various lengths, either with or without regard to the effective shift, and the other optimized for cross-sectional bending capacity.

2. Material and method

The EWM is one of the most frequently used methods in the design of CFS. The EWM takes into account the effect of local buckling via the effective width concept. The effective width is the width that is used to compute all of the section's properties during the design process Yu [16]. The effective width stress distribution across a plate is depicted in Fig.1. Compression elements' effective widths are denoted by

$$\rho = {}^{b_e}\!\big/_{b} \tag{2.1}$$

where ρ is the reduction factor applied to the plate width and b and b_e are the plate's total and effective widths, respectively Mojtabaei *et al.* [17]. The Egyptian code of practice (ASD and LRFD) Arab Republic of Egypt [18], Arab Republic of Egypt [19]; use the EWM in calculating the local buckling capacity of CFS as Eqs (2.2) and (2.3);

$$\rho = \frac{(\lambda - 0.15 - 0.05\psi)}{\lambda^2} \le 1, \tag{2.2}$$

$$\lambda = \frac{\left({}^{b}\!/_{t}\right)}{44} * \sqrt{{}^{F_y}\!\big/_{K_\sigma}} \tag{2.3}$$

where λ is the slenderness ratio, F_y is the material yield stress, K_σ is the plate buckling factor which depends on the stress ratio at the end of the plate, while, ${}^{b}\!/_{t}$ is the width to the thickness ratio.

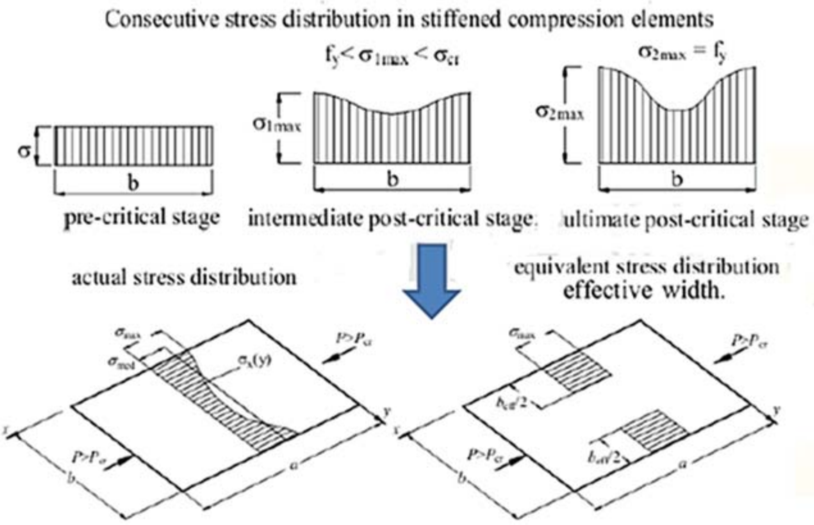

Fig.1. The effective width stress distribution [16].

Additionally, it is worth noting that determining the effective cross section in bending is an iterative process, as the effective cross-neutral section's axis shifts over a distance determined by the effective cross section loss in flanges and the upper portion of the web, affecting the stress distribution. Finally, the section's flexural strength owing to local buckling is determined using Eq.(2.4) for ASD and Eq.(2.5) for LRFD

$$M_{\mathrm{crl}} = \left(0.58 * F_y\right) * Z_e, \tag{2.4}$$

$$M_{\mathrm{crl}} = \left(0.8 * F_y\right) * Z_e \tag{2.5}$$

where M_{crl} is the critical elastic moment according to local buckling and Z_e is the elastic section modulus of the effective section calculated based on the extreme compression or tension fiber at F_y.

3. Problem statement

Choosing an optimization approach and methodology that is appropriate for CFS is a significant problem. Another difficulty is determining the most cost-effective cross section dimensions that meet the design criteria. Unfortunately, the number and complexity of parameters affecting CFS design impede the optimization process. The CFS optimization problem is extremely nonlinear in nature, with the objective function being a nonlinear function of the multi-design variables and the constraints being nonlinear at times as well. Optimization of CFS is defined as a problem of constraint satisfaction. The process of maximizing an objective function with regard to some variables in the presence of constraints on those variables is called constraint optimization.

In this paper, the dimensions of the elements of cold-formed laterally supported C-channel beams will be optimized with respect to their flexural capacity and cross-sectional area. A multi-objective optimization will be carried out using genetic algorithms. The difficulty in dealing with nonlinear optimization problems of CFS was handled by using the Egyptian code design regulations as a "black box" tool in the optimization procedure. The two objectives used in the optimization problem are maximizing the flexural capacity of the beam in the local buckling mode and minimizing the weight of the beam, which is taken as a function of the cross-sectional area.

The capacity of the section will be studied in the local buckling mode only, as the cold-formed beams are mainly used as secondary beams to support the cladding, so they will be laterally supported with no chance for the lateral torsional buckling mode to happen. While the distortional buckling mode is not mentioned in the Egyptian code, The many flat portions in the C-channel make it one of the most commonly used configurations. As in the fabrication field, the flat plate elements of the cross-section C-channel permit a straightforward manufacturing process, while in the construction field, the flat shape allows easy connections through the web element and the flange element. Figure 1 and Fig.2. shows the configuration of the C-channel cross section.

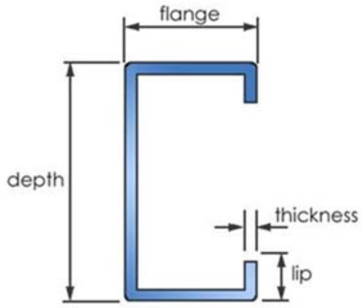

Fig.2. Cross section of C-channel section.

The aim of this paper is to apply a multi-objective optimization technique to cold-formed C-channel beams to acquire the optimum section dimensions using genetic algorithms. Also, multi-objective optimization will be applied to investigate its effect on the solution diversity when applied to CFS. The objective is as follows: applying multi-objective optimization in order to identify the effect of applying this technique to the results, creating an appropriate mathematical model for optimization that correctly simulates the problem obtaining in an accurate results, simulating the results from optimization to inspect the practicability of the results for the structural designer, which will be easier and more flexible to use in the design. Presenting the results in the form of tables and charts will make them easy to analyze, discuss, and use, and finally our objective is to investigate the influence of changing the dimensions of the different elements of the cross section (web depth, flange width, and lip depth) on the flexural capacity of the beam by creating and analyzing a parametric study.

4. Optimization

To maximize the projects' objectives under stated constraints, a multi-objective optimization model was constructed utilizing the NSGA-II approach. GA activities are carried out by the model in three distinct phases: (1) initialization of the population, (2) fitness assessment, and (3) generation evolution [20-22]. To handle the nonlinearity of the CFS design during optimization a developed visual basic program is used as a black box in the optimization model. The optimization will be done using a developed program in Microsoft Excel. This program has the ability to run multi-objective optimization problems successfully. To ensure that the results come from the optimization will be practical from the fabrication, construction and the design perspective, there will be upper and lower bounds for the variable used in the optimization problem (the cross-sectional dimensions). The upper bound will describe the design limitations in the local buckling mode (the width to the thickness ratio) introduced by the Egyptian code, while the lower bound will describe the minimum dimensions needed to satisfy the production and fabrication requirements. The coil thickness will be taken as discrete values describing the available coils in the market.

4.1. Description of the variables

The variables used in the optimization model are (t) is the coil thickness and it was taken as a discrete value and is equal to $(1.5, 2, 2.5, 3, 3.5, 4)$, (a) the web depth, (b) the flange width, and (c) the lip depth.

4.2. Description of the objective function

In the multi-objective optimization applied in this paper, there are two objectives used. There is a trade-off between these two objectives. The first objective function is to describe the flexural capacity of the section in the local buckling mode, and it should be maximized. The other is the area of the section, and it should be minimized. The flexural capacity is calculated using a program developed using visual basic, and this program will be used as a black box during the optimization process. The program can calculate the flexural capacity using the EWM under the provisions of the Egyptian code. The other equation in the multi-objective optimization is calculating the area of the cross section using the following equation:

$$Area = a*t + 2*t*(b-t) + 2*t*(c-t)\,. \tag{4.1}$$

4.3. Description of the constraints

Constrains are described using the upper and the lower limitations that ensure that the results will be practical from the fabrication, construction and the design perspective. The lower bound will be as follows (Fig.3):

I. The flange width should exceed $30\,mm$ to permit sufficient space for the connection between the flange and the metal decking, for example.
II. The lip depth should be at least ten millimeters to allow rolling or braking.
III. The minimum web depth should be $100\,mm$ to allow easy settlement of the connection between the web and any other portion.

While the upper bounds will explain the design limitations, they will be the width-to-thickness ratios of various cross-sectional parts in accordance with ECP [18, 19] (see Tab.1.).

Table 1. Listing the width to the thickness ratio (w/t) used in ECP.

Element	Web	Flange	Lip
w/t for different elements	200	60	40

There will be additional constraints describing the proportions of different elements to one another, and that is to ensure that the resulted sections are fully practical from the design perspective, these constraints are described in the chart below Fig.3.

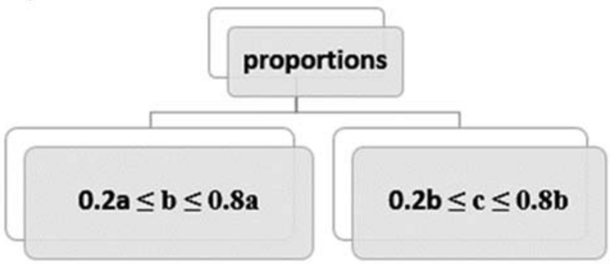

Fig.3. The ratios between elements used in the design of a cold-formed section where a is the web depth, b is the flange width and c is the lip depth.

4.4. Optimization results

In this paper, a multi-objective optimization problem is solved for a C-channel beam using genetic algorithms. The two objective functions were to maximize the local buckling moment capacity of the beam and minimize the cross-sectional area of the C-channel section. The results from the optimization problem are described in Tab.2. And Appendix 1 shows the optimal gross dimensions of 91 C-channel sections and the corresponding local buckling moment capacity and the corresponding gross area of the section while Fig.4. shows the Pareto optimal solution between the two objectives used in the optimization problem.

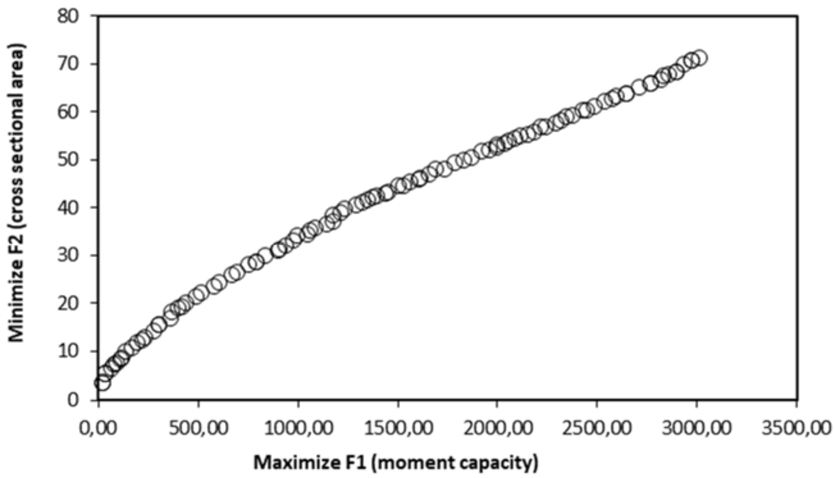

Fig.4. The Pareto optimal solution for the optimization problem.

5. Verification methods

5.1. Parametric study

The purpose of this research is to conduct a parametric investigation to determine the effect of altering the diameters of the elements in a CFS C-channel beam on the beam's moment capacity in the local buckling mode. To obtain more useful and trustworthy statistics, the dimensions of the C-channel elements are expressed as a percentage of the section's elements. The web depth (a) is infinitely variable and begins at $100\,mm$. The flange width (b) is calculated as a percentage of the studied web depth in random increments between 20% and 80%. The lip depth (c) is similarly expressed as a percentage; however, it is expressed as a percentage of the flange width, with random increments between 20% and 80%. Assume that the radius of curvature (R) is a constant value of four millimeters. Thickness (t) is defined as a discrete value between 1 and 1.5 millimeters, $2, 2.5, 3, 3.5$, and $4\,mm$. The yield strength is 2.4 tons per square centimeter, while the modulus of elasticity is 2100 tons per square centimeter. The dimensions of the parametric study's sections are summarized in Tab.2.

Table 2. Summary of the dimensions of the elements used in the parametric study.

Name of the element	Studied range	Increment
Web (a)	$100\,mm\ to\ 300*t$	random
Flange (b)	$0.2(ao)\ to\ 0.8(ao)$	random
Lip (c)	$0.2(bo)\ to\ 0.8(bo)$	random
Thickness (t)	$1.5\ to\ 4mm$	$0.5\,mm$

Some of the results from the parametric studies are shown in Figs 4, 5, 6. They illustrate the influence of the change in the cross-section dimensions on the local buckling capacity of the section at different coil thickness. The equation below Eq.(5.1) will be used to describe the variance in the moment capacities in all the charts shown in this section. The variance helps in investigating the influence of the dimension change in each element on the moment capacity of the section. Figure 5 depicts the effect of increasing the web depth on section capacity while keeping the percentage of the flange width constant at 50% of the web depth. In addition, the percentage of the lip depth was held constant at 50% of the flange width. The Figure 5 shows that the local buckling capacity of the section is directly proportional to the increase in the web depth and coil thickness. The curve at $t = 1.5$ shows the increase is smooth all over the studied depths with a variance of about $87\ \%$, and at $t = 2.5$ the increase starts to be more rapid with a variance of approximately $92\ \%$, while at $t = 3.5$ the increase was so rapid that the variance in the capacity of the section was more than $94\ \%$.

$$Variance = \frac{Maximum\,moment\,capacity\ \text{-}Minimum\,moment\,capacity}{Maximum\,moment\,capacity} \times 100\,. \tag{5.1}$$

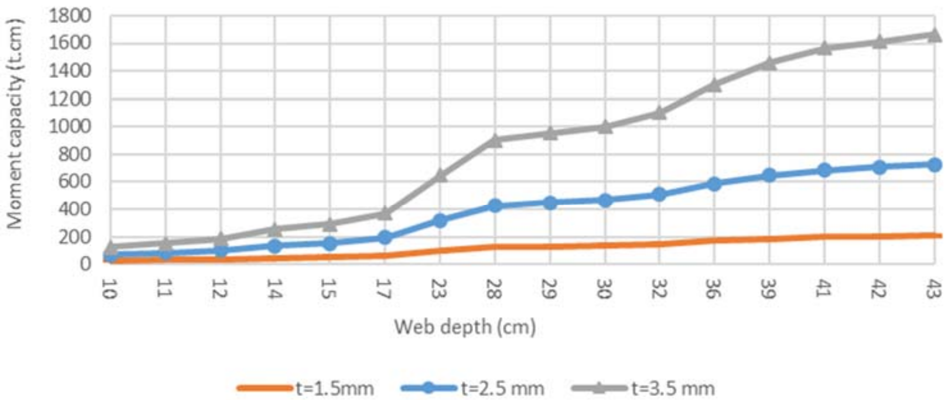

Fig.5. Comparison of local buckling moment capacities between different coil thicknesses at different web depths.

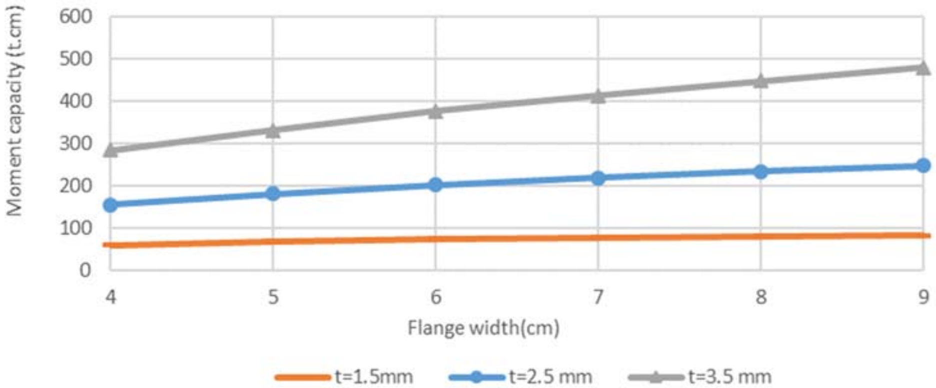

Fig.6. Comparison of local buckling moment capacities between different coil thicknesses at different flange width.

Figure 6 depicts the effect of increasing the flange width on section capacity at a constant web depth $(b = 20\,cm)$, while keeping the lip depth constant at 50% of the flange width. The Figure 6 shows that the local buckling capacity of the section is directly proportional to the increase in the flange and the coil thickness. The curve at $t = 1.5$ shows a slight increase in capacity with a variance of 27%, whereas the variance in the other two curves was roughly twice that at $t = 1.5$. Figure 7 shows the effect of increasing the lip depth on the capacity of the section at constant web depth (b=20 cm) and constant flange width $(c = 10 cm)$. The curve at $t = 1.5$ shows that the capacity was increasing between $c = 2 cm$ and $c = 3 cm$, then it starts to decrease as the lip depth increases. For the curve at $t = 2.5$, the capacity increases between $c = 2 cm$ and $c = 4 cm$, then it starts to decrease as the flange increases, while for the curve at $t = 3.5$, the capacity of the section increases with the increase in the lip depth (hint: it starts to decrease at a lip depth of $8 cm$).

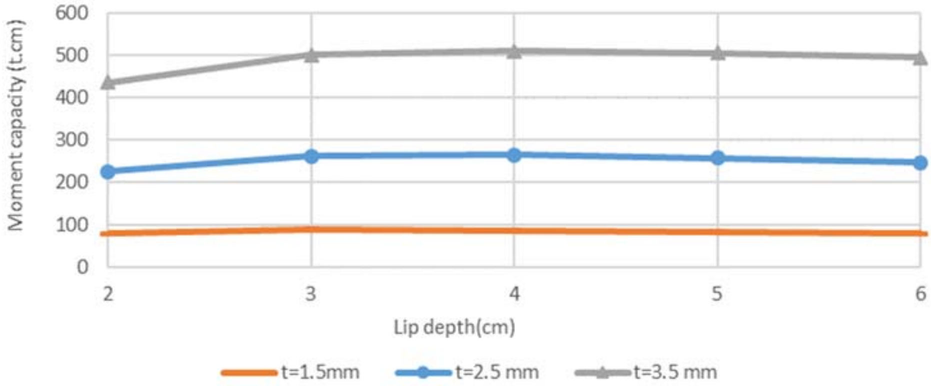

Fig.7. Comparison of local buckling moment capacities between different coil thicknesses at different lip depths.

5.2. Single optimization

Another method used in verification is applying single optimization for the seven discrete values of the thicknesses used in the multi-objective optimization, which were $1, 1.5, 2, 2.5, 3, 3.5$, and 4 millimeters. This will help in investigating the effect of increasing the thickness of the C-channel on the optimization results, and it will also help in exploring the directly and inversely proportional relationship between the moment capacity of the section and the increase in its element dimensions. The objective of the optimization problem was to maximize the moment capacity of the section using the same objective function used during multi-objective optimization. Also, the constraints, the upper and lower bounds, and the variables are the same as used during multi-objective optimization.

Table 3. and Fig.8. summarize the results of the single objective optimization. Showing that the capacity of the section is directly proportional to the increase in the thickness of the section and that the section capacity is directly proportional to the increase in the web and the flange dimensions and inversely proportional to the increase in the lip depth. As in each optimization run or for each thickness, the web depth and the flange width reached the upper bound, which was calculated according to the width to the thickness ratio following the Egyptian code (fully described in section 4.3), while for the lip depth, the upper-bound was not reached.

Table 3. Summary of the dimensions of the elements obtained from single optimization carried out at different thicknesses.

Section no.	$t(cm)$	$a(cm)$	$b(cm)$	$c(cm)$	Capacity $(t.cm)$
1	0.1	30	6	2.67	116.705
2	0.15	45	9	2.45	204.742
3	0.2	60	12	3.21	479.953
4	0.25	75	15	3.94	930.948
5	0.3	90	18	4.64	1601.107
6	0.35	105	21	5.40	2533.794
7	0.4	120	24	6.10	3772.425

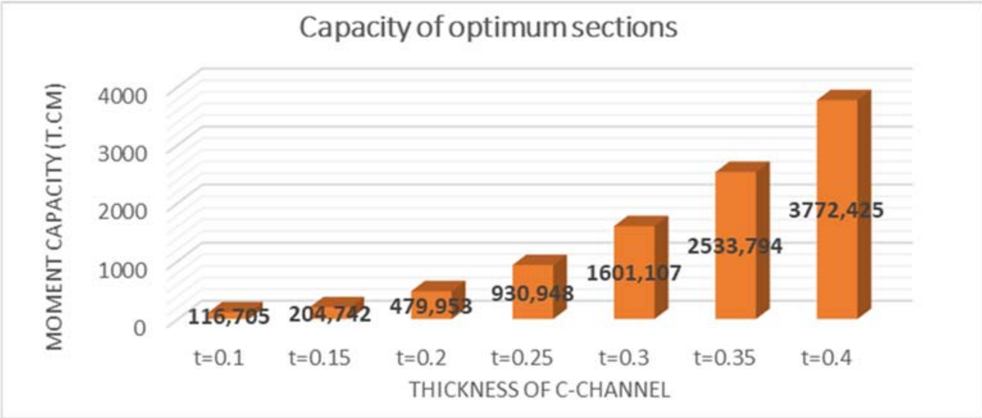

Fig.8. Moment capacity calculated using the dimensions obtained from single optimization at different thicknesses.

6. Summary and conclusion

Because there are no standard measurements or forms in CFS, it is difficult for a designer to choose the optimal section dimensions in order to obtain the cheapest section. Using evolutionary algorithms, this article performed multi-objective optimization on a C-channel beam. The optimization was accomplished by the development of a program in Microsoft Excel that utilized the NSGA-II technique to maximize the project's objectives within stated limits. For 91 parts, the Pareto optimum solution was obtained. The Pareto curve demonstrates that the solution is both diverse and convergent in its coverage of the objective space. Pareto optimum solution sets are frequently favoured over single answers because they are more practical when dealing with real-world situations, since the decision-final maker's solution is always a trade-off. The result demonstrates that there is no ideal solution between 1 and 1.5 millimetres in thickness. That is because the CFS behaviour is highly dependent on the section thickness; as the thickness grows, the effective width increases due to the reduction factor decreasing, resulting in an increase in capacity, and vice versa. Around 60% of answers are presented for coil thicknesses between 3.5 and $4\,mm$. The solution demonstrates a difference in the depth of the web, the width of the flange, and the depth of the lip. Additionally, it demonstrates that the section's capacity is directly proportional to all of the section's dimensions.

The parametric analysis indicates that increasing the size of the web or flange increases the section's capacity, but the rate of increase is dependent on the coil thickness; for thicker coils, the rise is greater than for thinner coils. While the relationship changes as the lip depth increases, it remains constant throughout the depths. However, as coil thickness increases, the domain or range of direct proportionality increases. Additionally, the results of the single optimization demonstrate that increasing the dimensions of the web, flange, and thickness increases the section's capacity, but increasing the lip depth does not. Finally, the designer can calculate the actual moment capacity of the beam based on the applied loads and compare it to the optimal solution obtained through multi-objective optimization in order to choose the section dimensions that are appropriate for the loads and boundary conditions of the section being designed. Knowing that the capacity used in the optimization is the allowable moment capacity in the local buckling mode calculated using the Egyptian code without taking the factor of safety into account in ASD or the reliability index into account in LRFD gives the designer a chance to choose the appropriate code.

Acknowledgment

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Nomenclature

b/t – width to the thickness ratio.

F_y – material yield stress,

K_σ – plate buckling factor which depends on the stress ratio at the end of the plate,

λ – slenderness ratio,

ρ – reduction factor

Appendix 1

Table 4. Results of the multi-objective optimization problem using genetic algorithm.

Sec no.	$a(mm)$	$b(mm)$	$c(mm)$	$t(mm)$	Moment capacity $(t.cm)$	Gross area (cm^2)
1	1197	240	61	4	3010.19	71.32
2	1192	233	62	4	2974.38	70.64
3	1181	230	61	4	2936.31	69.88
4	1199	206	57	4	2893.47	68.36
5	1192	201	59	4	2856.36	67.84
6	1179	203	61	4	2832.10	67.64
7	1199	188	56	4	2817.01	66.84
8	1187	183	56	4	2765.28	65.96
9	1193	169	57	4	2711.10	65.16
10	1161	171	54	4	2645.10	63.8
11	1143	169	59	4	2593.66	63.32
12	1134	170	55	4	2577.30	62.72
13	1111	173	58	4	2537.95	62.28
14	1093	171	54	4	2485.37	61.08
15	1068	175	54	4	2444.67	60.4
16	1053	179	56	4	2427.12	60.28
17	1031	180	55	4	2378.58	59.4
18	1041	166	58	4	2340.85	58.92
19	1026	169	55	3.5	2319.45	58.32
20	1011	171	54	3.5	2292.75	57.8
21	988	172	54	3.5	2242.95	56.96
22	989	165	59	4	2214.78	56.84
23	958	174	54	4	2180.47	55.92
24	954	169	54	3.5	2148.74	55.36
25	943	166	57	3.5	2110.74	54.92
26	929	168	57	3.5	2088.18	54.52
27	932	164	52	4	2056.42	53.92
28	904	170	54	3.5	2037.51	53.44
29	882	173	60	4	1996.35	53.28
30	884	171	54	3.5	1994.45	52.72
31	868	171	56	3.5	1957.03	52.24
32	883	159	54	4	1917.15	51.72
33	838	168	54	3.5	1871.28	50.64
34	824	167	54	3.5	1832.52	50
35	829	158	52	3.5	1783.18	49.32

cont. Table 4. Results of the multi-objective optimization problem using genetic algorithm.

Sec no.	$a(mm)$	$b(mm)$	$c(mm)$	$t(mm)$	Moment capacity $(t.cm)$	Gross area (cm^2)
36	774	170	54	4	1732.86	48.24
37	772	174	51	4	1691.65	48.24
38	743	170	54	3.5	1660.27	47
39	764	156	48	3.5	1613.37	46.24
40	722	169	54	4	1606.54	46.08
41	723	161	52	3.5	1561.11	45.32
42	685	171	54	3.5	1527.54	44.76
43	746	142	50	3.5	1502.27	44.56
44	653	170	54	3.5	1449.75	43.4
45	696	152	47	4	1440.34	43.12
46	670	152	52	3.5	1395.78	42.48
47	663	151	53	3.5	1377.44	42.2
48	688	140	44	3.5	1351.89	41.6
49	626	158	51	3.5	1325.34	41.12
50	659	137	50	3.5	1293.12	40.68
51	643	143	40	3.5	1233.66	39.72
52	635	137	40	3.5	1214.37	38.92
53	650	124	39	3.5	1177.15	38.4
54	879	145	43	3	1176.65	37.29
55	883	133	41	3	1144.16	36.57
56	779	168	48	3	1083.35	35.97
57	811	137	51	3	1061.42	35.25
58	817	127	46	3	1045.89	34.53
59	726	164	52	3	998.56	34.38
60	805	117	38	3	975.60	33.09
61	742	125	45	3	941.49	32.1
62	713	127	44	3	908.22	31.29
63	705	127	45	3	897.41	31.11
64	712	110	41	2.5	836.84	30.06
65	633	124	43	3	791.97	28.65
66	655	108	38	2.5	754.16	28.05
67	558	124	45	3	695.88	26.52
68	595	107	34	2.5	670.57	25.95
69	558	103	31	2.5	607.29	24.42
70	497	115	37	2.5	581.77	23.67
71	448	111	43	3	517.09	22.32
72	408	122	39	2.5	490.09	21.54
73	413	102	32	2.5	441.09	20.07
74	421	92	27	2.5	415.76	19.41
75	423	81	32	2.5	402.18	19.11
76	355	101	33	3	364.58	18.33
77	592	101	30	2	360.59	16.92
78	544	83	42	2	304.31	15.72
79	484	86	30	2	277.76	14.16
80	435	77	32	2	235.17	12.9
81	377	97	29	2	220.58	12.42

cont. Table 4. Results of the multi-objective optimization problem using genetic algorithm.

Sec no.	$a(mm)$	$b(mm)$	$c(mm)$	$t(mm)$	Moment capacity $(t.cm)$	Gross area (cm^2)
82	*397*	*83*	*21*	*2*	*195.46*	*11.94*
83	*351*	*76*	*20*	*2*	*168.82*	*10.7*
84	*263*	*80*	*41*	*2*	*137.78*	*9.94*
85	*247*	*79*	*21*	*2*	*118.54*	*8.78*
86	*267*	*60*	*18*	*2*	*114.05*	*8.3*
87	*279*	*32*	*21*	*2*	*90.90*	*7.54*
88	*186*	*70*	*22*	*2*	*78.88*	*7.24*
89	*171*	*59*	*24*	*2*	*64.04*	*6.58*
90	*107*	*59*	*25*	*2*	*33.96*	*5.34*
91	*106*	*31*	*12*	*2*	*19.88*	*3.68*

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