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DEFLECTION PREDICTION OF COLD FORMED C- SECTION ROOF PURLINS

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ABSTRACT

Cold-formed steel (CFS) sections are widely used on modern roof steel structure building. The majority of thin-walled open cross-section is used as purlin members. Those purlin-sheeting systems have been presented to several theoretic and practical applications over the past 30 years but the complications of the systems have led to large difficulty to be able to develop a new model. The purlins are asymmetric there for unavoidably produce a torsional moment that makes twisting or warping deformation and bending deflection. (non-linear) elasto-plastic finite element model, able to predict the role of purlin deflection with no need for both available empirical input or over-simplified is presented in this paper. Consequently, the stability model is capable of assess the cross-sectional distortion of the purlin, and the failure of purlin by local buckling. The validity of the proposed model is described by its perfect similarity with empirical results. An equation is developed to calculate the CFS - C shaped purlin deflection subjected to biaxial bending through finite element model analysis and statistical regression analysis.

I. INTRODUCTION

Cold-formed steel (CFS) sections applications are widely used in the construction of modern steel buildings. Concerning structural engineering or building, a purlin is a type of secondary element expressible as an average member in the load path to carry load from the roof sheeting to the main structure frame. Purlins sections are available in a number of common types contain channel, sigma and zee forms. The cross-sectional configurations of the zed and channel -section purlins are such that they undergo both twist from the beginning of loading and bending.

At this paper, a logical model developed using finite element (FE model) for the purlin– Section allows the elasto-plastic material, geometric and the material nonlinearity effects to predict and estimate the deflection of C-Section Purlins under gravity loads. A series of purlin tests conducted validate the finite element model [1]. In the past 30 years the purlin-sheeting system has been showed to several theoretical and practical applications, but the complication, of the system produced large difficulty in model improving. The rotational stiffness is different according to the sheeting type.

Torsional rigidity of rolled steel sections were investigated in 1973 by the University of Sheffield, England [2]. The results of torsion tests on steel sections have been 60 percent higher than the value given by simple theory. In 1981, Masahiro Kubo1 inspected lateral torsional buckling of thin walled I-beams [4] and presented an empirical study about the interaction of local and lateral-torsional buckling of thin-walled I-shaped beams. Further investigation on torsion in thin-walled cold-formed steel beams was done at Cornell University(2000) [3]. A research at Plymouth University, United Kingdom has shown that lateral–torsional buckling of cold-formed channel sections subjected combined compression and bending in 2012 [4]. The focus of this study is to determine the behavior of cold formed C- purlins under gravity load and the effect of the purlin fixation type to the sheeting.

II. FINITE ELEMENT MODELING

Scope

The aim of this section is to highlight a finite element model simulating the purlin deflection subjected to gravity and horizontal loads and to validate this model with the experiments mentioned in literature work. Modeling purlin deflection helps to predict the actual behavior of the deflection under gravity and uplift load. In addition, it lets the

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researchers understand the deflection affecting the behavior of the purlin under lateral torsional buckling loads, particularly the geometrical factors affecting the value of purlin deflection (Δ). The analysis is conducted using COMSOL Multiphysics [5]: a general purpose 3D finite element program to simulate the experimental behavior of the purlin section deflection.

III. FINITE ELEMENT MODEL

In 2013, a Zhao [6] presented an experimental study of the lateral–torsional buckling of cold-formed steel channel section beams subjected to up lift and gravity loads. The test setup consisted of a trapezoidal roof sheet with the dimensions 1070 x 1000 x 0.7 mm fixed onto a hot-rolled steel channel section with two rows of bolts at the center of each trough. Such fixing configuration aimed to form a rigidly supported cantilever system. A purlin section 1000 mm long was through-fastened to every sheet trough by self-drilling screws on the central line of the purlin flange. A purlin section of 1000 mm length was through-fastened to every sheet trough by self-drilling screws on the central line of the purlin flange.

Element Type

In the current experimental research of the lateral–torsional buckling of cold-formed steel channel section beams due to uplifting and gravity loads respectively. The test results are used in design that each specimen is allocated with a unique three-part ID denoting the purlin type, cross-sectional dimensions (illustrates the thickness and the web depth) and purlin directions (facing up or facing down indicates the uplifting and gravity load conditions and are denoted as FD or FU , respectively). For example of specimen ∑ 20025FD denotes a sigma section with and cross sectional thickness of 2.5 mm and web depth of 200 mm, fixed in a facing down manner. Torsional restraint tests (F-test) were done on a purlin profile connected to roof sheets in order to estimate the rotational stiffness under uplift and gravity loading conditions as shown in Figure 1.

Free Tetrahedral mesh solid elements are presented in this case to model the purlin sheeting and the connection profile. However, those elements have appropriate displacements and are appropriate to the model's boundaries. In the finite element model suggested the element is provided by 20 nodes with three degrees of freedom per node translation in the nodal x, y, and z directions and may have any spatial orientation. This procedure will give more accuracy and detailed stress distribution near the intersection by comparing with soft shell analysis. The efficiency of the element has been proved by the test results.

The experimental test can be compared with the finite element model was made for Σ20012FU and Σ20012FD. Modeling information was in detail and hence the model is simple to reproduce. The experimental tests were kept until the yield failure of the roof sheeting happened. As it is illustrated Figure 1 the experimental test and the finite element model for Σ20012FU at failure under gravity load.

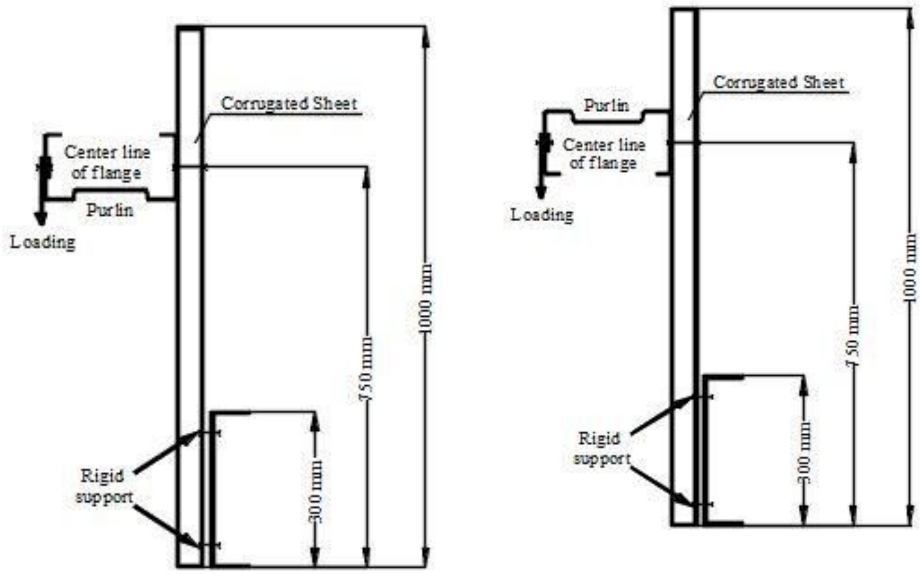


Figure 1. The elements of test used

Figure 2. Experimental deformation for Σ20012FU compared to the FE model

Figure 3. Experimental deformation for Σ20012FU compared to the FE model

Furthermore, Figure 2 illustrates the similar specimen Σ20012FD under uplift load at failure with the same configuration. The analysis using the FE shows good correlation between experimental results compared to the numerical one as shown in Table 1.

Table 1. Result comparison between experimental and finite element model.

Specimen ID	*Load (N)*	*Experimental Test - Vertical deformation (mm)*	*COMSOL (F.E) model - Vertical deformation (mm)*	*Predicted (F.E) model Experimental Test Predicted (F.E) model*
Σ20012 FD	141	21.50	21.00	0.95
Σ20012 FU	151	19.50	18.10	0.92

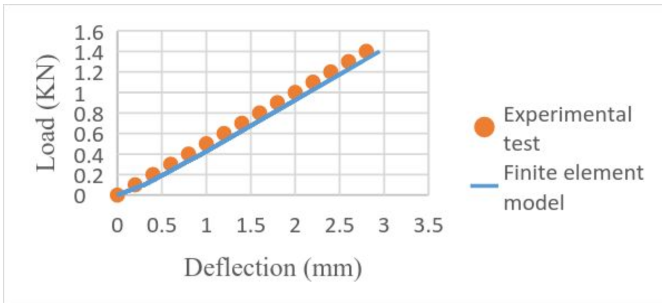


Figure 4. Comparison of the load deflection between the experimental test and (FE) model for specimen 20012 FU

From the graph, we can deduce that the finite element model is consistent with the test results, which suggests that it can predict sufficiently accurate results for vertical deformation. By comparing the experimental and finite element model results, we obtain the test/finite element model ratios from Table 1 that indicate that the prediction of the deflection (94% accuracy) could be acceptable.

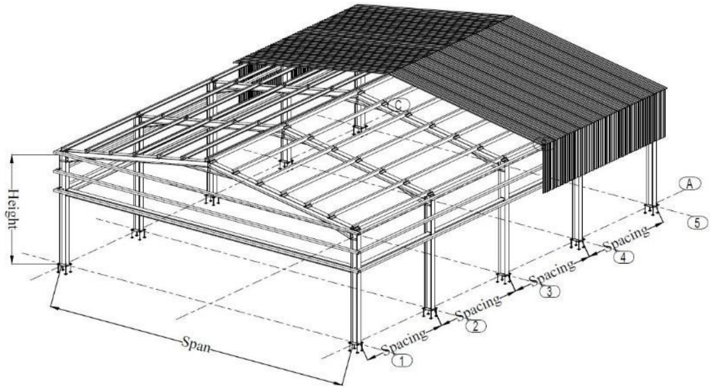
IV. Proposed ANALYSIS

The steel frame is performed a building technique which includes a "skeleton frame". This skeleton frame comes vertically as steel columns and horizontally I-beams, built in a rectangular grid to assist the walls of a building accompany the frame, walls and ceiling, as it shown in Figure 4.

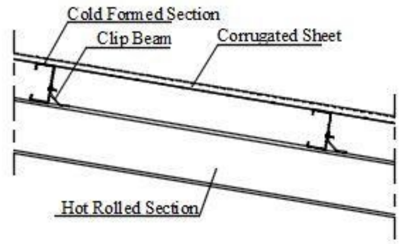
Thin sheets of galvanized steel could be cold formed into steel purlins for extensively used as a structural or nonstructural building material including both internal and external walls either in residential, industrial construction or commercial projects [7].

Steel framed walls could be designed to supply acoustic features and well thermal - one of the specified considerations that should be set into account when building using cold formed steel is that the appearance of the thermal bridging could be across the wall system between the outside environment and inner conditioned space. Thermal bridging can be preserved against by installing a layer of externally fixed isolation along the steel framing. However, the wall system between the outside environment and the inner suggested space. In this method installing a layer of externally fixed insulation can keep the thermal bridging along the steel framing.

The common spacing between main frames is typically 6 meters, the common height of main frame is typically 8 meters and the width of main frame is approximately 10 meters shown in Figure 5.



(a) 3D Building



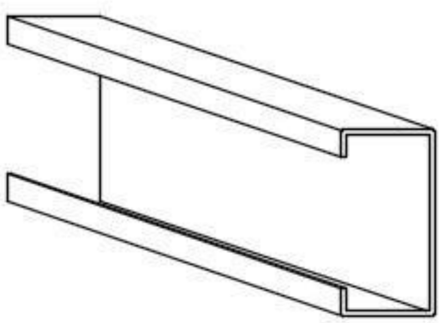
(b) Roof purlins

In steel construction, the term purlin typically indicates to roof framing members that span parallel to the building eave. The purlins are in turn proposed by walls or rafters. Purlins are most usually used in Metal Building Systems, where C-shapes are applied in a manner that gives flexural continuity between spans as it illustrated in Figure 5.

The most widely-used practice in the steel industry that structural shapes are allocated representative designations for convenient shorthand description on documentation and drawing: Channel sections, without or with flange stiffeners, are generally indicated as C shapes; Channel sections without flange stiffeners are also indicated as U shapes.

Parameters Affecting The Rotational Stiffness Analysis

Rotational stiffness analysis of purlin subjected to gravity and horizontal loads represents an extremely complex and indeterminate analytical problem with a large number of parameters affecting its structural behavior. The main concern is the stress factor affecting the buckling behavior of the purlin section with support. The geometrical parameters which control the values of purlin deflection. These geometrical parameters of purlins include H (height of purlin), B (flange width of purlin), t (purlin thickness), and Φ (the angle support of purlin) S (thickness of support) as shown in Figures 6 and 7.



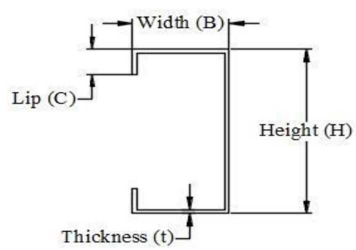


Figure 6. Purlin Section Geometry

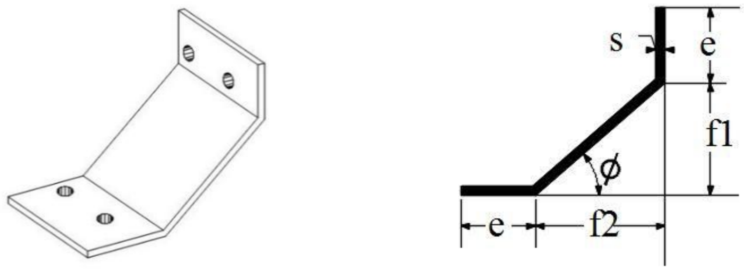


Figure 7. Clip Support Geometry

Fully Extended Model

Material Used
The material behavior in the finite element model was defined as elastic and plastic. The main purpose of this research is to determine the purlin deflection. Elastoplastic materials have a minimum yield strength of 360 N/mm^2. The mechanical properties of the material resulting from the relationship which is performed in transverse direction according to (ECP) requirements [8]. For the elastic analysis type used in this study, we need only the value of Youngs modulus (E) and Poissons ratio which are 200000 N/mm^2 and 0.33 respectively shown in Figure 8.

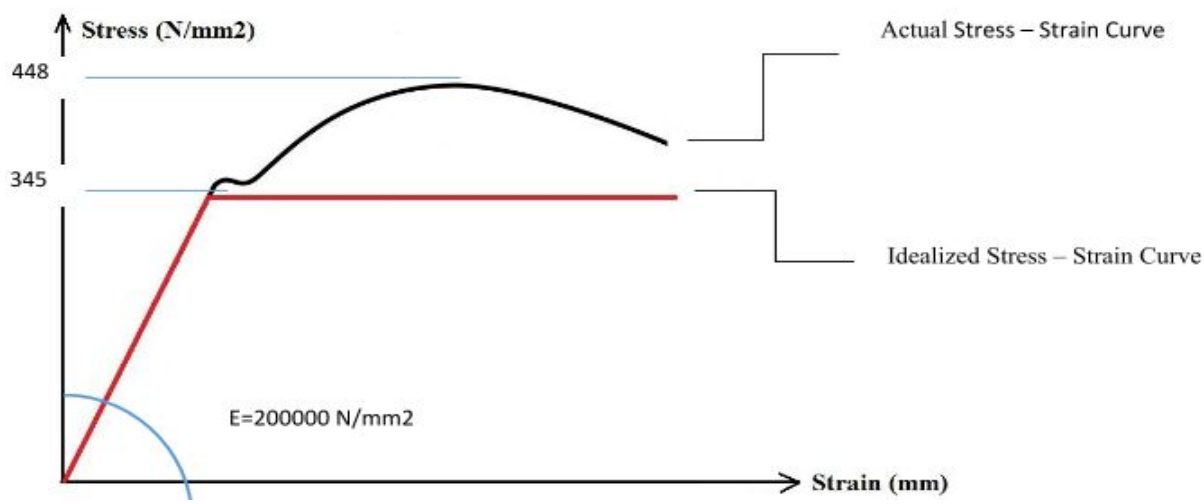


Figure 8. Mechanical properties of the material

Parameters Used
Cold formed steel channel section member is used on a wide range as purlin, the intermediate members between the main structural frame and the corrugated roof sheeting. Purlins are associated to the roof sheeting by a self-drilling screw through the purlin flange (which is often the case in countries, especially Egypt) as it is presented in Figure 9. Those cold formed sections are usually thinner than hot rolled members and for this reason makes differently from the heavier beams investigated in standard steel design. The cross-sectional arrangement of channel section purlins is such that they undergo both bending and twist from the beginning of loading. For multiple-stiffened compression elements, the effective widths of sub elements are determined by the following Equations according Egyptian code $b/t < 60$

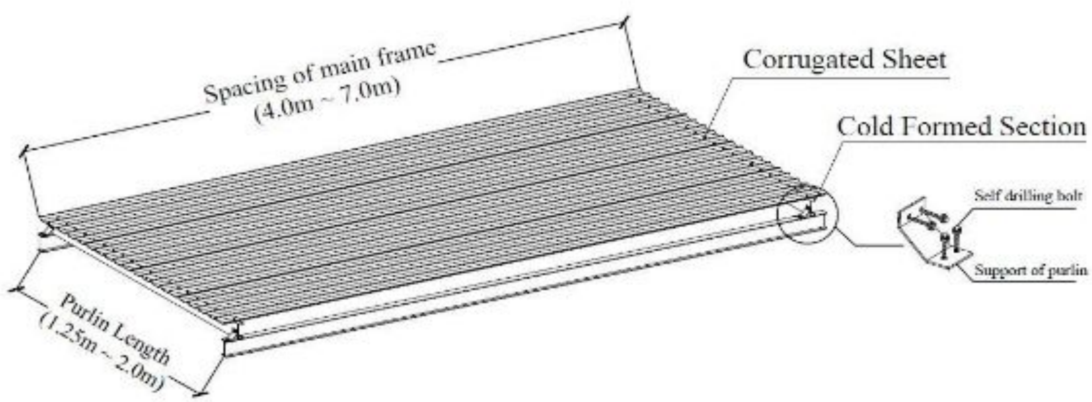


Figure 9. Extended Model

Table 2. Channel parameters used in the parametrical study

Parameters	*L (mm)*	*H (mm)*	*B (mm)*	*C (mm)*	*t (mm)*	*f1&f2 (mm)*	*Φ (degree)*
Different value of parameters	*4000* *5000* *6000*	*120* *145* *175* *200* *225* *240* *265*	*50* *63* *65*	*15* *20*	*1.30* *1.40* *1.50* *1.60* *1.80* *2.00* *2.5* *3.00*	*1* *6*	*30* *45*

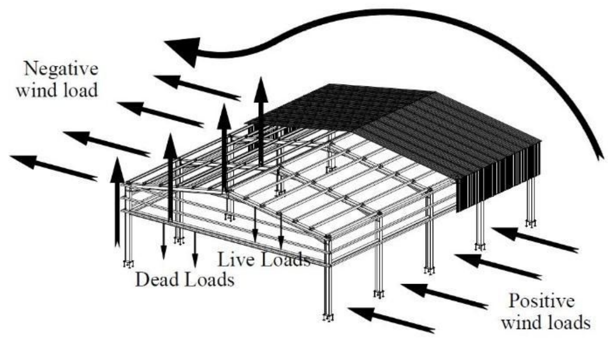
The purlin profiles connected to roof sheets in the variable to estimate the rotational stiffness under uplift and horizontal load conditions. The spacing between two purlins is 1500 mm and the purlin length is 4000 mm as the most commonly used in practice. The channel purlin section dimensions which range in height from 120 mm to 265 mm and thickness 1.5 mm to 3 mm are the most frequently used sections. A finite element model is developed and presented here to predict the deflection of the purlin specimen under the applied gravity load [4]. These dimensions have been chosen because they are the most widespread dimensions in the facilities located in the industrial buildings as shown in Table 2 . Each specimen is assigned with a unique three part ID indicating the purlin type and its cross sectional dimensions (the web depth and thickness). For example, specimen C14514 indicates a C-Section with a web depth of 145 mm and cross-sectional thickness of 14 mm. 1055 models of purlin were appropriate from the Egyptian Code guidance [8].

Acting Loads On Purlins

Each system can be complicated to design as a whole; thus, soft analysis generally focuses on the individual elements that form the system. In some conditions, system effects may be considered in simplified form and applied to the design of confirmed elements that form specifically defined systems [9].

The structural loads are complicated problem. The nature of which will vary basically according to architectural design, the materials being using, and the location . Loading conditions on the same structure keeps on changing from time to time, or might vary quickly over time.

As a result of wind loads, there is a up load and down load. These loads affect the purlins and have been taken into account in the study and analysis.



Figurer 10. The Load distribution on the roof

The types of loads can be broadly classified as two groups: live loading and dead loading. Live loads Live loads (LL) refer to loads that generally vary greatly such as the occupancy of weight, vehicles, snow, and the forces produced by wind. The magnitudes of those loads are unknown with high precision and the design values must base on the purposed use of the structure.

Dead loads (DL) refer to stationary loads which are constant throughout the life of the structure and it consists of the weight of the structural elements. On the other side, As usual daily basis design office process, the expanded use of the FE method for the purlin sections analysis not possible. Instead of, a parametric equation cleared in the form of dimensionless geometrical parameters is helpful and desired for the torsional buckling design.

Finite Element Analysis Model

The model consists of four main elements the type of solution in all elements of this model is structural mechanics. The first element is beam, which is a hot-rolled section. It is considered when the solution is solid mechanics. The second part is the purlins, which is the main part of the study and research, and these purlins are cold formed sections it is considered when the solution is shell elements, and the last part is the roof sheeting based on the purlins It is considered when the solution is also shell elements.

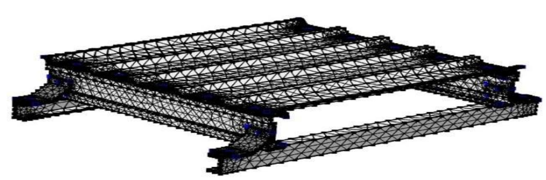


Figure 11. Automatically generated mesh by the program at the proposed model.

F.E mesh provides the possibility to perform design optimization. To verify the convergence of FE results, convergence trail with different mesh densities was conducted; and the optimum densities for different parts of the model were determined before generating the 1055 FE models for the parametric study. the different type of meshing and densities used in different mesh type is the extrapolation zone where the mesh density was extremely fine, the highest mesh density generated by the program, and the meshing type was free tetrahedral as shown in Figure 11. All previous studies study the purlin only. In this research, a study was carried out for the entire building part of the purlins, corrugated sheet and support between purlins and main frame.

Finite Element Model Results

Load-Deflection Relationships

The deflection of the cold formed C-section is mainly affected by the dimensions as well as the clip beam dimensions is one of the important factors on the rigidity of the cold formed C-sections. An investigated numerical study for a wide range of cold formed C-sections thickness is considered.

For the model having thickness / height = 0.0125 and from the load deflection relationship, it is obviously clear that, the stiffness and the ultimate load are increased by increasing the cold formed C-sections thickness. Moreover, the relation is nonlinear of cold formed C-sections thickness equal 30 mm as shown in Figure 11. For the models having thickness / height = 0.0089 is also nonlinear relationship of cold formed C-sections thickness equal 13 mm. In general, the stiffens of cold formed C-sections is increased when increasing the thickness.

The load deflection relationships are plotted for numerous models, which having different cold formed C-sections thickness to study the effect of the cold formed C-sections thickness in the behavior of the clip beam connections. The load deflection relationship, which study the maximum load attained by the model at a vertical deflection and it measured at the middle of cold formed C-sections as shown in Figure 12. Mostly, the load deflection relationship is nonlinear.

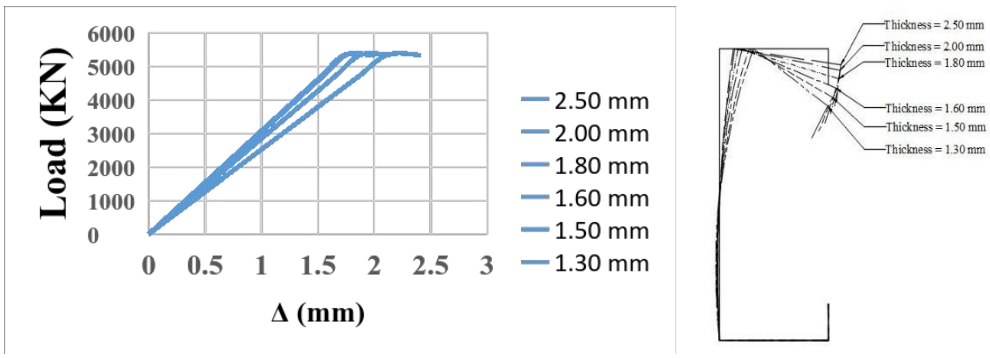


Figure 12. Load – deflections of cold formed section with equal Height (H= 265 mm).

Deflection Prediction Using A Proposed Formula

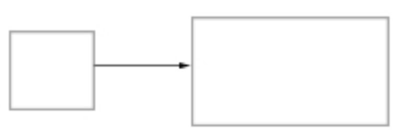
Imperfections In Thin –Walled Cold Formed Steel Member

As usual day-to-day design office operation, the extensive use of the FE method for the purlin sections analysis is not possible. Instead of, a parametric equation cleared in the form of dimensionless geometrical parameters is helpful and desired for the torsional buckling design. The present papers attempt to show an individual parametric equation for determining the purlin deflections [10]. This equation is based on the previous 1055 generated models.

In the torsional buckling, it was hypothesized that there would be an occurrence of the buckling by bending in the place of symmetry of the cross section. This torsional buckling failures take place if torsional stiffness of the section is very low.

The following equation shows the three main parts that the beams are exposed to lateral torsional buckling, the first part (A) is about torsional buckling, the second part (B) is about type of loading, and the last part (C) is about support of cold formed section, the method used is virtual work.

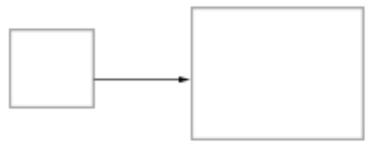
A. Torsional Buckling Effect



The pure tension of thin walled open cross section is twisted by couples applied at the ends and acting in plans normal to the axis of the cross section, and if the ends of the member are free to warp, we have the case of pure torsion. The only stress produced are the shearing stress at each section. The distribution of these stress depends on the shape of cross section and is the same for all sections [11].

For a beam of thin walled open section it can be assumed with reasonable that the shearing stress at any point is parallel to the corresponding tangent to the middle line of the cross section and is proportional to the distance from the line.

B. Axial Load Deflection Effect



Channels sections are some of singly symmetric open shapes. If these members are subjected to bending moments in the plan of symmetry, they may be fail in one of the following two ways:

1. The member deflects gradually in the plane of symmetry without twisting and finally fails by yielding or local buckling at the location of maximum moment.
2. The member starts with a gradual flexure bending in the plan of symmetry, but when the load reaches a critical value, the member will suddenly buckle by torsional – flexural buckling.

The type of failure mode, which will govern the maximum strength of the member, depends on the shape and dimensions of the cross section, the eccentricity of applied load [12].

C. lateral support to effect:

We solve this part of equation by virtual work method according to:

1. In determining the resistance of a cross section, the effective width of a compression element should be based on compressive stress $\sigma_{com,Ed}$ in the element when the cross section resistance is reached;
2. The cross sections are used in design: gross cross section and effective cross section of which the function of loading (compression, major axis bending).
3. For serviceability verifications, the effective width of a compression element should be based on the compressive stress $\sigma_{com,Ed,ser}$ in the element under the serviceability limit state loading;
4. Distortional buckling shall be taken into account where it constitutes the critical failure mode [13].

In this case analysis can provide with different types, taking into consideration that the flexible support and flexibility was given in consideration to determine the type of support.

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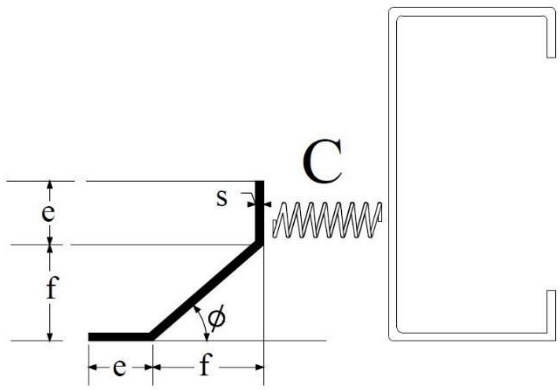

Figure 13. Mechanical model used.

Proposed Equation

$$\Delta = A + B + C \qquad \text{Equ. (7)}$$

The formula proposed depends on multiplied nonlinear regression analysis executed by the statistical software package, SPSS. Constant of calculated are obtained from the (Δ) values calculated in the given parametric study as shown in Table 3.

Table 3. Constant of calculated from the parametric study.

b1	*b2*	*b3*	*b4*	*b5*	*b6*
0.05	*1.00*	*0.50*	*0.50*	*-0.20*	*50*

Comparison between horizontal applied loads against deflection shows close agreement as presented in Figure 21. Values of R2 indicates the confidence interval used for determination of the given constants. This value was taken as R2 92% for all parameters [14].

V. APPLICATION OF THE PROPOSED EQUATION

The proposed equation is validated using results extracted from 1055 finite elements models, as presented in Figure 14. Figure 15 shows that the values obtained from the proposed equation are fitting with the analytical results with some under estimated values.

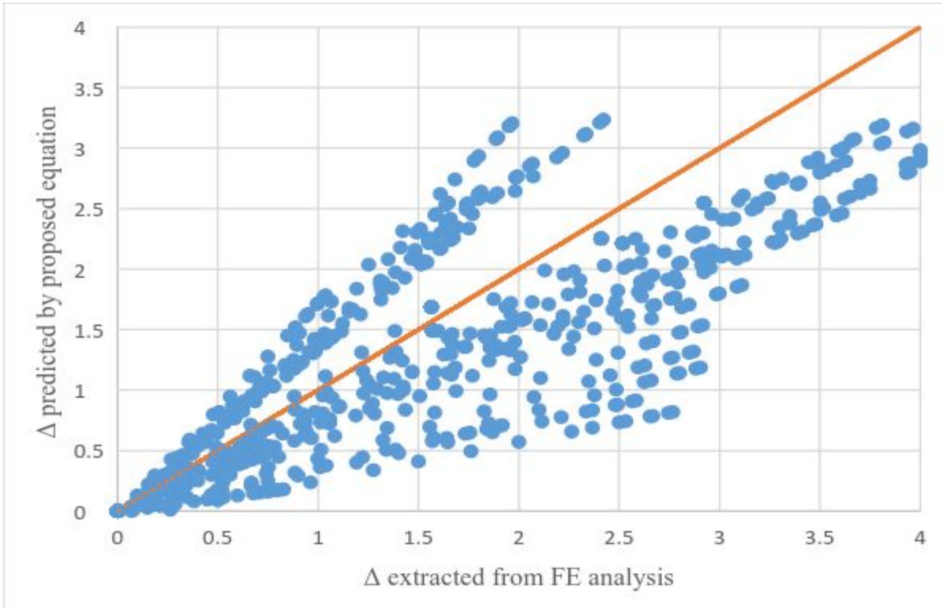

Figure 14. Δ predicted by the proposed equation compared to the ones extracted from FE analysis .

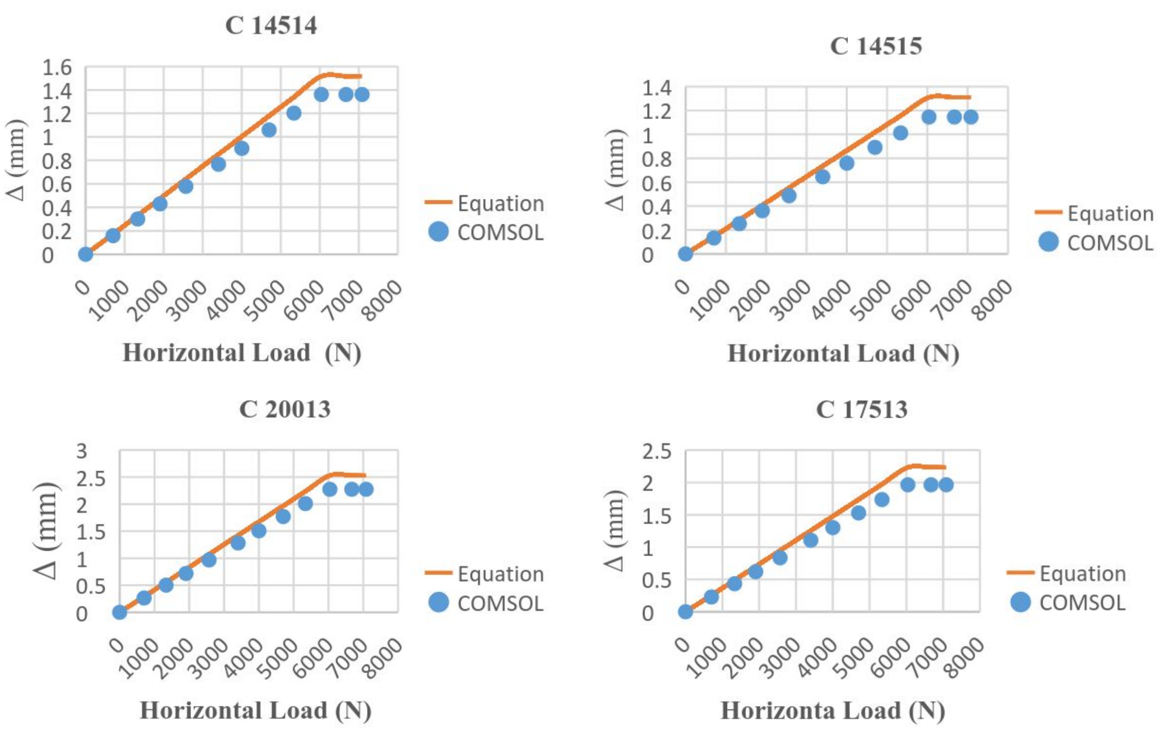

Figure 15. load deflection curves from finite element result compared to the proposed method

VI. CONCLUSION

The purposes of this study showed the complexity of the given system which led to great difficulty calculating purlin deflection, as well as establishing a methodology using finite element. Furthermore, investigating the effect of each dimensionless parameter led to a simplified solution for estimating the deflection of C-shaped purlin supported with clip supported using a proposed equation.

The shown assembly method gives a solution closer to the reality and the study covers almost all geometrical variables and loading conditions affecting the deflection of the purlins.

The proposed equation estimates the deflection of the purlins and shows very good fitting to the theoretical ones and could be used with confidence for simply predefining deflections.

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