IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE)
e-ISSN: 2278-1684,p-ISSN: 2320-334X, Volume 12, Issue 4 Ver. VI (Jul. - Aug. 2015), PP 55-64
www.iosrjournals.org

Global Optimization Using Genetic Algorithm for Portal Steel Frame with Tapered I-Section

N. M. Yossef [1]
[1](Department of Structural Engineering, Tanta University, Tanta, Egypt)

Abstract : *This study highlights the possibility of using GA (Genetic Algorithm) in everyday design. The global optimization of a frame using linear buckling of 3D model was introduced. The proposed optimal model is compared to the commonly used member checks with interaction formula based on Egyptian code of practice. The results of the proposed model clearly point the advantages of using GA, instead of the classical member checks. The proposed model was used in a parametric study, many influential factors were studied, and then the design recommendations are introduced. The study shows that no need for using lower flange bracing, since the optimal model presents the section dimensions to resist lateral buckling. Using non-compact section and the recommended span-to-depth ratio were introduced as a design guideline.*
Keywords: *Portal frames; Genetic algorithm; Global optimal analysis; Linear buckling.*

I. Introduction

Single story buildings are the largest sector of the structural steel work market, representing upwards of 60% of total activity [1]. These buildings are typically used for workshops, factories, industries, distribution warehouses, retail and leisure. It sometime called 'sheds', sizes vary from small workshops of just a few hundred square meters up to massive distribution warehouses covering over one hundred thousand square meters. The design of steel frame needs choice of initial geometrical configurations and parameters, before proceeding further with the analysis assumed section and checking for the adequacy of the section. The designers need to carry out a lot of iterations in the design process, until the assumed section satisfies the design criteria.

Many researches present the optimization of sections [2-6]. Tashakori (Tashakori & Adeli, 2002) made optimum design of cold-formed steel space structures using neural dynamics model. The patented robust neural dynamics model of Adeli And Park has been used to find the least weight design for several space trusses commonly used as roof structures in long-span commercial buildings and canopies, including a large structure with 1548 members with excellent convergence results. Where, Jaehong et al. [4] studied optimum design of cold-formed steel channel beams by using micro genetic algorithms. The design curves are generated from optimum values of the thickness and the web flat-depth-to-thickness ratio of un-braced beams under uniformly distributed load. As numerical results, the optimum design curves are presented for various load levels. Jaehong extend his research [5] to present optimum design of cold-formed steel columns by using micro genetic algorithms.

The design of a system can be formulated as problems of optimization. Many numerical methods of optimization have been developed and used to design better systems [7]. The design of steel truss arch bridges is formulated as an optimization problem by Jin [8]. An efficient, accurate, and robust algorithm is proposed for optimal design of steel truss arch bridges. The proposed algorithm integrates the concepts of the genetic algorithm (GA) and the finite element method. A numerical example involving a detailed computational model of a long span steel truss arch bridge with a main span of 552 m is presented to prove the applicability and the merits of the proposed method.

The genetic algorithm (GA) is used also by Safari et al. [9] with improved reproduction operators. The efficiency of the proposed method is demonstrated through optimizing two benchmark problems, including a three-bay, three-story steel frame and a five-bay, 22-storey special steel frame. Significant improvements in the optimal solutions are obtained with reduced number of finite element analyses, resulting in a less computational effort.

A global analysis of steel frame used by many researchers [2, 5, 10] present an important advantage to consider many factors affecting steel frame. Using GA Duoc et al. [11] studied the effect of serviceability limits on optimal design of the rolled steel frame. Parametric studies are carried out on frames with spans ranging between 15 m to 50 m and column heights between 5 m to 10 m. It is demonstrated that for a 50 m span frame, use of the SCI recommended deflection limits can lead to frame weights that are around twice as heavy as compared to designs without these limits.

Hradil et al. [12] highlight the possibility of using GA in everyday design. Their study clearly points to the advantages of using advanced modeling, for design steel portal frames. Even Hradil et al. use rolled sections in their models, the experience shows that using complex 3D models is possible with current computational capabilities.

Hussien [13] submitted a master thesis to study the optimization of single story steel frame. He presents an effective procedure to achieve the optimum design of steel sections. Many factors were considered such as local buckling, lateral torsion buckling, global buckling and section strength under the condition of Allowable Stress Design ASD [14]. Even the presented procedure was very effective for steel I section, put it's week for global analysis of steel frame since it neglect the interaction between frame section and its geometrical configuration.

This study was therefore carried out to present design guidelines for optimal design of a welded steel frame with tapered section, and it introduces a global analysis based on Genetic Algorithm (GA) under the condition of ASD (ECP205). This paper describes the modeling technique using ANSYS^{TM} software [15]. The 3D model is used with linear buckling analysis, taking into consideration the effect of local buckling, lateral buckling and frame stability under serviceability limit state.

II. Problem Statement

It's clearly known that performing optimum analysis early in the design cycle has the potential to identify and solve design problems and highly affect the cost [16]. To keep up the best optimized geometry of steel portal frame, welded tapered section is modeled using ANSYS^{TM} software. The design optimization of 3D steel framed structures with solid element discretization is used. Figure 1 shows the flow of framework for optimal design. Subsequently, the optimized geometry of the finite element model is validated with suggested geometry presented by local fabricators and the code checks. Then parametric study is carried out to investigate the effect of further influential parameters.

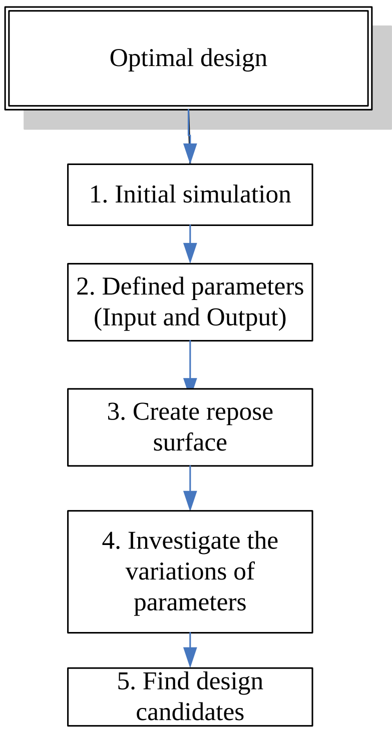

Figure 1: Framework for optimal design

III. Optimal Design Model

3.1 Initial Simulation

The first step of any design simulation is to create the simulation model. A 3D solid model is build up. The geometry of the portal frame shown in figure 2 is considered herein, in which, L is the frame span; h is the column height; and z is the rafter slop. The geometry of the portal frame shown in Table 1 was fabricated by local steel fabricators, it is considered in this paper as a reference frame. In which, L = 30 m, h = 6 m; z = 10:1. The lateral torsional buckling of the reference frame is fully braced. Figure 2 also presents the section's dimensions, where the upper and lower flanges were assumed to have equal dimensions.

The distance between adjacent frames is 6 m, which is considered to be typical for industrial building.

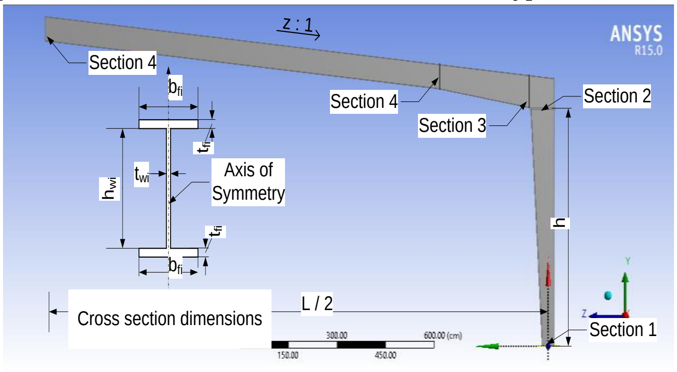

Figure 2: Geometry dimensions of the portal frame

Table 1: Geometry of the reference frame

Input parameters	Dimensions suggested by local fabricators	Optimized geometry of the candidate point
P1 – b_{f1} (cm)	22	25
P2 - t_{w1} (cm)	0.6	0.7
P3 - t_{f1} (cm)	1.2	1.2
P4 - d_{w1} (cm)	35	40
P5 - d_{w2} (cm)	70	70
P6 - b_{f3} (cm)	15	15
P7 - t_{w3} (cm)	0.8	1
P8 - t_{f3} (cm)	1	0.9
P9 - d_{w3} (cm)	80	95
P10 - d_{w4} (cm)	60	40

The columns and rafter sections are composed of welded plates, both in steel grade 52. The length of the eaves haunch is 10 % of the frame span, and such length is considered to be typical for portal frames designed plastically [11]. The eaves haunches are assumed to be fabricated such that the flange width bf is constant, as that of the rafter.

Due to the symmetry of the typical portal frame, half frame is modeled and the symmetry region is defined at frame apex. A hinged support is assumed at the column base ($U_x = U_y = U_z = 0$). The rafter is sliced into equal pieces to impose lateral support ($U_x = 0$), the lateral supports are the simulation of the purlins.

Two design methods are suggested for the 3D portal frame model, the first method is nonlinear analysis on imperfect structure. The model includes both in-plane and out-of-plane imperfections, and the analysis method is materially and geometrically nonlinear, the effect of buckling is implicitly taken into account. The second method uses a linear buckling analysis method, this method takes into account out-of-plane stability using the Eigen value buckling analysis, and the resistance of the frame is checked. The second method has the advantage of faster numerical calculation compared to the first. So the second method is considered.

The dead load (DL) and live load (LL) acting on the Reference Frame, according to ECP, are as follows:

Steel frame weight: is considered as gravity load.

DL is the weight of the cover, purlin and lighting system = 1 kN/m.

LL is the live load assumed for inaccessible roof = 3 kN/m.

3.2 Defined Parameters

This step is used to define the input, the output and the custom parameters to be investigated. The input parameters (also called design variables) are identified, which include 1) geometry parameters, where 10 parameters are considered as shown in Table 2, that identify the geometry of the modeled frame, 2) material properties such as yield strength (f_y = 3.6 E+08 Pa, St52).

The output parameters (also called performance indicators) are chosen from the simulation results and include 1) maximum stresses, 2) solid volume, 3) directional deformation (in and out of plane) and 4) directional deformation load multiplier. Note that, the minimum load multiplier of the design loads reaches the characteristic resistance of the most critical cross-section without out-of-plane buckling effect.

Custom parameters are also introduced. Width to thickness ratios of compression elements of the column and rafter are the custom defined parameter based on input parameters to study the effect of local buckling.

Table 2: Section dimensions and parameter ranges

Section	The section dimensions							
	b_{fi}	The parameter range (cm)	t_{fi}	The parameter range (cm)	d_{wi}	The parameter range (cm)	t_{wi}	The parameter range (cm)
1	P_1	20 : 30	P_3	0.8: 2.2	P_4	25 : 55	P_2	0.5 : 1.4
2					P_5	40 : 110		
3	P_6	15 : 30	P_8	0.8: 2.2	P_9	40 : 120	P_7	0.5 : 1.4
4					P_{10}	40 : 100		

3.3 Create response surface

Once the initial model has been created and the parameters defined, the next step is to create a response surface. The design space must be defined by giving the minimum and maximum values to be considered for each of the input variables as listed in Table 2. The response surface is created based on what if analysis performed by ANSYS called "Design of Experiments". The "Design of Experiments" is changing the values of the input parameters between the minimum and maximum values, then solve the model to find the output values.

3.4 Investigation the variation of parameter

After the response surfaces have been computed, the design can be thoroughly investigated using a variety of graphical and numerical tools, and valid design points identified by optimization techniques.

The investigation is carried over a reference frame to investigate the effect of input parameters on the output values. The Kriging response surface is used, it allows Design Explorer to decide the accuracy of the response surface. Figure 3 shows that Kriging fits the response surface through all the design points.

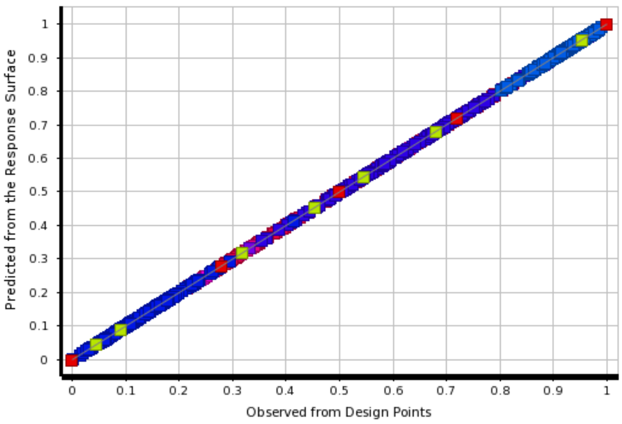

Figure 3: Comparison between response surface and design point.

The local sensitivity bar chart, for the response point of the reference frame, is presented in figure 4. This chart shows the impact of four input parameters (depths of sections 1, 2, 3, and 4) on two output parameters (vertical deflection and the maximum equivalent (von-Mises) stresses). Where, d_{w3}, the hunch depth, has the most impact for the deflection and the stresses, the input parameters d_{w2} and d_{w4} have a moderate impact. This impact is positive for the deflection and negative for the stresses. Otherwise d_{w1} has no impact if compared with other parameters.

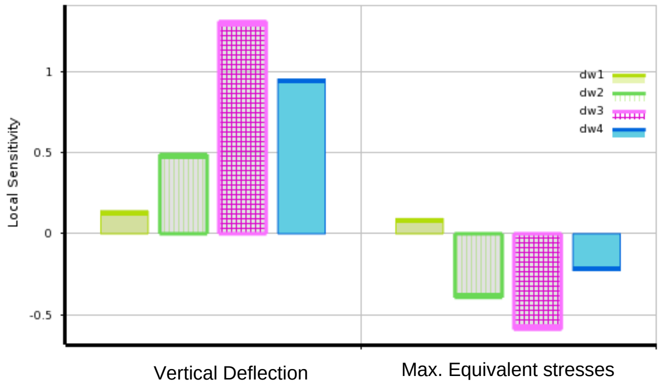

Figure 4: The impact of input parameters (depths d_{wi}) on the output values (deflection and stresses)

3.5 Find design candidates

At this stage, the optimization study needs to be defined, which includes choosing the optimization method, setting the objectives and constraints, and specifying the domain.

The Screening optimization method, used by the author, uses a simple approach based on sampling and sorting. It supports multiple objectives and constraints as well as all types of input parameters.

This section investigates the effect of the described method to optimize frame weight, taking into account serviceability limit states roles of ECP, so the objective and constraints are summarized as follows:

- The geometry volume is minimized (the objective).
- The minimum vertical deflection ≤ span/200.
- The maximum equivalent (von-Mises) stresses ≤ 0.58 maximum yield stress.
- The Total Deformation Load Multiplier ≥ 1 (No Lateral buckling).
- $d_{w2}/t_{w2} \leq 190/\sqrt{f_y}$ (web compactness).
- $d_{w3}/t_{w3} \leq 190/\sqrt{f_y}$ (web compactness).
- $b_{f1}/2t_{f1} \leq 21/\sqrt{f_y}$ (flange compactness).
- $b_{f1}/2t_{f1} \leq 21/\sqrt{f_y}$ (flange compactness).

The optimization problem can be solved after setting the domain of the input parameters as studied by response surface. Three candidate points are presented, Table 3 lists the outputs of the optimized reference frame at the best candidate point.

A comparison demonstrated in Table 3 shows that the proposed optimization method provides a tool to analyze and optimize a typical frame with a reasonable accuracy.

Table 3: Output parameter of reference frame (L=30 m, h = 6 m, z = 10:1)

Output parameters	**Reference frame**	**Candidate Point**
Minimum vertical deflection (m)	-0.101	-0.112
Maximum Equivalent Stress (Pa)	2.2 E+08	2.2 E+08
Geometry Volume (m^3)	0.186	0.186
Total Deformation Load Multiplier	5.79	4.86

3.6 Verification of the model

Linear structural analysis followed by design using cross-sectional checks to express Allowable Stresses Limit States conditions are the commonly used methods well described in ECP205.

Therefore, it was necessary to verify the best candidate dimensions, presented from optimal analysis, by the code conditions as presented in Table 4.

Table 4 shows that the proposed optimal dimensions are safe, according to the code conditions with a reasonable accuracy.

While both methods, manual codes checks and proposed optimal model, are accepted as indicated by the results, using GA can result in important savings, because it eliminates some of the conservativeness brought in by the unavoidable simplifications of the manual method.

Table 4: Code Checks for reference frame sections (L=30 m, h = 6 m, z = 10:1)

Sections	Calculated compressive bending stress based on moment f_{bc} (Pa)	Allowable compression stress in bending F_{bc} (Pa)	Calculated compressive stress due to axial compression f_{ca} (Pa)	Allowable stress in axial compression F_c (Pa)	Interaction equation for bending and axial stresses*
1	0.00E+08	2.08 E+08	0.08 E+08	0.6 E+08	0.13
2	1.05 E+08	2.08 E+08	0.06 E+08	0.6 E+08	0.61
3	1.9 E+08	2.08 E+08	0.07 E+08	0.61 E+08	1
4	1.01 E+08	1.62 E+08	0.05 E+08	1.14 E+08	0.67

*According to ECP205, for safely designed section $(f_{ca} / F_c) + (f_{bc} / F_{bc}) A_1 < 1$

IV. Parametric Study

Selecting the correctly dimensions of steel I section is very important for structural design. The overall procedure of selecting the correct size is based upon mechanical design calculations. After loading and finding the bending moment diagram that the steel frame is expected to experience, choosing the approximate dimensions of steel I section is puzzling for many engineers. Many influential parameters were discussed to help designers in selecting the suitable dimensions. The considered parameters are 1) the effect of lateral and torsional restrains, 2) the effect of column height, 3) the section compactness, and finally 4) the relation between the optimal depth of the web d_w and the span of the frame.

A couple of important points must be highlighted to understand the study presented here:

- The configurations considered based on welded tapered section with constant flange width.
- A manufacture dimensions were presented
- The linear buckling analysis was used
- The frames were considered fully pinned and the connections are fully rigid.
- The eaves length is considered 0.1 of the clear frame spans.
- The serviceability check was according to ECP.

4.1. Effect of the lateral restrains

The design optimization of steel portal frames has previously been considered by many researchers, for which the position of lateral and torsional restraints were fixed [11]. In this section the effect of the lateral restrains of upper and lower flange is investigated. 12 runs have been considered, where the distance between purlins (a) are changed from small value (a = 1.5) to moderate value (a = 1.875 m and a = 2 m) and wide value (a = 2.5 m) as shown in Table 5. For each frame two cases are considered, the first case is for the frame with lateral restrains at upper flange only, the second case is for the lateral restrains at upper and lower flanges.

The results show that, the frame design was shown to be controlled by lateral-torsional buckling for wide distance between purlins (a = 2.5 m). Lateral restrains of lower flange reduce the optimal geometry volume by 13.11%, although the reduction in volume for small and moderate distance between purlins was negligible and not compared with the increase in total weight due to lateral restrains members. Which means that the presence of the lateral restrains of lower flange don’t always reduce the total weight of the frame, especially for distance between purlin less than or equal 2 m. And that the dimensions of the flanges can be optimized to resist lateral buckling without the need of using lateral restrains.

4.2. Effect of the column height

Frames with various column heights are studied to assess the effect of column height in optimal frame dimensions. Three portal frames are analyzed with varying column heights. The column height of reference frame is changed to be 6, 8 and 10 m. The initial simulation for the three frames shows that, a considerable increase in the apex deflection with the increment of the column height is observed as shown in figure 5.

Table 5: Effect of lateral restrains on the optimal frame volume

Frame	Span (L)	a (m)	Geometric volume (m^3)		
			(1) Lateral restrains for upper flange	(2) Lateral restrains for upper and lower flange	Reduction*%
1	15	1.5	0.059	0.059	zero
2	30	1.87	0.192	0.186	3.12
3	20	2	0.087	0.085	2.30
4	24	2	0.129	0.129	zero
5	28	2	0.168	0.165	1.79
6	30	2.5	0.206	0.179	13.11

*Difference of geometry volume case 1 and case 2 values divided by case 1 value.

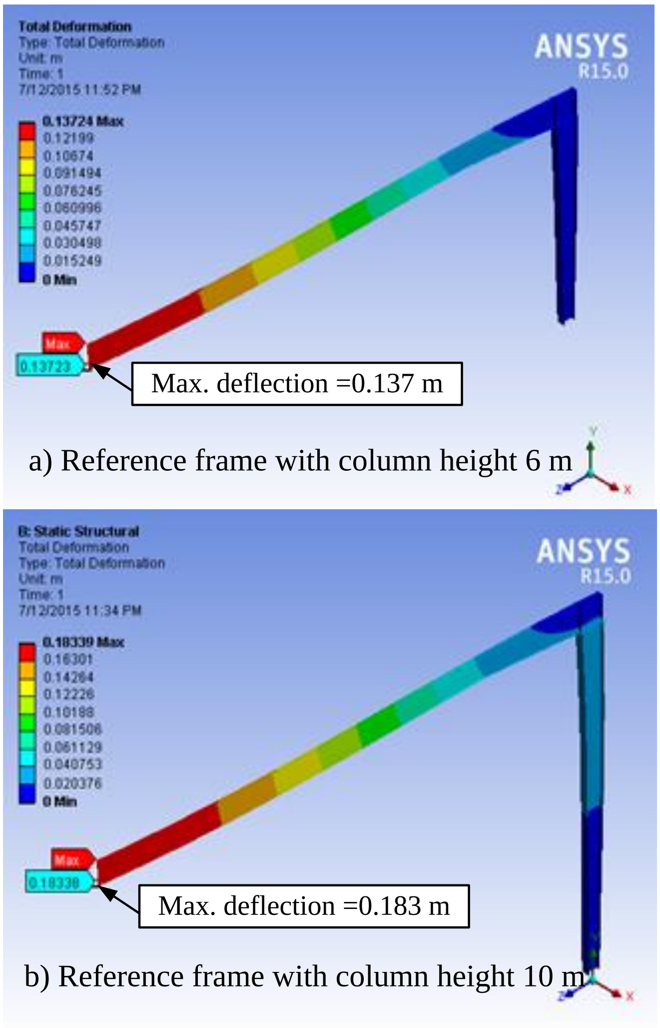

Figure 5: Initial simulation of portal frame with different height (L = 32 m; z = 10:1).

Table 6: Geometry of portal frame with different height h

Frame	The Span (L)	h (m)	Optimal geometry	
			Geometry Volume (m^3)	Volume increment
1	32	6	0.215	-
2		8	0.238	10.6%
3		10	0.267	24.2%

After initial simulation, the optimal design is carried out and the optimal volumes are listed in Table 6. The results of optimal design show that, the optimal volume is highly affected by the incremental of the frame height. Where the volume increases as the height of column increases, to allow the defection to be within the code limits (span/200).

4.3. The section compactness

Studying the section compactness for frame having different spans can be useful as a design aid for engineers. Frames with eight different spans will be considered. The frame span changed from L = 20 m to 48 m as shown in Table 7. For each frame, the upper flanges are supported by lateral restrain every 2 m and with column height h = 6 m.

Table 7: Geometry of frame with different span

Frame	Span (L)	Section 2				Section 3			
		d_w/t_w	Comp.	c/t_f	Comp.	d_w/t_w	Comp.	c/t_f	Comp.
1	20	80	Non	8.75	Non	91.6	Non	9.5	Non
2	24	100	Non	8.12	Non	92.8	Non	8.83	Non
3	28	100	Non	8.8	Non	100	Non	8.66	Non
4	32	87.5	Non	7.33	Comp	100	Non	6.3	Comp
5	36	80	Non	7.1	Comp	75	Non	9.2	Non
6	40	100	Non	8	Comp	100	Non	8.2	Non
7	44	100	Non	8.7	Non	78.6	Non	5.7	Comp
8	48	84.4	Non	6.26	Comp	100	Non	5.1	Comp

Limiting slenderness ratio for compact section ($127/\sqrt{fy}$ = 66.4 for web) or ($15.3/\sqrt{fy}$ = 8.06 for the welded flange).
Limiting slenderness ratio for non-compact section ($190/\sqrt{fy}$ = 100 for web) or ($21/\sqrt{fy}$ = 11 for the welded flange).

The results of the optimal design show that, according to ECP, the critical section of the column and the rafter (sec 2 and sec 3 respectively) are non-compact section, since the web elements are always non-compact.

4.4. The relation between the optimal depth d_w and the frame span L.

The depth of the section has a major effect in estimating the optimal dimension of the frame members. Suitable depth is the first acquires for the designer to begin his design estimations. This section investigates the effect of changing span on the estimating of the depth dimension. Span considered in this section are varied from 15 m to 48 m with height (h) equal 6 m the slop and distance between frames are the same as before z = 10:1 and S = 6 m. For each case, the minimum frame volume was obtained. Figure 6 shows the relation between the span and the depth of section 2 (d_{w2}) and section 3 (d_{w3}) respectively. The results remain in a narrow band, suggesting that the ratio of the span to d_w can be represented as:

d_{w2} = span / (41)

d_{w3} = span / (39.7)

These values can be used as an initial suggestion of the frame depth at section 2, 3.

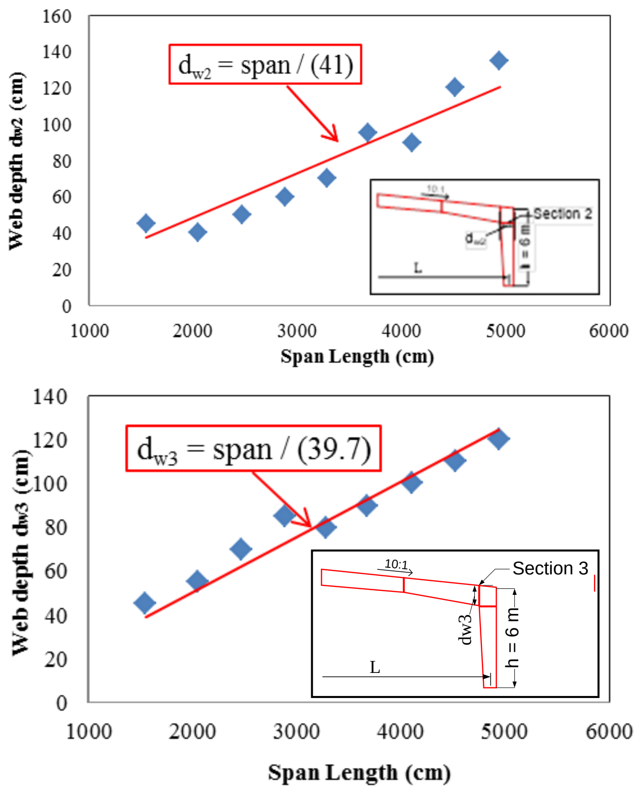

Figure 6: relation between the span and depth of sections d_w (a = 1.5: 2 m, z = 10:1, h = 6 m).

V. Conclusions

The optimal design of the welded steel frame has been determined using the GA algorithm, the global analysis of steel frame was performed by ANSYS software. The optimal model was presented and has been verified with commonly used member checks. It provides a tool to analyze and optimize a typical frame with a reasonable accuracy. Using GA can result in important savings, and using complex 3D models is possible with current computational capabilities.

The proposed optimal technique described here can be applied to a wide variety of optimization problems.

Some recommendations are presented for the optimal design with the objective function being minimum volume as follows:

- No need for lateral torsional restrains of the lower flange of the rafter as long as the spacing between purlin are between 1.5: 2 m, where the dimensions of the flanges can be optimized to resist lateral buckling.
- The volume of the frame increases with the increase of the column height, to reduce the deflection of the apex within the allowable limit.
- The sections of the optimal frame (column and rafter) are recommended to be non-compact section.
- Initial suggestions for a span/ depth ratio of section 2 and 3 are presented, such that d_{w2} = span/ (41), and d_{w3} = span / (39.7).

However, the results will be more reasonable if the optimum design of purlins, cladding and other user requirements is included in the optimization process. The work presented here can be considered as a first step towards globally optimizing of steel portal frames.

References

[1]. SteelConstruction.info, "Single storey industrial buildings," in the free encyclopedia for UK steel construction information, ed: http://www.steelconstruction.info/Single_storey_industrial_buildings.

[2]. A. Karim and H. Adeli, "Global optimum design of cold-formed steel hat-shape beams," Thin-Walled Structures, vol. 35, pp. 275-288, 1999.

[3]. A. Tashakori and H. Adeli, "Optimum design of cold-formed steel space structures using neural dynamics model," Journal of Constructional Steel Research, vol. 58, pp. 1545-1566, 2002.

[4]. J. Lee, S.-M. Kimb, H.-S. Parkc, and B.-H. Wood, "Optimum design of cold-formed steel channel beams using micro Genetic Algorithm," Engineering Structures, vol. 27, pp. 17-24, 2005.

[5]. J. Lee, S.-M. Kima, and H. S. Par, "Optimum design of cold-formed steel columns by using micro genetic algorithms," Thin-Walled Structures, vol. 44, pp. 952-960, 2006.
[6]. T. Tran and L.-y. Li, "Global optimization of cold-formed steel channel sections," Thin-Walled Structures, vol. 44, pp. 339-406, 2006.
[7]. J. S. Arora, Introduction to Optimum Design, 3rd ed. ed.: Elsevier Inc., 2012.
[8]. J. Cheng, "Optimum design of steel truss arch bridges using a hybrid genetic algorithm," Journal of Constructional Steel Research, vol. 66, pp. 1011-1017, 2010.
[9]. D. Safari, M. R. Maheria, and A. Maherib, "Optimum design of steel frames using a multiple-deme GA with improved reproduction operators," Journal of Constructional Steel Research, vol. 67, pp. 1232-1243, 2011.
[10]. D. T. Phan, J. B. P. Lim, C. S. Y. Ming, T. Tanyimboh, H. Issa, and W. Sha, "Optimization of Cold-Formed Steel Portal Frame Topography Using Real-Coded Genetic Algorithm," Procedia Engineering, vol. 14, pp. 724-733, 2011.
[11]. D. T. Phana, J. B. P. Lima, T. T. Tanyimbohb, R. M. Lawsonc, S. Yixiang Xub, and W. S. Martinb, "Effect of Serviceability Limits on Optimal Design of Steel Portal Frames," Journal of Constructional Steel Research, vol. 86, pp. 74-84, 2013.
[12]. P. Hradil, M. Mielonen, and L. Fülöp, "Advanced design and optimization of steel portal frames," Journal of Structural Mechanics, vol. 43, pp. 44-60, 2010.
[13]. E. S. Hussien, "Optimum Design of Single story steel frames," Master, Civil Eng. Dept., Helwan University, Faculty of Eng. , 2011.
[14]. "Egyptian Code of Practice for Steel Construction and Bridges," vol. Code No. 205, ed, First Edition 2001.
[15]. ANSYS®, "Release 15.0," vol. Release 15.0, Version 3 ed: ANSYS, Inc., 2007.
[16]. M. Robinson, "Robust Design and Optimization for Structural Mechanics" in Technical Services ANSYS, ed, 2013.