Missouri University of Science and Technology
Scholars' Mine

International Specialty Conference on Cold-Formed Steel Structures

(2012) - 21st International Specialty Conference on Cold-Formed Steel Structures

Aug 24th, 12:00 AM - Aug 25th, 12:00 AM

An Efficient Genetic Algorithm for the Design Optimization of Cold-formed Steel Portal Frame Buildings

Duoc T. Phan

James B. P. Lim

Tiku T. Tanyimboh

Wei Sha

Follow this and additional works at: https://scholarsmine.mst.edu/isccss

Part of the Structural Engineering Commons

Recommended Citation

Phan, Duoc T.; Lim, James B. P.; Tanyimboh, Tiku T.; and Sha, Wei, "An Efficient Genetic Algorithm for the Design Optimization of Cold-formed Steel Portal Frame Buildings" (2012). *International Specialty Conference on Cold-Formed Steel Structures*. 1.
https://scholarsmine.mst.edu/isccss/21iccfss/21iccfss-session8/1

This Article - Conference proceedings is brought to you for free and open access by Scholars' Mine. It has been accepted for inclusion in International Specialty Conference on Cold-Formed Steel Structures by an authorized administrator of Scholars' Mine. This work is protected by U. S. Copyright Law. Unauthorized use including reproduction for redistribution requires the permission of the copyright holder. For more information, please contact scholarsmine@mst.edu.

Twenty-First International Specialty Conference on Cold-Formed Steel Structures
St. Louis, Missouri, USA, October 24 & 25, 2012

AN EFFICIENT GENETIC ALGORITHM FOR THE DESIGN OPTIMIZATION OF COLD-FORMED STEEL PORTAL FRAME BUILDINGS

Duoc T. Phan[1], James B.P. Lim[2], Tiku T. Tanyimboh[3], Wei Sha[4]

Abstract

The design optimization of cold-formed steel portal frame buildings is considered in this paper. The real-coded genetic algorithm (GA) optimizer proposed considers both building's topology (i.e. frame spacing and pitch) and cross-sectional sizes of the main structural members as the decision variables that are optimized. Previous GAs in the literature were characterized by poor convergence including slow progress that usually results in excessive computation times and/or frequent failure to achieve an optimal or near-optimal solution. This is the main issue addressed in this paper. In an effort to improve the performance of the conventional GA, a niching strategy is presented that is an effective means of enhancing the dissimilarity of the solutions in each generation of the GA. Through a benchmark example, it is shown that the efficient GA proposed generates the optimal solution more consistently with three times faster of the computation time in comparison to the conventional GA.

Keywords: portal frame, cold-formed steel, optimization, genetic algorithm

[1] PhD Student, School of Planning, Architecture and Civil Engineering, Queen's University Belfast, Belfast, UK
[2] Lecturer, School of Planning, Architecture and Civil Engineering, Queen's University Belfast, Belfast, UK
[3] Senior Lecturer, Department of Civil Engineering, University of Strathclyde, Glasgow, UK
[4] Professor, School of Planning, Architecture and Civil Engineering, Queen's University Belfast, Belfast, UK

1. Introduction

Cold-formed steel portal frames are an increasingly popular form of construction in Australia and the UK, used for low-rise commercial, light industrial and agricultural buildings. For frames of modest spans, up to 20 m, this type of construction has been established to be a viable alternative to conventional hot-rolled steel portal frames.

The design optimization of the portal frames has attracted the attention of many researchers recently (Saka 2003, Hernández *et al.* 2005, and Issa and Mohammad 2010). However, those researches have concentrated mainly on hot-rolled steel frames, in which a fixed frame spacing and pitch of the rafter was assumed with the binary-coded GA designating the hot-rolled steel sections as discrete design variables from a manufacturer's catalogue, containing a discrete set of commercially available standard steel sections.

In the optimum design of cold-formed steel portal frames, there is however a scope to vary the roof pitch and frame spacing, in conjunction with selecting the most appropriate cross sections for members. This is because the cold-formed sections are lighter than hot-rolled steel sections, so that the structural members can be bolted and erected on site by semi-skilled workers, without the need for an onsite crane, and the erection costs are therefore considerably lower than for the hot-rolled steel portal frames. The design optimization described demonstrated that topology can have a significant effect on minimising the cost of the primary members per meter length of the building (Phan *et al.* 2011, Phan *et al.* 2012).

In engineering optimization, there can be a large number of complex (i.e. multi-modal and non-continuous) objective functions with implicit constraints that require the global optimum solution to be determined. In such problems, the traditional methods of mathematical programming that require the gradients of the objective functions and the associated constraints are not guaranteed to achieve the global or near global optimum solution due to the possible existence of local minima. As an alternative, GAs that simulate natural phenomena, such as survival of the fittest and adaptation, have been widely used in many fields including in the design optimization of steel structures (Camp *et al.* 1998).

Although GAs have been applied to many engineering problems, the main disadvantage of the conventional GAs is that they often suffer premature convergence and weak exploitation capabilities (Goldberg and Richardson 1987). Premature convergence, which often leads to a non-optimal solution or a local optimum solution, can occur because of loss of diversity in the population of candidate solutions. This loss of population diversity is due to the tendency of the selection operator in GAs to favour the better candidates when choosing those individuals to take part in crossover to create the next generation. In later generations, the best individuals will therefore dominate the population in evolutionary processes.

In an effort to enhance the searching performance of the GA, the distributed GA (DGA) was suggested to use with a number of variable mutation schemes to increase the diversity of the population in the earlier stages (Issa and Mohammad 2010). In addition, the niching techniques were suggested that have been successfully incorporated into GA to determine the global or near-global optimum solution of many complicated mathematical functions with multiple constraints (Deb and Goldberg 1989, Deb 2001).

In this paper, a niching strategy as proposed in Deb (2001) is incorporated into the RC-GA to improve the exploration of the solution space to help determine the optimum solutions, which are building topology as the continuous variables and section sizes as the discrete variables. The proposed optimization method, to be referred to as real-coded niching GA (RC-NGA), maintains the diversity of the population, thereby increasing the probability of achieving the near-global optimum solution, by the preferential retention of candidate solutions from regions that are under-represented while simultaneously eliminating some of the candidate solutions from regions that are overcrowded based on the presumption that candidate solutions in the same neighbourhood would tend to be similar.

The results of RC-NGA, in terms of cost of the primary members per square meter of floor plan, are shown to be identical to the benchmark examples presented in Phan *et al.* (2012). It is shown that the effectiveness in determining the near-global optimum solution increases significantly in terms of the reliability of the solutions, robustness and computational efficiency. The Australian code of practice is used for demonstration purposes, although any design codes can also be applied. It is because that there is less snow in many regions in Australia, so that the large span can be achieved.

2. Design optimization of the cold-formed steel portal frames

2.1 The details of portal frame building

In this paper, the design optimisation of a cold-formed steel portal frame is considered (Fig. 1). As can be seen, the geometry parameters are as follows: span of frame L_f, height to eaves h_f, pitch of frame θ_f; another dimension is frame spacing b_f. The joints between members are formed through brackets bolted to the webs of the channel-sections being connected (Fig. 2); matching swages rolled into both the brackets and webs of the channel-sections interlock under load forming a joint that can be considered to function as rigid (Kirk 1986).

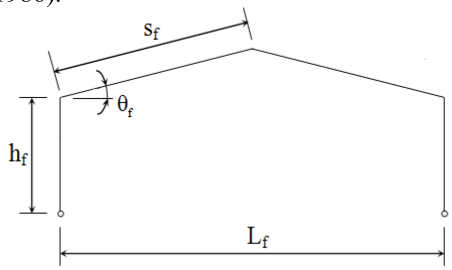


Fig. 1 Geometries of the portal frame

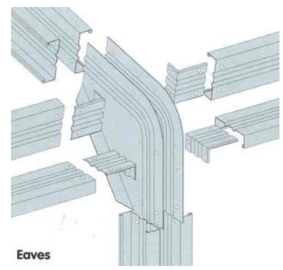
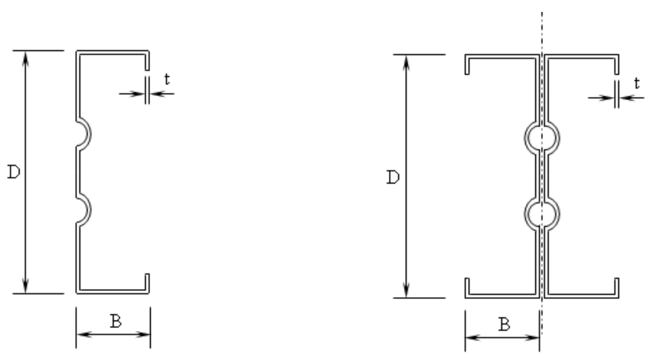


Fig. 2 Swagebeam eaves joint

For a specific portal frame building, in which span of frame and column height are given, the remained parameters, i.e. the pitch of frame and frame spacing, can be varied as the topology variables to investigate their effect on the unit cost of the building. In this research, the pitch θ_f varies in the range of [5^o; 45^o]; frame spacing b_f changes in the range of [2 m; 8 m]. Apart from that, the section sizes of members are other discrete decision variables that are also optimized. The most appropriate cross-section sizes are selected from the list of 40 available channel-sections in Australia from C10010 to C35030 (Phan *et al.* 2012). These channel-sections can either be used singly or back-to-back (Fig. 2).



a. Single channel-section (C) b. Back-to-back channel-section (BBC)

Fig. 2 Details of cold-formed steel channel-section

It is assumed that the columns bases are pinned (Fig. 1). Also, it is assumed that the purlins and side rails are positioned within the web of the members and are spaced sufficiently close to each other to prevent out-of-plane buckling from being the critical failure mechanism.

2.2 Optimization formulation

The objective of the overall design optimization, including the building topology and section sizes of members, is to determine the portal frame building having the minimum cost, whilst satisfying the design requirements. The cost of the main frame, which depends on frame spacing, pitch and cross-section sizes, can be expressed in terms of the cost of the primary members per square metre of the floor area as follows:

$$\text{Minimize W} = \frac{1}{L_f b_f}\sum_{i=1}^{m} w_i l_i \qquad (1)$$

where:

W	is the cost of main frame per square meter of floor area
w_i	are the cost per unit length of cold-formed steel sections (Phan *et al.* 2012)
l_i	are the lengths of cold-formed steel structural members
m	is the number of members.

2.3 Frame loadings

2.3.1 Permanent and imposed roof loads

The permanent and imposed roof loads according to Australian code (AS/NZS1170-1 2002) that will be applied to the frames are as follows:

Permanent load (G): 0.10 kN/m^2 (purlins, rails, cladding) + self-weight of the members

Imposed load (Q): 0.25 kN/m^2

2.3.2 Wind loads

In this paper, wind pressures from wind region W in Australia having a regional wind speed V_R of 49.4 m/s are used, based on the Australian code of practice on wind load for the design of buildings (AS/NZS1170-2 2002). A detailed example of determining the design wind speed and basic wind pressure for a typical portal frame building having span of 20 m, column height of 4 m, and pitch of 10^o was presented in Phan *et al.* (2012). In this case, the design wind speed V_{des} is 42.98 m/s and the basic wind pressure q_u is 1.1 kN/m^2.

The design wind pressures acting on each of the four sides of the frame are obtained by multiplying q_u by a coefficient of pressure and other related factors.

The coefficient of pressure acting on each face is obtained from a combination of the external pressure coefficient C_{pe} and the internal pressure coefficient C_{pi}. The eight wind load combinations (WLC1 to WLC8) for the frame, and their corresponding coefficients for both side wind and end wind, are shown in Table 1 (Phan *et al.* 2012).

Wind load combination	Description	Coefficient on faces			
		LHS column	LHS rafter	RHS column	RHS rafter
WLC1	Wind on side + internal pressure	0.7+0.2	-0.3+0.2	-0.3+0.2	-0.3+0.2
WLC2	Wind on side + internal suction	0.7-0.3	-0.3-0.3	-0.3-0.3	-0.3-0.3
WLC3	Wind on side + internal pressure	0.7+0.2	-0.7+0.2	-0.3+0.2	-0.3+0.2
WLC4	Wind on side + internal suction	0.7-0.3	-0.7-0.3	-0.3-0.3	-0.3-0.3
WLC5	Wind on end + internal pressure	-0.65+0.2	-0.9+0.2	-0.9+0.2	-0.65+0.2
WLC6	Wind on end + internal suction	-0.65-0.3	-0.9-0.3	-0.9-0.3	-0.65-0.3
WLC7	Wind on end + internal pressure	-0.2+0.2	0.2+0.2	0.2+0.2	-0.2+0.2
WLC8	Wind on end + internal suction	-0.2-0.3	0.2-0.3	0.2-0.3	-0.2-0.3

Table 1. Coefficients of pressures ($C_{pe}+C_{pi}$) corresponding to eight wind load cases

2.3.3 Limit state design

In accordance with Australian code in (AS/NZS1170-0 2002), the frame will be checked at the ultimate limit state for the following three ultimate load combinations (ULC):

$$\begin{aligned} ULC1 &= 1.2G + 1.5Q \\ ULC2 &= 1.2G + WLC \\ ULC3 &= 0.9G + WLC \end{aligned} \tag{2}$$

It should be noted that ULC3 is used for the uplift wind load combination.

2.4 Frame design

A first-order elastic frame analysis program is used to analyze the portal frame. For each load combination, bending moment, shear force and axial force diagrams for the frame are determined. The frame analysis program is called from the proposed algorithm to analyse each candidate solution in each generation as shown in Fig. 3.

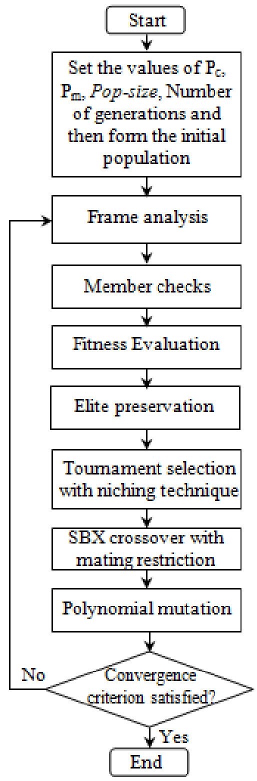


Fig. 3 Flowchart of the real-coded niching genetic algorithm

3. Real-coded niching genetic algorithm (RC-NGA)

As addressed in Section 2.1, the design optimization considered in this paper contains mixed discrete and continuous decision variables. For this problem, Phan *et al*. (2012) has proved that the real-coded genetic algorithm (RC-GA) can search for the optimum solution very effectively, especially as the optimization of the topology of the cold-formed steel portal frame building involves continuous decision variables. Another benefit of RC-GA is that genetic operators, namely simulated binary crossover (SBX) and polynomial mutation, are directly applied to the design variables without coding and decoding as compared with the binary string GAs.

In the proposed RC-NGA, tournament selection with a niching technique is applied. The process is conducted by selecting at random two individuals from the current population. The normalized Euclidean distance between two solutions is computed. If this Euclidean distance is smaller than an empirical user-defined critical distance, these solutions are compared using their fitness function values. Otherwise, they are not compared and another solution is selected at random from the population for comparison. If after a certain number of checks, no solution is found to satisfy the critical distance, the first one is selected for the crossover operation. In this way, only solutions in same region (or *niche*) compete against each other for selection and crossover (Deb 2000).

The flowchart of the RC-NGA used in this paper is shown in Fig. 3. The constant probabilities, namely, crossover probability P_c of 0.9 and mutating probability P_m of 0.1, are assigned to both crossover and mutation operators in the evolution process. Since the normalized Euclidean distance has a range from 0 to 1, it is found empirically that a suitable value of the critical distance is of 0.1, for which tournament selection and crossover operators worked effectively in this study. According to (Deb 2000), the minimum appropriate population size *(Pop-size)* is around 10*n*, where *n* is the number of decision variables in the design optimization problem

4. Fitness function

In this paper, ultimate limit state (ULS) is the basis of the design constraints for the optimization problem. A penalty function is used to transform this constrained problem to an unconstrained one. Penalty values are imposed empirically, in proportion to the severity of constraint violation. The fitness function adopted has the form (Camp *et al.* 1998):

$$F = W\,[1 + C] \tag{3}$$

where

F	is the fitness function
W	is the objective function being the cost of frame per unit area
C	is the constraint violation penalty

The proposed optimization procedure aims to minimize the value of the fitness function F (Eq. (3)). This is achieved by minimizing the cost W and reducing the penalty C to zero. The procedure involves RC-NGA and frame analysis modules (Fig. 3). In this optimization process, the evaluation process computes the fitness function values using the objective function (Eq. (1)) along with the corresponding penalty values. Better (i.e. cheaper) solutions will yield smaller fitness values, and consequently are selected preferentially by the tournament selection operator. The criterion for terminating the program is a predefined total number of function evaluations or generations.

5. Benchmark examples

The design optimization for the portal frame building is considered in this research using RC-NGA. The frame geometry has a span of 20 m and column height of 4 m. This benchmark example was described in Phan *et al.* (2012) and solved using RC-GA. The design optimization that accounts for the effect of both the pitch and frame spacing is conducted with the GA parameters and operators described in the Section 3. This problem has four decision variables, viz. pitch and frame spacing processed as continuous variables, whilst cross-section sizes of the columns and rafters being the discrete ones. Through a number of trials, the suitable population size was found as 40 and the suitable number of function evaluations was 6000 to terminate the RC-NGA program.

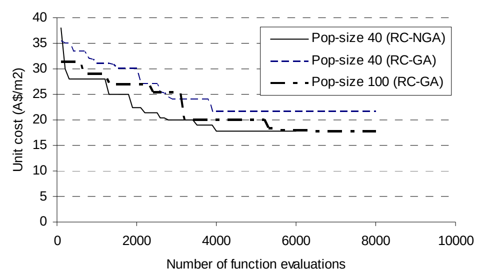


Fig. 4 Convergence progress of the optimal design processes

The progress of the optimization is shown in Fig. 4. As can be seen, the RC-NGA converged to the best optimum solution within the predefined number of function evaluations. The results obtained from the RC-NGA with the most appropriate cross-section size for both the columns and rafters is BBC25024; the optimum pitch is 21^{o}, the optimum bay spacing is 3 m, and the unit cost is A\$ 17.75/m^2. These same results were obtained from the RC-GA (Phan *et al.* 2012). It is observed that the design constraint for the combined actions of axial compression and bending on rafter was critical, with ULC3 load combination. The CPU time for RC-NGA was 1.5 hours for an IBM laptop having a processor speed of 1.86 GHz and memory of 1 GB. The RC-NGA, with a population size of 40 produces the optimum solution in 8 out of 10 runs within 6000 function evaluations.

It should be noted that with the same population size of 40, the authors solved this problem with the RC-GA routine (Phan *et al.* 2012) with a termination criterion of 8000 function evaluations. It was found that RC-GA was trapped at a local optimum solution with a unit cost of A\$ 21.55/m^2. According to the result in Phan *et al.* (2012), the appropriate population size used for RC-GA to obtain the optimum solution was found to be 100 (Fig. 4). For RC-GA, it was observed that only 3 out of 10 runs, with population size of 100, generated the same optimum solution. This means that on average RC-GA requires around 26667 function evaluations to reach the best solution, compared to RC-NGA which requires 7500 function evaluations. Based on these results, RC-NGA is approximately 3.5 times more efficient than RC-GA.

6. Conclusions

The RC-NGA was developed to minimize the cost of the primary members per square meter of floor plan for cold-formed steel portal frame buildings. The consistency of the optimum solution obtained has been improved after a number of runs, conducted with the small population size within more reasonable computing time. This means that the diversity in the population has been maintained, so that the probability of achieving the near global optimum result increased effectively.

The optimization program aims to determine the optimum topology and the most suitable cross-sections for members. The frame design obtained from the program can be considered as the most economical design in each case, since the critical design constraint in all examples becomes active. The computational efficiency and robustness of the algorithm has also been demonstrated. The length of computation time for solving the optimization problem was therefore reduced significantly by more than three times of the computation time in comparison to the RC-GA.

Acknowledgement

The financial support from the Queen's University Belfast is gratefully acknowledged.

Appendix. – References

AS/NZS1170-0, 2002. Autralian/New Zealand Standard^{TM}, *Structural design actions – Part 0: General principles.*

AS/NZS1170-0, 2002. Autralian/New Zealand Standard^{TM}, *Structural design actions – Part 1: Permanent, imposed and other actions.*

AS/NZS1170-0, 2002. Autralian/New Zealand Standard^{TM}, *Structural design actions – Part 2: Wind actions.*

AS/NZS4600, 2005. Autralian/New Zealand Standard^{TM}, *Cold-formed steel structures.*

Camp, C., Pezeshk, S., and Cao, G., 1998. Optimum design of two dimensional structures using genetic algorithm. *Journal of Structural Engineering, ASCE*, 124(5), 551-559.

Deb, K., 2000. An efficient constraint handling method for genetic algorithms. *Computer Methods in Applied Mechanics and Engineering*, 186, 311-338.

Deb, K., 2001. *Multi-objective optimization using evolutionary algorithms*. Chichester: John Wiley and Sons, Inc.

Deb, K., Goldberg, D.E., 1989. An investigation of niche and species formation in genetic function optimization. In: Schaffer, J., D., ed., *In: Proceedings of the 3rd International Conference on Genetic Algorithms.* San mateo: Morgan Kauffman, 42-50.

Goldberg, D.E., Richardson, J., 1987. Genetic algorithms with sharing for multimodal function optimization. *In: Proceedings of the 2nd International Conference on Genetic Algorithms.* L Erlbaun associates 1987; 41-49.

Hernández, S., Fontán, A.N., Perezzán, J.C., and Loscos, P., 2005. Design optimization of steel portal frames. *Journal of Advances in Engineering Software,* 36, 626-633.

Issa, H.K., and Mohammad, F.A., 2010. Effect of mutation schemes on convergence to optimum design of steel frames. *Journal of Constructional Steel Research*, 66(7), 954-961.

Kirk, P., 1986. Design of a cold-formed section portal frame building system. *In:* Yu, W.W., and Senne J.H., ed. *Proceedings of the 8th International Specialty Conference on Cold-formed Steel Structures*, 11-12 November 1986, St Louis. Missouri: University of Missouri-Rolla, 295-310.

Phan, D.T., Lim, J.B.P., Siew, C., Tanyimboh, T., Issa, H., Sha, W., 2011. Optimization of cold-formed steel portal frame topography using real-coded genetic algorithm. *In: Proceedings of the 12th East Asia-Pacific Conference on Structural Engineering and Construction (EASEC-12).* City University of Hong Kong, China, 26-28 January 2011; 724-733.

Phan, D.T., Lim, J.B.P., Sha, W., Siew, C., Tanyimboh, T., Issa, H., Mohammad, F. 2012. Design optimization of cold-formed steel portal frames taking into account the effect of topography. *Engineering Optimization.* In press.

Saka, M.P., 2003. Optimum design of pitched roof steel frames with haunched rafters by genetic algorithm. *Computers and Structures*, 81, 1967-1978.