Advanced Design Optimization of Cold-formed Steel Portal Frame Buildings

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Abstract

The design optimization of cold-formed steel portal frame buildings is considered in this paper. The objective function is based on the cost of the members for the main frame and secondary members (*i.e.,* purlins, girts, and cladding for walls and roofs) per unit area on the plan of the building. A real-coded niching genetic algorithm is used to minimize the cost of the frame and secondary members that are designed on the basis of ultimate limit state. It is shown that the proposed algorithm shows effective and robust capacity in generating the optimal solution, owing to the population's diversity being maintained by applying the niching method. In the optimal design, the cost of purlins and side rails are shown to account for 25% of the total cost; the main frame members account for 27% of the total cost; claddings for the walls and roofs accounted for 48% of the total cost.

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

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1. Introduction

Steel portal frame structures are a popular of the construction for low-rise commercial, industrial and agricultural buildings. The benefit of such buildings is that they can provide clear spans, without intermediate columns, which are erected easily and quickly on site. For buildings having small and medium spans, the use of cold-formed steel portal frames is a viable alternative to conventional hot-rolled steel portal frames. The advantages of cold-formed steel frames compared to hot-rolled steel are as follows. Pre-galvanised cold-formed steel sections that do not require painting to prevent rusting are maintenance-free. Transportation costs are lower due to efficient stacking of cold-formed steel sections. Acquisition costs are lower as the cold-formed steel used for the secondary members can be purchased from the same manufacturer/supplier (Lim and Nethercot 2004).

The design optimization of hot-rolled steel portal frames is a topic that has achieved some attention in the literature in recent years (Saka 2003, Issa and Mohammad 2010). In these papers, a fixed frame spacing and pitch has been assumed, with the design optimization focusing on minimizing the weight of the main frame by selecting the most appropriate size of hot-rolled steel sections for the column and rafters, as well as the size of the haunches. Binary-coded genetic algorithm has been used in these researches. More recently, Phan *et al.* (2012) have considered the design optimization of a cold-formed steel portal frame using a real-coded genetic algorithm (RC-GA) to minimize the cost of the frame, where the building topology (i.e., frame spacing and pitch) is treated as design variables.

By focusing on the main frame, previous researchers have not considered the effect of the weight of the secondary members (*i.e.,* purlins, side rails and sheeting) on the overall weight of the building. However, with cold-formed steel portal frames working under snow load, where the spans being considered are modest (around 12 m), and the cost of the secondary members can be considerable. This paper presents a design optimization of a cold-formed steel portal frame building which includes the cost of these secondary members.

Although GAs have been widely applied to design optimization, 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. To overcome this problem, a simple niching strategy is incorporated into the selection process (Deb 2000). In this way, only solutions in same region (or niche) compete against each other for selection, by the preferential retention of candidate solutions from such region; this procedure helps eliminate 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 advantage of the RC-GA over the binary-coded GA has been demonstrated in the researches of Deb (2001). In this paper, the RC-GA, combining with niching method is therefore applied to optimize the design problem. The proposed optimization method, to be referred to as real-coded niching GA (RC-NGA), will maintain the diversity of the population, and so improving the exploration of the solution space to help effectively determine the optimum solution.

The optimization design is conducted on a frame with span of 12 m and eaves height of 3 m, typically used in the UK. All the relevant combinations of the permanent and imposed loads, incorporating the full range of design constraints and all feasible wind load combinations are applied. It is observed that RC-NGA shows a robustness and high consistency in achieving the optimum solution. In the optimal design, the cost of purlins and side rails accounted for 25% of the total cost and the main frame accounted for 27% of the total cost; claddings for the walls and roofs accounted for 48% of the total cost.

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

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).

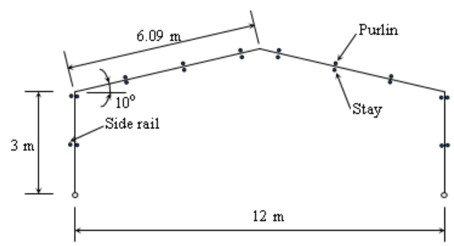


Fig. 1 Geometries of the portal frame

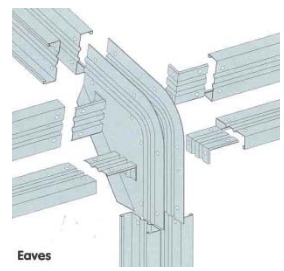
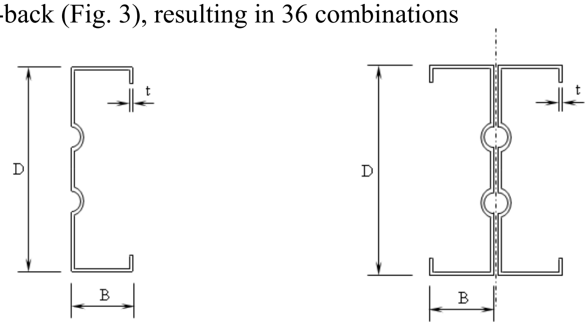


Fig. 2 Swagebeam eaves joint

The optimum section sizes for the frame members are selected from a list of 18 cold-formed steel channel-sections available in the UK, from C15014 to C40040 (Steadmans Brochures 2010). The member sections can either be used singly or back-to-back (Fig. 3), resulting in 36 combinations



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

Fig. 3 Details of cold-formed steel channel-section

As can be seen, the swages on the web of channel-section forming the rigid joints obviously improve the load carrying capacity of the members. However, for simplifying the checking procedure and obtaining a conservative design, it should be noted that the section properties and member checks are based on plane channel-sections and therefore ignore the benefit of the swages.

In this paper, cold-formed steel Zed sections are used for the purlins and side rails, which are placed on the top of the rafters and on the columns, outside of the building. As can be seen in Fig. 1, lateral torsional buckling restraints are also assumed to be applied at every position of the purlins and side rails through stays. The spacing of purlins and side rails and their sections which will depend on the frame spacing and are treated as design variables in the optimization process. The same distance for the purlins spacing and side rails spacing are assumed to be used for the rafters and columns, respectively. It is observed from the Steadmans Brochure for Zeds sections that there are 16 sections from Z14014 to Z24030, associated with their properties used for the optimization process (Steadmans Brochures 2010). The cost per unit length of each channel or Zed section is taken from industry.

The cost of metal cladding profile on purlins and side rails spacings of the portal frame building is also considered. The POSCO AS30 cladding profile in Steadmans Brochures is used for roof and wall cladding, with sheeting thickness of 0.5 mm; the cost per metre length used in this paper is £7.79 per metre length. It should be noted that the allowable span for this cladding profile is determined based on load span tables with deflection limits of cladding of span/200 for both live load and wind suction.

2.2 Frame loadings

The dead load and live load that will be applied to the frames are as follows:

Dead load (DL): 0.15 kN/m2 (including cladding and service) and selfweight of members of columns, rafters, purlins, and side rails

Live load (LL): 0.6 kN/m2

In this paper, it is assumed that wind loads (WL) are determined from a site location assumed within the UK having a basic wind speed V_b of 29.5 m/s, which leads to the dynamics wind pressure (q_s) of 1.0 kN/m^2, based on BS6399 (2002). The design wind pressures acting on each of the four sides of the frame are obtained by multiplying qs 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 acting on the frame and their corresponding coefficients for both side wind and end wind, as provided in BS6399, are considered.

The design of frame will be checked at the ultimate limit state for the following ultimate load combinations (ULCs):

$$ULC1 = 1.4DL + 1.6LL \tag{1a}$$

$$ULC2 = 1.2DL + 1.2LL + 1.2WL \tag{1b}$$

$$ULC3 = 1.4DL + 1.4WL \tag{1c}$$

$$ULC4 = 1.0DL + 1.4WL \text{ (for wind uplift)} \tag{1d}$$

These load combinations are also applied to design purlins, side rails and cladding system. It should be noted that for side rails and wall cladding, dead load (DL) and live load (LL) are neglected in those ultimate load combinations, basing on the assumption that these gravity loads do not cause significant bending in the vertical plane, due to the wall sheeting worked as an effective diaphragm

2.3 Frame design

A first-order elastic analysis package is used to analyze the cold-formed steel portal frame. The frame analysis program, written by the authors, is embedded in the optimal algorithm to analyse each candidate solution in each generation, as shown in Fig. 4. For each ultimate load combination, bending moment, shear force and axial force diagrams for the frame are determined. These results are then passed to design modules to carry out the member checks at the critical sections or segments between two lateral restraints.

In this paper, the effective width method (EWM) was applied to work out the section capacities in axial, shear, and bending, which can be referred in details from Steadmans Brochures (2010). It should be noted here that section capacities are determined for the lipped channel-section without stiffeners, due to simplification of the problem as explained in the Section 2.1.

For frame design, the columns and rafters are checked for combined axial force (either tension or compression) and bending moment, combined shear and bending, according to BS5950-5 (1998). In this paper, the normalized forms of the design constraints given in BS5950-5 are expressed as follows:

The combined tension and bending moment check is:

$$g_1 = \frac{F_t}{P_t} + \frac{M_x}{M_{cx}} - 1 \le 0 \qquad (2)$$

where

F_t is the applied tensile load at the critical section

P_t is the tensile capacity of a member, which is calculated from effective net area Ae of the section and design strength py of 390 N/mm2

M_x is the applied bending moment at the critical section

M_{cx} is the moment capacity in bending about x axis

The combined compression and bending moment are checked for local capacity at positions having greatest bending moment and axial compression and for lateral torsional buckling:

For the local capacity check:

$$g_2 = \frac{F_c}{P_{cs}} + \frac{M_x}{M_{cx}} - 1 \le 0 \qquad (3)$$

where

F_c is the applied compression load at the critical section

P_{cs} is the short strut capacity subjected to compression, which is calculated from effective net area Ae of the section and design strength py of 390 N/mm2

For the lateral torsional buckling check:

$$g_3 = \frac{F_c}{P_c} + \frac{M_x}{M_b} - 1 \le 0 \qquad (4)$$

where

P_c is the axial buckling resistance in the absence of moments

M_b is the lateral resistance moment about major axis.

For the members subjected to both shear and bending moment, the webs of members should be designed to satisfy the following relationship:

$$g_4 = \left(\frac{F_v}{P_v}\right)^2 + \left(\frac{M_x}{M_{cx}}\right)^2 - 1 \le 0 \qquad (5)$$

where

F_v is the shear force in associate with the bending moment Mx at the same section

P_v is the shear capacity or shear buckling resistance

For purlins, side rails and cladding design constraints, the load acting on those secondary members (p_{design}) should satisfy the following relationship:

$$g_{5,6,7} = \frac{p_{design}}{p_c} - 1 \le 0 \qquad (6)$$

where

p_c is the bending moment capacity of members of Zed section.

2.4 Optimization formulation

The objective in the design optimization is to minimize the cost of materials used in unit floor area of the building, whilst satisfying the design codes of practice. The material cost for all members used per square metre of the floor area, which depends on the frame spacing, frame geometry, cross-section sizes of members, purlins, side rails and cladding for the wall and roof, can be expressed as follows:

$$\text{Minimize} \qquad W = \frac{1}{L_f b_f}\left[\sum_{i=1}^{m}(w_{fi} + w_{cl})l_{fi} + b_f\{\sum_{j=1}^{n} w_{pj} + \sum_{l=1}^{k} w_{sl}\}\right] \qquad (7)$$

where

- W is the cost of the building per square meter of floor area
- w_{fi} are the cost per unit length of cold-formed steel sections for frame members
- w_{cl} is the cost per unit length of AS30 cladding
- l_{fi} are the lengths of cold-formed steel frame members
- m is the number of structural members in portal frame
- w_{pj} are the cost per unit length of purlin sections
- w_{sl} are the cost per unit length of side rail sections
- n are the number of purlins on the rafters
- k are the number of side rails on the columns

As can be seen, the objective function, in terms of the cost for the frame and secondary members (Eq. 7), contains six discrete decision variables, namely, cross-section sizes for columns, rafters, purlins and side rails, the number of purlins on the rafters, and the number of side rails on the columns. Specifically, the number of purlins and side rails varies in the range of [2; 20], where 20 purlins or side rails can lead to the full lateral restraint applied on the rafter or column. The optimum solution for such design variables, which produce the lowest cost for the objective function, will be searched in the design space subjected to those relevant design constraints as described in Section 2.3.

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

In the proposed RC-NGA, tournament selection using niching technique (Deb 2000) 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. Moreover, the convenience of using 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 (Deb 2001).

The flowchart of the RC-NGA used in this paper is shown in Fig. 4. The constant probabilities, namely, crossover probability P_c of 0.9 and mutation 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 0.3, 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 10n, where n is the number of decision variables in the design optimization problem.

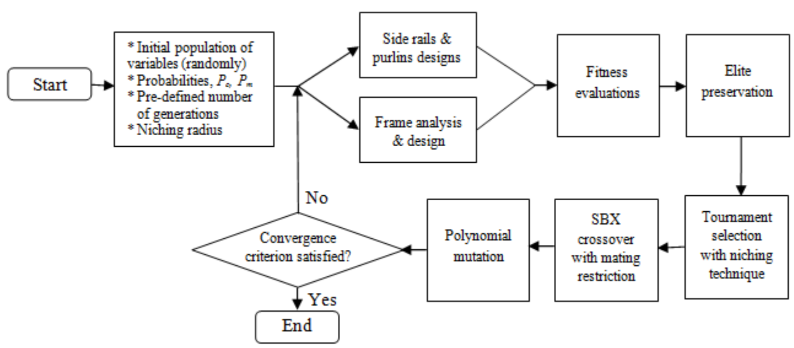


Fig. 4 Flowchart of real-coded niching genetic algorithm

4. Fitness function

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 based on the ultimate limit state design. The fitness function adopted has the form:

$$F = W\,[1 + C] \tag{8}$$

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. 8). 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. 4). In this optimization process, the evaluation process computes the fitness function values using the objective function (Eq. 7) 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 generations.

5. Optimal design of portal frame building

5.1 Optimization for main frame

In this Section, the optimal design of the frame presented in Section 2.1 using RC-NGA is carried out, according to the design constraints as presented in the Section 2.4. First of all, the full lateral restraint on the frame members is assumed; the frame is optimized under local capacity checks. The objective function, excluding the cost of secondary members, is minimized, in which the section sizes of the columns and rafters are optimized as design variables. The population size of 40 is empirically selected for the optimal process which is terminated after 200 generations after a number of trials. The probabilities of crossover and mutation operators are 0.9 and 0.1, respectively; the normalized niching radius is set as 0.3. The design is also optimized 5 times to check for the consistency with different seed values, due to the random characteristics of the proposed method.

It is observed that 5 runs converged to the same optimum solution with the minimum cost being £6.27 per m^2. The optimum cold-formed steel section used for columns is shown in Table 1. It is observed that in the final design for the strength constraint of combined compression force and bending moment on the left hand side column governed the design, *i.e.,* $g_2 = 0$, under the load combination ULC2. The CPU time for the evolutionary process observed was around 6 hours, running on the machine having processor of 2.0 Ghz and memory of 2.0 GB.

Table 1. Optimal design of main frame

Optimum sections				Frame cost ($£/m^2$)
Column	Rafter	Purlin	Side rail	
BBC30025	BBC30030	N/A	N/A	6.27

5.2 Optimization for portal frame building

When the cost of secondary members is taken into account, the objective function is minimized, in which the section sizes of the columns and rafters, purlins and side rails, number of purlins and the number of side rails spacings are optimized as the design variables. The population size of 100 is empirically selected for the optimal process which is terminated after 250 generations after a number of trials.

Table 2. Optimal design of frame including secondary members

Optimum sections				Purlin spacing	Side rails spacing	Total cost (£/m^2)
Column	Rafter	Purlin	Side rail			
BBC30030	BBC30030	Z14016	Z14016	1.52 m (10 purlins)	1.50m (6 girts)	24.70

It was observed that the evolutionary process converged to the same final design in total of 5 cases with the minimum cost of £24.7 per m^2. The detailed information of the optimum design obtained is shown in Table 2. Breaking down the total cost shows that the cost of main frame is £6.6 per m^2; the cost of purlins and side rails is £6.17 per m^2; the cost of claddings for the walls and roofs is £11.93 per m^2. The percentage of the cost for each part in the total cost is shown in Fig. 5. As can be seen in the optimal frame design, percent of the main frame and percent of the purlins and side rails is nearly the same, whilst the percentage of cladding cost accounted for nearly 50% of the total cost.

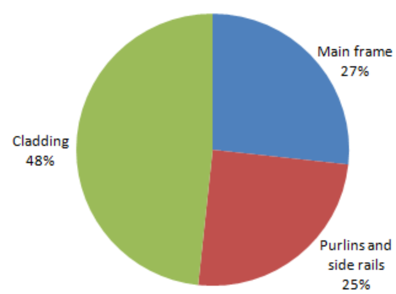


Fig. 5 Percentage of main frame and secondary costs

In the case of the sheeting AS30 profile from Steadmans Brochures used for the roof and wall claddings, the optimum spacings of purlins and side rails, the Z14016 is the optimum section for purlins and side rails with frame spacing of 6 m. It should be noted that these spacings are converted from the number of purlins and side rails, which are uniformly arranged on the rafters and columns, respectively. This layout of purlins and side rails leads to an optimal design for the main frame, which lateral torsional buckling constraint on the column (*i.e.,* g_3 = -0.02) controlled the design under load combination ULC2. The effect of lateral torsional buckling on the column leads to the bigger section being used; the cost of main frame is 5% higher than in the optimal design of frame using full lateral restraint.

The convergence progress of RC-NGA for a typical seed values from the 5 runs, such as seed 1, is shown in Fig. 6. The minimum cost in each generation is plotted in association with maximum, mean values to show the distribution of the population through the evolutionary process. As can be seen, the diversity of population is effectively maintained in each generation; thereby increases the probability to achieve into the optimum solution.

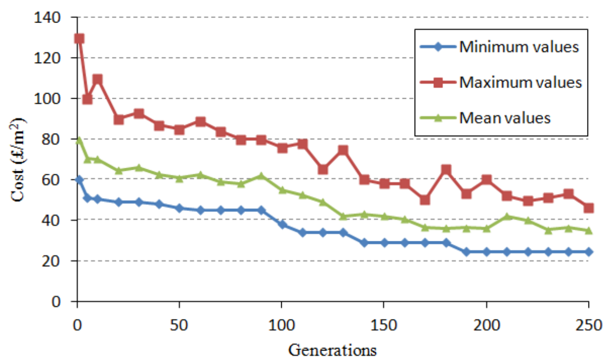


Fig. 6 Population distribution through evolutionary process in RC-NGA

6. Conclusions

The design optimization of a typical frame has been carried out in this paper, taking into account the cost of secondary members. The RC-NGA was used to minimize the objective function in terms of the total cost of a main frame and the secondary members subjected the design constraints according to BS5950-5. It was shown that the proposed optimization method searched the optimum solution effectively and reliably, through the high consistence of convergence to the optimum solution in the evolutionary process.

As expected, the cost of purlins, side rails and cladding is considerable, which account for 73% of total cost as compared to the cost of the main frame accounted for 27% only. This factor proved the need of minimizing the cost of these members. The effect of lateral torsional buckling on sizing the member section leads to the cost of frame 5% higher than in the design using full lateral restraint. For a building having typical topology, namely, pitch of 10o and frame spacing of 6 m, it was shown that using the section of Z14016 for purlins and side rails is the most appropriate for a low cost design. It was observed that the optimum spacing for purlins and side rails is around 1.5 m which can be commonly applied in practical design.

Acknowledgement

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