# Optimum design of steel telecommunication poles using genetic algorithms

**Mohamed A.H. Khedr**

**Abstract:** This study implements the genetic algorithm (GA) method in the optimization of steel telecommunication poles subjected to normal operating loads. In formulating the optimization problem, the objective function is defined as the pole weight. The imposed constraints on the design are: interaction ratios, sway angle limitations, minimum and maximum pole bottom diameters, and segment heights. The formulated problem is a mixed continuous–discrete problem where the main dimensions of the pole, top and bottom diameters, and segment heights are continuous variables whereas other variables are discrete. A Microsoft® Visual Basic® computer program is written implementing the requirements of TIA/EIA-222-G standards and using genetic algorithms (GAs). A verification problem and a generic telecommunication pole example are presented that show the effectiveness of the proposed approach. This program can be extended to cover other design standards of telecommunication poles as well as different types of poles, such as lighting and transmission poles.

*Key words:* optimization, telecommunication poles, genetic algorithm, multilevel optimization and steel design.

**Résumé :** L'étude utilise la méthode de l'algorithme génétique dans l'optimization des pôles de tours de télécommunications en acier sujettes à des charges opérationnelles normales. Lors de la formulation du problème d'optimization, la fonction de décision est le poids des pôles. Les contraintes imposées à la conception sont les rapports d'interaction, les limites de l'angle d'oscillation, les diamètres minimums et maximums du bas des pôles et la hauteur minimale et maximale des segments. Le problème formulé est un problème mixte continu-discret dans lequel les dimensions principales du pôle, les diamètres au haut et au bas et les hauteurs des segments sont des variables continues alors que les autres variables sont discrètes. Un programme en « Visual Basic® » de Microsoft® incorporant les exigences des normes TIA/EIA-222-G a été écrit; il utilise la méthode de l'algorithme génétique. Un problème de vérification et un exemple de pôle générique de télécommunications sont présentés montrant l'efficacité de l'approche proposée. Ce programme peut être étendu pour incorporer d'autres normes de conception de pôles de télécommunications ainsi que différents types de pôles tels que les pôles d'éclairage et de transmission.

*Mots-clés :* optimization, pôles de télécommunications, algorithme génétique, optimization à niveaux multiples et conception de structures d'acier.

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## Introduction

Steel poles are commonly used in numerous applications, including but not limited to highway signs and lighting, storage area lighting, advertisement signs, transmission, and telecommunication. Telecommunication steel poles are used as an alternative to lattice towers, to benefit from their acceptable appearance, smaller footprint, and speed of installation. Recently, camouflage poles have been used extensively, where poles are disguised in the form of pine trees, palm trees, clock towers, etc. Poles can be classified into three main types based on their connection method: flanged poles, where pole segments are connected using flange plates; welded poles; and telescopic tapered poles, where telescopic or slip connections are used. Pole cross sections are either round or polygonal, having 4, 8, 12, 16, or 18 or more sides.

Optimization of tapered steel poles is an important as well as a challenging problem due to several factors, including: the wide range of variables considered in their design, geometry-dependant wind loads, and the usual mass production of each design. The design of tapered steel poles requires dealing with a wide range of unknowns, such as shape of cross section, top and bottom diameters, number of segments, and wall thicknesses. These unknown variables can be classified into two main groups. The first group contains continuous variables, such as top and bottom diameters and segment heights. The second group contains discrete variables, such as number of segments and wall thicknesses. A significant part of the wind load acting on this type of structure is wind on the shaft itself. This requires a complete recalculation of the acting loads each time a change is made to the shaft geometry. In addition, the production of poles is usually done in mass quantities, especially for traffic and transmission applications.

To solve this optimization problem, a nonlinear optimization technique capable of dealing with continuous as well as discrete variables must be used. Nonlinear optimization methods typically use calculus-based gradient approaches

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that require the linearization of the optimization problem constraints around a local point, therefore a local optimum may be located instead of the true optimum. Unlike traditional calculus-based optimization methods, evolutionary search methods are capable of handling nonlinear optimization problems without the need of linearization. In addition, these methods are capable of dealing with integer, floating point, and discrete variables equally.

One of the evolutionary search methods that has gained a great deal of popularity is the genetic algorithms (GAs) for search and optimization. Genetic algorithms replicate the Darwinian theory of evolution, where the fittest individual in a pool of individuals has the highest chance of survival, whereas the weakest individual has the lowest probability of survival.

Genetic algorithms have been used in solving many practical problems in different fields and applications, such as maximizing project profitability, pattern recognition, and structural optimization. In the structural optimization field, GAs have been used successfully in locating the optimum design of several types of space and planar structures (Erbatur et al. 2000), concrete frames (Lee and Ahn 2003), steel frames (Foley and Schinler 2003), trusses (Turkkan 2003), liquid retaining structures (Chau and Albermani 2003), and latticed towers (Kocer and Arora 2002). The design variables dealt with in these applications were either discrete, as in the case of selecting a steel cross section from profile tables, or continuous, as in the case of designing a reinforced concrete cross section (Camp et al. 2003). The formulation of the optimization problem was either performed on a predefined geometry of the structure or the topology of the structure was considered as a design variable. Optimum design of steel tubular telescopic poles has been studied by Dicleli (1997). In his work, Dicleli used an iterative method to obtain the optimum design for the poles. The design variables considered during the optimization process were thetop and bottom diameters of the pole and wall thicknesses of the pole segments. The number of segments and length of each segment were kept constant throughout the optimization process.

The objective of the current study is to present a genetic algorithm (GA) approach capable of locating the optimum weight of tapered telescopic steel telecommunication poles. During the formulation of the optimization problem, all required loading conditions and stress limitations imposed by the design standards are considered. Deflection or sway angle limitations required by antenna manufacturers, customer requirements or standard requirements are taken into account. The geometrical parameters of the pole considered in the design are: slope, number of segments, segment heights, and wall thickness.

## Design of steel telecommunication poles

There are several internationally recognized design codes and standards governing the design of steel telecommunication poles and one of these is the American standard TIA/EIA-222-G (ANSI–TIA 2005). The current work implements the requirements of TIA/EIA-222-G in the design of telecommunication steel poles. It is important to note that the proposed algorithm will work equally well when coupled with other design codes and standards for communication, lighting, or transmission poles. The following sections present a brief discussion of the requirements of the TIA/EIA-222-G standard, which is used in the current study.

### Acting loads

Telecommunication poles are subjected to three main types of loads: dead loads that include self-weight of the pole, antenna weight, platforms weight, and weight of ladders; wind acting on the pole shaft, antennas, and platforms; and ice accumulated on the pole surface as well as on the elements attached to the pole body. In addition, TIA/EIA-222-G (ANSI–TIA 2005) considers seismic forces as a fourth type of loading acting on telecommunication poles.

These types of loads are briefly described below; the reader should refer to the TIA/EIA-222-G standard for an in-depth understanding of the methods and formulas used in calculating these loads.

#### *Wind loads*

Wind pressure acting on the pole is calculated using a wind speed that is escalated with height according to the terrain characteristics surrounding the pole site. The exposure categories are the same as those contained in ASCE/SEI 7–05 (ASCE 2005). Wind speed-up effects due to significant topographic features, such as hills, ridges, and escarpments, are accounted for through simplified equations. The wind gust effects are accounted for through the application of a constant gust factor of 1.10.

#### *Ice loads*

Ice accretion around the pole shaft, attachments, and antennas results in an increase in the gravitational loads and the effective projected area subjected to wind pressure. As ice accumulation is known to increase with increasing of wind speed, ice thickness is escalated with height similar to wind speed escalation. The weight of ice accumulated on an element is calculated by taking the factored radial thickness of ice around it into consideration. The projected area of ice is calculated by using twice the factored radial thickness of ice.

#### *Earthquake loads*

Earthquake loads rarely govern the design of poles that support antennas. However, pole response to earthquake loads requires special considerations, especially in regions of high seismicity. Therefore, the TIA/EIA-222-G standard (ANSI–TIA 2005) provides design criteria to ensure sufficient strength and stability to resist the effects of seismic ground motions.

### Design philosophy

The TIA/EIA-222-G standard (ANSI–TIA 2005) implements the limit states design method. Accordingly, poles are designed to satisfy two main limit states: (*i*) strength limit state to ensure that structures are safe under extreme loading conditions; (*ii*) serviceability limit state to ensure that the structure is capable of providing the required service under normal conditions.

When considering limit state design, the above mentioned loads are grouped into two main loading combinations and appropriate load factors are applied accordingly as discussed hereunder.

***Strength limit state load combinations***

For strength limit states design, a load factor of 1.6 is applied to nominal wind loads. To account for the probability of the wind blowing from the worst-case direction, a directionality factor is applied to the factored wind loads.

As mentioned earlier, the nominal ice thickness is multiplied by a load factor of 2.0; hence, ice weight and wind projected area due to ice accretion are factored. Therefore, a load factor of 1.0 is applied to ice dead load and wind loading for the ice condition.

In a mathematical form, the strength limit state load combinations are:

$$[1] \qquad 1.2D + 1.6W_o$$

$$[2] \qquad 0.9D + 1.6W_o$$

$$[3] \qquad 1.2D + 1.0D_i + 1.0W_i$$

Where $D$ is the dead load; $W_o$ and $W_i$ are wind load without ice and wind load associated with ice, respectively; and $D_i$ is the ice weight.

***Serviceability limit state load combination***

The service load condition is defined by a wind load resulting from a 27 m/s wind speed without ice and using a gust effect factor of 1.0. Unless more stringent requirements are imposed, poles are limited to a maximum of 4° twist or sway rotation and a maximum horizontal displacement equal to 5% of the height of the structure.

The load combination for the serviceability limit state stated in TIA/EIA-222-G (ANSI–TIA 2005) is given by:

$$[4] \qquad 1.0D + 1.0W_o$$

Unlike several design standards that include ice load in the serviceability limit state load combination, such as the Canadian standard CSA S37–01 (CSA 2001), eq. 4 from TIA/EIA-222-G (ANSI–TIA 2005) does not include ice loads. The current Microsoft® Visual Basic® (VB) code can be changed to handle other serviceability requirements if mandated by the design standards.

**Nominal resistances**

Equations [5] through [8] are used to calculate the nominal axial ($P_n$), flexural ($M_n$), shear ($V_n$), and torsion resistance ($T_n$) of the pole cross section, respectively:

$$[5] \qquad P_n = F'_y A$$

$$[6] \qquad M_n = F'_y S$$

$$[7] \qquad V_n = 0.5F'_y A$$

$$[8] \qquad T_n = F'_y J/c$$

where $F'_y$ is the effective yield stress as given in Table 1, $A$ is the area of the cross section, $S$ is the minimum elastic section modulus, $J$ is the polar moment of inertia, and $c$ is the maximum distance from the center of twist.

These calculated nominal values are then multiplied by the resistance factors $\phi_c$, $\phi_f$, $\phi_v$, and $\phi_T$, where the subscripts c, f, v, and T stand for compression, flexural, shear, and torsion, respectively.

**Analysis procedure**

The TIA/EIA-222-G (ANSI–TIA 2005) standard requires, as a minimum, that the pole be modelled as three-dimensional beam elements and each pole segment be subdivided into at least five beam–column elements. In addition, the effects of displacements on member forces, i.e., P-Δ effects, must be considered. Geometrical nonlinearities or P-Δ effects are generally taken into account through the use of a nonlinear finite element analysis procedure or an alternative simplified approach, such as moment amplification. One widely used simplified methods is presented in the AASHTO (2001) standard, where the bending moment is divided by a coefficient of amplification, $C_{P\Delta}$, to account for secondary moment. This coefficient is used for poles where secondary P-Δ effects are significant and is given by the following equation:

$$[9] \qquad C_{P\Delta} = 1 - \left( \frac{\sqrt[3]{I_B/I_T} P_T + 0.38\ W_P}{2.46EI_B/L^2} \right) \leq 1.0$$

provided that

$$\sqrt{\frac{2\pi^2 E}{F_y}} \leq \frac{kL}{i}$$

In eq. [9], $I_B$ and $I_T$ are the moment of inertia of the pole base cross section and pole top cross section, respectively; $P_T$ is the vertical concentrated load at the top of the pole; $W_p$ is the total pole weight; $E$ is the material modulus of elasticity; $L$ is the pole height; $F_y$ is the specified minimum yield stress; $k$ is the slenderness factor; and $i$ is the radius of gyration at $0.5L$. The $C_{P\Delta}$ coefficient was based on an approximation of the buckling equation for prismatic bars subjected to top load and distributed axial load; the reader is referred to Nunez and Fouad (2000) for a complete explanation of the derivation of eq. [9].

It should be noted that the proposed optimization method was tested successfully using a geometrical nonlinear finite element procedure. However, the AASHTO (2001) simplified moment amplification method was chosen to reduce the computation time.

**Interaction ratio**

The following interaction equation shall be satisfied at every cross section along the height of the pole:

$$[10] \qquad \left(\frac{P_u}{\phi_c P_n}\right) + \left(\frac{M_u}{\phi_f M_n}\right) + \left[\left(\frac{V_u}{\phi_v V_n}\right) + \left(\frac{T_u}{\phi_T T_n}\right)\right]^2 \leq 1.0$$

where $P_u$ is the factored axial compressive force, $M_u$ is the

**Table 1.** Effective yield stress under flexural and axial loads for polygonal tubular steel members.

| Shape | $(w/t)$ ratios | Effective yield stress, $F'_y$ |
|---|---|---|
| 18 sided | $(F_Y/E)^{1/2}(w/t) < 1.17$ | $F'_y = F_Y$ |
| | $1.17 \le (F_Y/E)^{1/2}(w/t) \le 2.14$ | $F'_y = 1.404\ F_Y\ [1.0 - 0.245\ (F_Y/E)^{1/2}(w/t)]$ |
| 16 sided | $(F_Y/E)^{1/2}(w/t) < 1.26$ | $F'_y = F_Y$ |
| | $1.26 \le (F_Y/E)^{1/2}(w/t) \le 2.14$ | $F'_y = 1.420\ F_Y\ [1.0 - 0.233\ (F_Y)^{1/2}(w/t)]$ |
| 12 sided | $(F_Y/E)^{1/2}(w/t) < 1.41$ | $F'_y = F_Y$ |
| | $1.41 \le (F_Y/E)^{1/2}(w/t) \le 2.14$ | $F'_y = 1.450\ F_Y\ [1.0 - 0.220\ (F_Y)^{1/2}(w/t)]$ |
| 8 sided | $(F_Y/E)^{1/2}(w/t) < 1.53$ | $F'_y = F_Y$ |
| | $1.53 \le (F_Y/E)^{1/2}(w/t) \le 2.14$ | $F'_y = 1.420\ F_Y\ [1.0 - 0.194\ (F_Y)^{1/2}(w/t]$ |

**Note:** $F_Y$, specified minimum steel yield strength (MPa); $w$, actual flat side dimension (mm), but not less than dimension calculated using a bend radius equal to $4t$; $t$, wall thickness (mm); $E$, modulus of elasticity (MPa).

factored flexural moment, $V_u$ is the factored transverse shear force, and $T_u$ is the factored torsion moment.

## Formulation of the structural optimization problem

### Optimization method

The GA method used in solving the current optimization problem was chosen for its robustness, effectiveness, and ability to handle discrete and continuous variables equally well. In the following sections, brief definitions of the genetic algorithm operators and common terminologies are presented for completeness. The reader is referred to Goldberg (1989) for a comprehensive and complete explanation of this method.

*Pool size* — The number of individuals in a given generation; this number is an even number that is kept constant throughout the analysis cycle. A pool size of 500 is selected for the problem at hand.

*First generation* — The genetic algorithm method starts with selecting the initial pool of designs with a size depending on the number of variables. The gene length of each individual depends on the number of variables and the range of numerical values each variable is mapped to. The gene of each individual is then populated by 1s and 0s at random; the process is then repeated for each individual in the pool of designs. In the current work, the number of generations is preset to a maximum of 50 generations.

*Objective function evaluation* — For each individual in the population, the objective function is evaluated by substituting the numeric values equivalent to the binary string containing the genetic information of the individual into the objective function. Then the constraints are evaluated and the penalty term is added to account for any constraint violations.

*Mapping objective function to fitness form* — The GA searches for the fittest individual in the current generation. Setting the fitness as pole weight (objective function) will result in finding the pole with the maximum weight. It is therefore necessary to map the objective function of each individual to a fitness value. This is achieved by first determining the largest objective function in the current generation, then subtracting the objective function of each individual from that value. The pool of designs is subsequently arranged in descending order according to the individual fitness.

*Fitness scaling* — The aim of fitness scaling is to overcome two main problems associated with GA. The first problem occurs early in the solution process, where dominance by extraordinary individuals causes premature problem convergence. The second problem occurs late in the solution as the difference among individual fitness becomes small, thus preventing the best solutions from having a significant advantage in the reproduction process. Fitness scaling is performed to convert the calculated fitness values to values in a range that is suitable for the selection process. This is achieved while maintaining the population average fitness unchanged, through scaling up individuals with fitnesses below the population average fitness and scaling down those with fitnesses above the population average.

*Number of copies* — Each individual is copied a number of times based on its fitness using a biased Rolette wheel simulation. This step will result in a pool of parents with the same number of individuals as the initial pool.

*Crossover and reproduction* — Pairs of parents are chosen at random with a total number of mating pairs based on a predefined value for crossover probability, taken as 0.6 in the current study. The crossover site is also chosen at random for each pair and a swap of bits is performed to produce the offsprings.

*Mutation* — A mutation probability is defined to ensure that new genes are introduced at random in the new generation to widen the exploration search space.

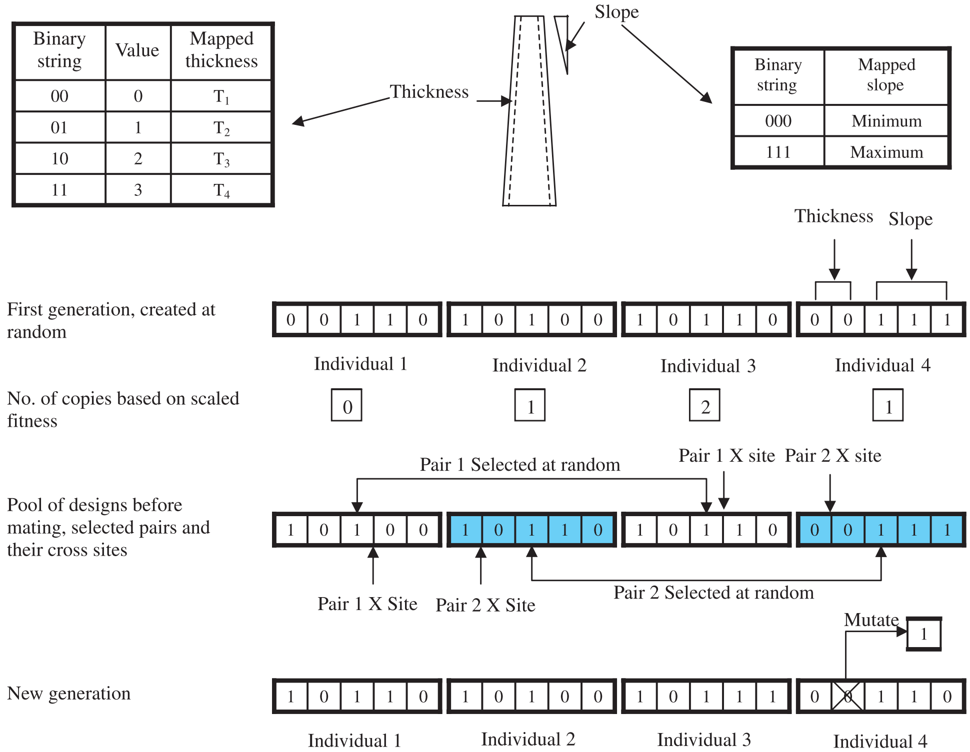
*Elitism* — In this study, elitism is used to ensure that the best individual of the current generation is preserved and is copied to the next generation.

The formulation of the optimization problem as well as the main GA processes used in solving this problem is encapsulated in Fig. 1.

### Design variables

The current optimization problem is formulated considering the following design variables: slope, number of segments, segment heights, and wall thicknesses.

**Fig. 1.** Schematic illustrating the main genetic operators and pole problem formulation.




## Objective function

In the current work, the objective function is set to be the total weight of the pole, $W_P$ and is calculated using the following equation:

$$[11] \qquad W_P = \sum_{i=1}^{n} \frac{(A_{\mathrm{Top}_i} + A_{\mathrm{Bottom}_i})}{2} L_i$$

where $A_{\mathrm{Top}i}$ and $A_{\mathrm{Bottom}i}$ are the top and bottom cross-sectional areas, respectively, of segment $i$; $L_i$ is the segment length; and $n$ is the total number of pole segments.

The objective function can be rewritten to include the pole cost rather than weight. In that case, the objective function must include: material cost, workmanship, galvanization or painting cost, scrap value, and depreciation cost and overhead costs of the machines.

## Imposed constraints

The optimum solution must satisfy the following inequality constraints:

$$[12] \qquad g_{\sigma_j} = |\sigma_j| - \sigma_{\mathrm{limit}} \leq 0 \qquad j = 1, \ldots, m$$

$$[13] \qquad g_{\delta_i} = |\delta_i| - \delta_{\mathrm{limit}} \leq 0 \qquad i = 1, \ldots, k$$

where $g_{\sigma_j}$ is the $j$th stress constraint, $g_{\delta_i}$ is the $i$th sway angle constraint, $\sigma_j$ is the $j$th stress value, $\delta_i$ is the $i$th sway angle value, $\sigma_{\mathrm{limit}}$ is the stress limit, $\delta_{\mathrm{limit}}$ is the sway angle limit, and $m$ and $k$ are the number of stress constraints and sway angle constraints, respectively.

Additional constraints are imposed to keep the design variables within a realistic and practical range. For continuous variables, $x$, such as the segment diameters and lengths, eq. [14] is used:

$$[14] \qquad x_i^{\mathrm{l}} \leq x_i \leq x_i^{\mathrm{u}}$$

where superscripts l and u represent the lower and upper bounds, respectively. Imposing the constraints on slope and wall thicknesses is achieved through the numeric conversion of design variables from a binary string to real numbers. Therefore, the violation of these constraints will not be enforced through the application of penalty multipliers as discussed in the next section.

The imposed constraints have different units and numerical ranges. For instance, the interaction ratio is a dimensionless number whose value is less than one (if there is no stress violation), whereas the sway angle is measured in degrees and its upper bound is problem dependant. Geometry constraints, on the other hand, are dimensionless conditions that will only accept true or false values or 1 and 0. Therefore, constraint equations are normalized to provide equal penalty distribution, which is a common practice in optimization problems.

## Penalty function

The GA searches for the optimum solution of an unconstrained objective function; therefore, any constrained optimization problem must be transformed into an unconstrained problem. This transformation process is achieved through the use of a penalty multiplier approach. Several penalty multipliers are suggested in published literature (Dicleli 1997): some can be classified as dynamic penalty multipliers, whereas others are constant. The term dynamic penalty multiplier means a nonconstant multiplier that is a

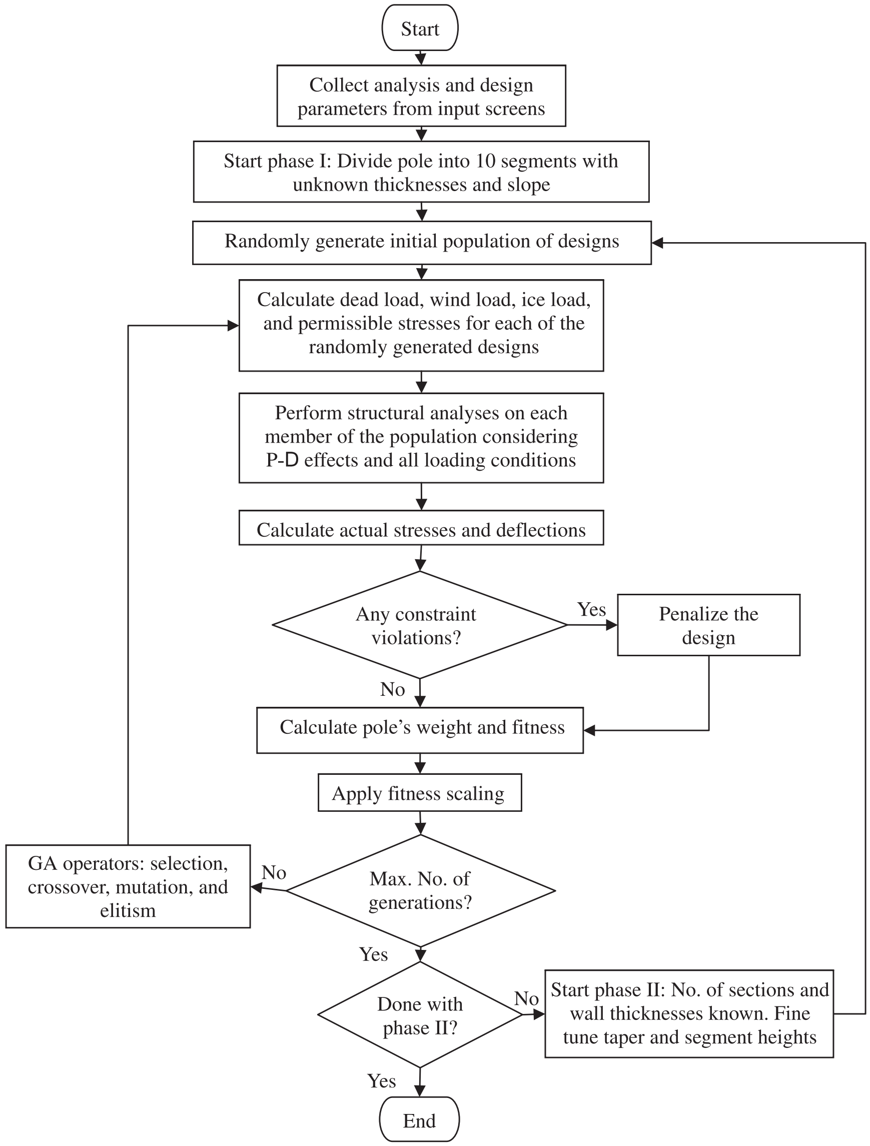



**Fig. 2.** Flow chart of the pole optimization program Optimum Pole.

function of the current generation and increases the intensity of the imposed penalty with the advancement of the solution.

In the current study, the constrained optimization problem is converted into a nonconstrained problem through the use of a dynamic penalty parameter, $p$, as shown in the following equation:

$$[15] \qquad \phi(x) = W_{\mathrm{P}}(x) + p\left[\sum_{j=1}^{m}\max(0, g_{\sigma_j})^2 + \sum_{j=1}^{n}\max(0, g_{\delta_j})^2\right]$$

where $\phi(x)$ is the nonconstrained optimization function. This penalty parameter will only penalize designs with constraints violations, whereas designs with no violations will not be penalized.

## Optimum Pole computer program

A computer program has been written in VB implementing the GA method; the flow chart of the program is shown in Fig. 2. The set of variables considered in the optimization problem includes: minimum and maximum slope, number of segments, wall thickness, and segment heights. When examining these variables, it is obvious that the total number of unknowns is a function of the number of segments, which is an unknown in itself. To overcome this hurdle, the optimization process was divided into two main phases:

*Phase I* — In this phase the pole is divided into 10 equal segments that are welded together. Thus, the design variables will be reduced to slope and wall thicknesses of the 10 segments. The number of generations for this stage is preset to 50 generations.

*Phase II* — After convergence of phase I, segments with the same wall thicknesses are grouped together while considering maximum and minimum allowed heights and the total number of segments is determined. The range between the minimum and maximum slope is then reduced to ±5% of the optimum slope obtained in phase I. In addition, each segment height is allowed to vary within a window of 15%

**Fig. 3.** Screen capture showing the main screen of the pole optimization program.

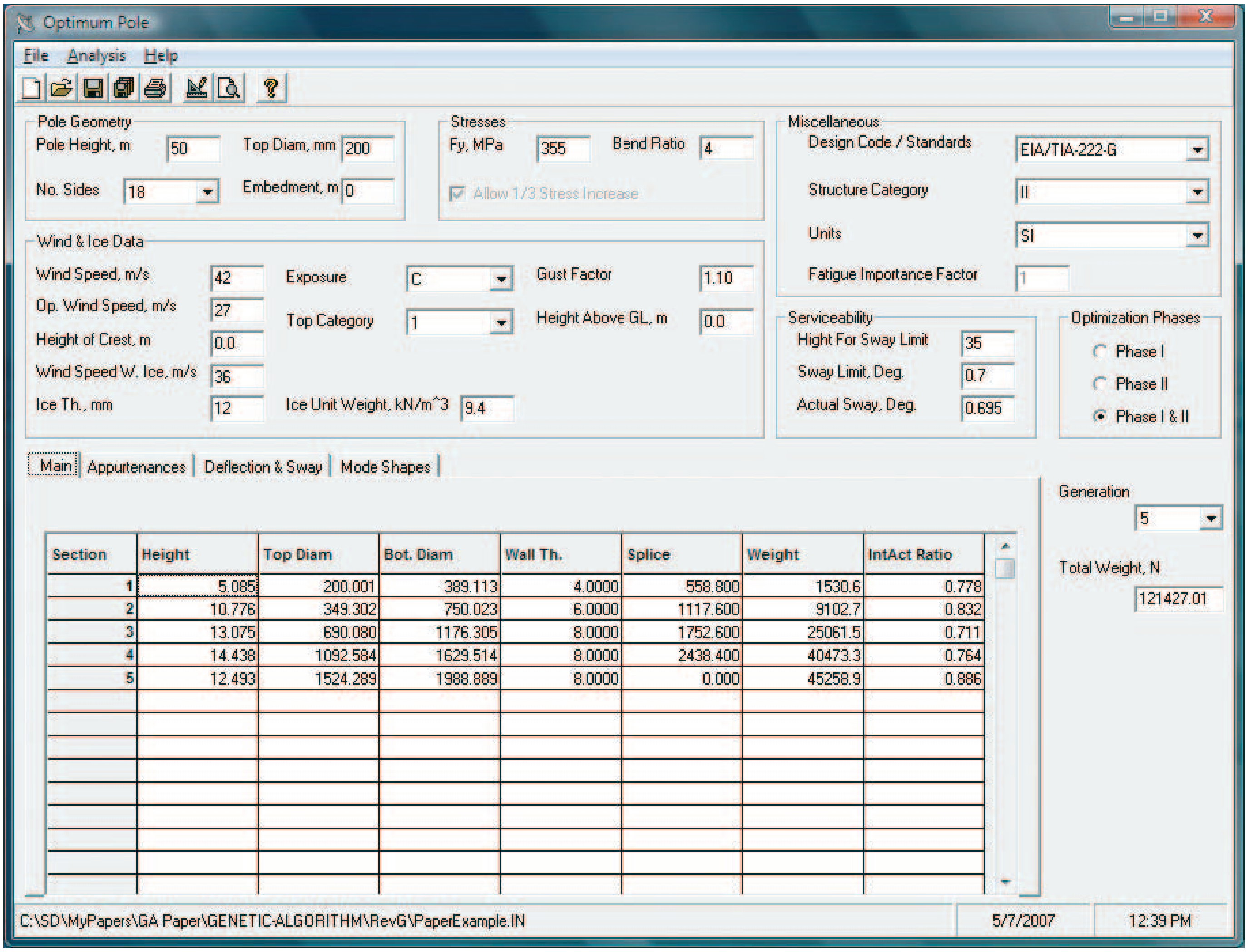



**Fig. 4.** Stepped cantilever verification problem.

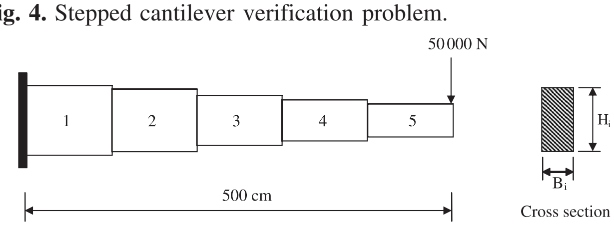



**Table 2.** Design data for the stepped cantilever problem.

| Parameters | Design data |
|---|---|
| **Constraints** | |
| Displacement | Vertical tip deflection ≤ 2.7 cm |
| Stress | $\sigma_b \leq 14\,000$ N/cm$^2$ for all sections |
| Aspect ratio | $H/B \leq 20$ for all sections |
| **Design variables (cm)** | |
| Integer | $B_1$, $H_1$ |
| Continuous | $B_4$, $H_4$, $B_5$, $H_5$ |
| Discrete | $B_2, B_3 \in \{2.4, 2.6, 2.8, 3.1\}$ |
| | $H_2, H_3 \in \{45.0, 50.0, 55.0, 60.0\}$ |

of its initial height. Therefore, the design variables in this phase are segment heights and slope. In this phase, the weight of the lap splices is included in calculating the total weight of the pole. It should be noted that the lap length is set to be 1.5 times the inside diameter of the female section, which is a TIA/EIA-222-G (ANSI–TIA 2005) recommendation.

Figure 3 shows a screen capture of the VB program main form illustrating the various input fields. A hidden tap with the caption "Appurtenances" is used to input the effective projected areas and weights of the antennas mounted on the pole and a third tap is used to output the interaction ratios, sway angles, and lateral displacements along the pole height. An output file is generated that includes: problem description, input parameters, main dimensions and weight of the optimum pole, interaction ratios, sway angles, and lateral displacements along the pole height.

## Verification and illustration examples

To verify the proposed method's ability to locate the optimum design of telecommunication poles, a stepped cantile-

**Table 3.** Comparison for the stepped cantilever beam.

| Optimization method | Design variables (cm, except for volume that is in cm$^3$) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | $B_1$ | $B_2$ | $B_3$ | $B_4$ | $B_5$ | $H_1$ | $H_2$ | $H_3$ | $H_4$ | $H_5$ | Volume |
| **Thanedar and Vanderplaats (1995)** | | | | | | | | | | | |
| Precise discrete | 3 | 3.1 | 2.6 | 2.276 | 1.75 | 60 | 55 | 50 | 45.528 | 34.995 | 64 537 |
| Linear approximate discrete | 3 | 3.1 | 2.6 | 2.262 | 1.75 | 60 | 55 | 50 | 45.233 | 34.995 | 64 403 |
| Conservative approximate discrete | 3 | 3.1 | 2.6 | 2.279 | 1.75 | 60 | 55 | 50 | 45.553 | 35.004 | 64 558 |
| **Erbatur et al. (2000)** | | | | | | | | | | | |
| Genetic algorithms level 1 | 3 | 3.1 | 2.6 | 2.300 | 1.80 | 60 | 55 | 50 | 45.500 | 35.000 | 64 815 |
| Genetic algorithms level 2 | 3 | 3.1 | 2.6 | 2.270 | 1.75 | 60 | 55 | 50 | 45.250 | 35.000 | 64 447 |
| **Current work** | | | | | | | | | | | |
| Proposed method | 3 | 3.1 | 2.6 | 2.270 | 1.75 | 60 | 55 | 50 | 45.260 | 34.990 | 64 447 |

ver problem is solved. This stepped cantilever problem was solved previously by different researchers and a comparison between the solution obtained using different optimization techniques and the proposed approach is presented in Example 1. The proposed two-phase method is used in finding the optimum weight of a 50 m generic telecommunication pole. A full description of the problem, design data, and final design are presented in Example 2.

**Example 1**

The stepped cantilever problem shown in Fig. 4 was presented in Thanedar and Vanderplaats (1995) and Erbatur et al. (2000) and was solved using several optimization techniques. The design criteria and imposed constraints are shown in Table 2. The optimization of this structure involves dealing with continuous, integer, as well as discrete variables, while enforcing stress and displacement constraints. The above factors make the problem an excellent candidate in the verification stage of the proposed algorithm. In solving this example, a slight modification was performed on the optimum pole computer program by stripping out the design and load calculation subroutines while the main GA subroutines are kept without any modifications. The number of individuals was set to 500 and acrossover probability of 60%, a mutation probability of 1%, and elitism were used. The solution of the problem converged after 16 generations with a total volume of 64 447 cm$^3$. The stress ratios of the five sections were found to be: 1.00, 0.92, 0.99, 0.92, and 1.00 for sections 1 to 5, respectively. The dimensions of the five cross sections associated with the optimum design obtained by different optimization methods and the proposed method are shown in Table 3. Comparing the optimum volume of the cantilever with previously published data, it is evident that the proposed method has achieved the same minimum weight as Erbatur et al. (2000) and outperformed all other methods while satisfying all the imposed constraints.

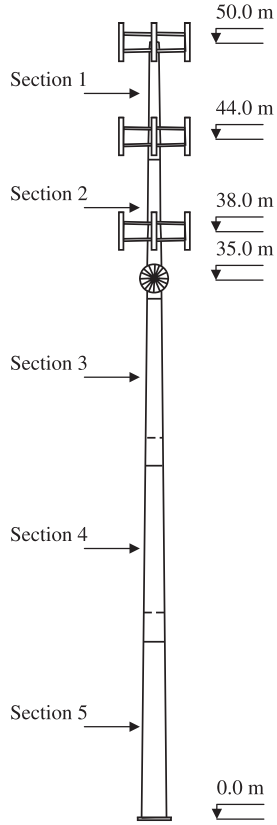
**Example 2**

A 50 m tapered steel 18-sided pole was designed to support three levels of panels of 5 m$^2$ effective projected area each and were located at the top, top minus 6 m, and top minus 12 m. In addition, a parabolic dish with effective projected area of 2 m$^2$ was installed at the 35 m elevation. The pole will be installed at a site with a design wind speed of 42 m/s and 12 mm of radial ice. The steel used in manufacturing the pole is Steel 52–3, with a yield stress of 355 MPa. The pole was designed using the TIA/EIA-222-G (ANSI–TIA 2005) standard while limiting the sway angle at the dish elevation to 0.7° at an operational wind speed of 27 m/s. The computer program Optimum Pole, implementing the two-phase approach, was used in solving this problem. The program converged after 55 generations and the optimum weight was found to be 121 kN. Figure 5 shows the general layout of the optimum pole, the installed antennae effective projected area, the maximum stress ratio in each of the five segments, and the resulting sway angle. The history of generations for this pole is given in Fig. 6, where two distinct curves can be observed. The first curve is the progress of solution throughout phase I, where the weight of the lap splice is not included. The second curve, starting from generation 51, is associated with phase II of the optimization process, where the sudden increase in weight is due to the inclusion of the lap splice weights. The solution time for this problem was 184 s on an Intel® Pentium® 4 3.0 GHz personal computer.

## Concluding remarks

In this study, GA was used in the topological and optimum weight design of steel telecommunication poles. This method was used because of its robustness and its ability to handle discrete and continuous variables without the need of any gradient information. This study represents a two-phase method with changes in design variables from phase I to phase II. In phase I, the pole is divided into 10 segments with equal lengths, considering pole bottom diameter and wall thicknesses of each segment as design variables. In phase II, segments with the same wall thicknesses are grouped together to reduce the total number of segments. The slope and the grouped segment heights are considered as design variables while keeping the wall thicknesses unchanged. A computer program, Optimum Pole, was written using VB implementing the proposed GA-based method. This computer program was verified by solving a stepped cantilever structure as illustrated in Example 1. The program was then used to solve a generic telecommunication pole design problem considering the appropriate loading conditions. The program was successful in locating the optimum weight of the pole while satisfying all imposed constraints. The Optimum Pole computer program presented in this paper is capable of implementing different design codes and stan-

**Fig. 5.** Layout and design data for the 50 m telecommunication pole.



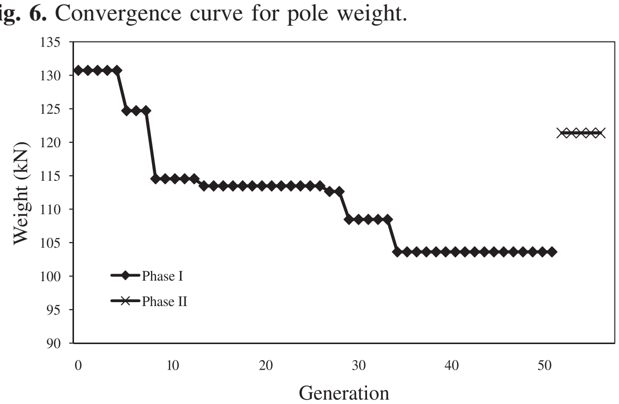

| Elevation (m) | Effective projected area ($m^2$) | |
|---|---|---|
| | No ice | 12 mm ice |
| 50.0 | 5 | 6 |
| 44.0 | 5 | 6 |
| 38.0 | 5 | 6 |
| 35.0 | 2 | 2.5 |

| Section | Length (m) | Thickness (mm) | Diameter (mm) | |
|---|---|---|---|---|
| | | | Top | Bottom |
| 1 | 5.1 | 4 | 200 | 398 |
| 2 | 10.8 | 6 | 349 | 750 |
| 3 | 13.1 | 8 | 690 | 1176 |
| 4 | 14.4 | 8 | 1093 | 1630 |
| 5 | 12.5 | 8 | 1524 | 1989 |

| Elevation (m) | Required sway | Actual sway |
|---|---|---|
| 35 | 0.700° | 0.695° |

| Section | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Interaction ratio | 0.78 | 0.83 | 0.71 | 0.76 | 0.89 |

**Fig. 6.** Convergence curve for pole weight.




dards and can be used by design engineers as an effective design tool.

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