EXPERT SYSTEM TO CREATE BUILDING DESIGN SCHEME

Žilvinas Steckevičius[1], Darius Mačiūnas[2], Elena Glėbienė[3], Renata Birbalaitė[4]

Vilnius Gediminas Technical University
E-mails: [1]zilvinas.steckevicius@gmail.com; [2]darius.maciunas@vgtu.lt;
[3]elena.glebiene@vgtu.lt; [4]renata.birbalaite@vgtu.lt

Abstract. In this paper the technology for creation of optimal design scheme for building is presented. Optimization of design scheme is based on genetic algorithm. Rectangular perimeter of single-storey structure with a linear load in all its locations is investigated. In such case, finite element, finite difference and other methods are not necessary – in order to evaluate the stress of design elements it is sufficient to use formulas of material strength.

Keywords: design optimization, genetic algorithm, structure optimization, strength of material.

Introduction

Structure design optimization is one of the most relevant problem challenging engineers. Optimal design is defined by low structure cost, while meeting all the operational and architectural requirements. The requirements may be very different, such as the stability of the structure, strength, binding position of columns, the maximal allowable distance between the load-bearing columns, etc.

There are universal methods such as the finite element method for dealing with this challenge, but despite of the simplicity of a design, they take up a lot of time to execute. Appears a natural aim to build such a technology, which would exploit the simplicity of a design and calculations would be carried out instantaneously.

This paper analyses the technology, which starting point is the generation of the structural scheme. In other words, the rendering of the parameters, which fully describe the structure, is executed. Then structural elements are automatically localized (partially localized) – hereinafter this phase is referred to localization. Further, the most appropriate cross-sections of elements – fulfilling all the requirements including minimal cost – are selected. Then the total cost of the whole structure, including additional costs (such as anchorage of column node; connections of beams and purlins) is calculated. Finally, the optimization algorithm is incorporated. This algorithm generates far better design schemes and selects the cheapest one. In the paper the cost of a whole structure and its components is evaluated with mass equivalent. Since the analytical expression of the objective function does not exist, (whereas the objective function parameters, according to which the design can be generated and the price calculated, are known) the optimization problem is solved by a stochastic algorithm. Genetic algorithm (hereinafter GA) (Goldberg 1989) is selected.

Localization

The investigated structure is the simplest, but also has the most common design – the perimeter of a rectangular shape. One floor of a structure is considered. Such structure is composed of beams, purlins and their supporting columns. The model of structure is shown in Fig. 1; columns are marked as points, beams – as vertical lines, purlins – as horizontal lines.
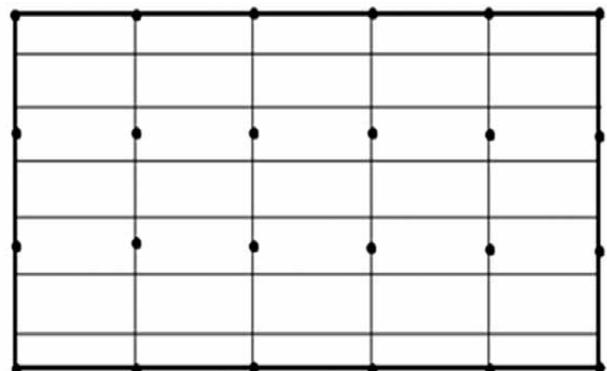

Fig. 1. The structure and its elements

All elements are arranged at equal distances, since the optimal design will be obtained when the layout of its elements shall be symmetrical. Purlins are placed on the beams so that each of them would have the same load. Since the columns are not to be dimensioned, purlins shall not be added on the edges of the beams, i. e. columns.

In order to describe such scheme in full, one needs to know the following parameters:

  − Length of the perimeter.
  − Width of the perimeter.
  − Number of columns along the length of the perimeter.
  − Number of columns along the width of the perimeter.
  − Number of purlins per beam.

The first two parameters are constant, and the rest ones are varied by GA. Full localization is not necessary for each GA generated scheme, as in the following phase of the algorithm in order to calculate the cost of such structure it is not necessary to know the exact position of its elements. The partial localization is executed and the following data is transferred for dimensioning:

  − Length of beams and purlins.
  − Quantities of beams and purlins.
  − Mass of a purlin.
  − Load per purlin.
  − Number of purlins per beam.

For dimensioning of beams it is necessary to calculate the weight of purlins. The purlins are directly leaned on the beams and transfer both active loads and self-weight. Since the beams are not dimensioned, the weight of beams is calculated in order to evaluate the overall construction cost.

Positions (coordinates within the selected coordinate system) of structure elements are calculated when the optimal structure scheme is obtained. These positions are needed only as the output results, since finite element method or other methods are not used in this paper.

Dimensioning

During the phase of dimensioning the cross-sections of beams and purlins are to be determined: the most appropriate cross-section is determined for purlins from rectangular cross-section assortment, while for beams – from double "T" shape cross-section ("I" beam) assortment (since their share of the load is several times higher). The columns are not to be dimensioned; therefore their mass can be evaluated together with mass of anchorage node. The formulas of material strength are used in order to assess the strength of bending beams.

The condition for dimensioning:

$$\left|\sigma_{\max}\right| = \frac{M_{\max}}{W} \le f, \tag{1}$$

here $\sigma_{\max}$ – the maximal stress; W – the moment of resistance; f – the strength of steel; $\sigma_{\max}$ – the bending moment.

The shear of structure is taken into account, since it is one of the main measures of structural strength evaluation. The condition for shear from Eurocodes (Eurocode 1, Eurocode 3):

$$V_{\max} \le 0.5 \cdot A_s \cdot 0.58 \cdot f_y, \tag{2}$$

here $V_{\max}$ – the maximal shear force; A_s – the cross-sectional area of the vertical wall; f_y – the yield point of steel.

First of all the condition for dimensioning (1) is verified according to the maximal bending moment. The maximal bending moment is calculated using bending beam formulas of material strength (Rajput 2007). The selected cross-section (selected from cross-section assortment tables) must satisfy this condition and the resistance moment must be the minimal. Then such cross-section is verified according to the condition for shear force (2): if the condition is satisfied then the cross-section is accepted, if not – then the strength of steel is recalculated and the dimensioning is executed again. The procedure of recalculation of steel strength is the following:

$$f_y^n = (1 - \xi) \cdot f_y, \tag{3}$$

here:

$$\xi = \left(\frac{2 \cdot V_{\max}}{V_{pl,Rd}} - 1\right), \tag{4}$$

$$V_{pl,Rd} = A_s \cdot 0.58 \cdot f_y. \tag{5}$$

Then:

$$f = \frac{f_y^n}{1.1}. \tag{6}$$

When the new steel strength is obtained, once again the search of the appropriate cross-section – satisfying the condition of the minimal resistance moment and dimensioning condition (1) – is executed. This procedure is applied to both beams and purlins. In both cases, the maximal bending moment will arise in the middle point of the elements. However, the calculation of the maximal bending moment for beams and purlins is different. This is predetermined by the fact, that several concentrated loads (the weights of purlins at support points) are applied to the beams, and distributed loads are applied to the purlins.

The maximal bending moment for purlin:

$$M_{\max} = \frac{w \cdot L}{8}, \qquad (7)$$

here w – the intensity of distributed loads; L – the length of a purlin.

The maximal shear force for purlin:

$$V_{\max} = \frac{w \cdot L}{2}. \qquad (8)$$

The maximal bending moment for beam:
In the case of even number:

$$M_{\max} = \frac{n \cdot F \cdot L}{8}. \qquad (9)$$

In the case of odd number:

$$M_{\max} = \frac{n \cdot F \cdot L}{4} - \frac{F \cdot L (n-1)(n+1)}{8n}. \qquad (10)$$

The maximal shear force for beam:

$$V_{\max} = \frac{n \cdot F}{2}, \qquad (11)$$

here n – the number of purlins per beam from one side; L – the length of a beam; F – the force of purlin to a beam. This force is calculated by dividing the load imposed on the structure and number of purlins, and adding the weight of a purlin. Since number, length and cross-section of elements are known, the total mass of the structure is calculated. Additionally the cost (weight) of the following parameters (determined prior to data entry) should be included: anchorage of columns pad or beam-purlin connection.

Optimization

Mathematically the optimization problem is formulated as a search of the minimal value f^* of functional $f(x)$ and a search of arguments x^*, which lead to the minimal value f^*:

$$f^* = \min_{x \in D} f(x), \qquad (12)$$

$$f(x^*) = f^*, \qquad (13)$$

here D – a set covering all valid arguments, i. e. all valid schemes of structure:

$$x = \begin{pmatrix} NCL \\ NCW \\ NPB \end{pmatrix}, \qquad (14)$$

here NCL – number of columns along the length of the perimeter; NCB – number of columns along the width of the perimeter; NPB – number of purlins per beam.

The problem is solved using GA with standard operators (Weise 2013):
- Selection.
- Cross-over.
- Mutation.

At first the initial population is generated using random values from the possible range. The possible range is calculated using the minimal and the maximal allowable distances between the columns and the allowable number of purlins per beam. If unfit individuals prevail, they are replaced with new ones, thus ensuring high-quality initial population.

A new population development phase (NPDP) consists of selection, cross-over and mutation. NPDP is executed for the initially set number of times.

In this paper, the selection procedure is realized utilizing roulette wheel selection strategy along with elitist selection. Such selection procedure directly transfers the best individuals into the new generation of the population, thus ensuring such individuals will not be lost. At first, fitness rate (FR) is calculated. FR is equal to sum of values of inverse objective function of all individuals within population multiplied by a random number from the range (0; 1). Thus the quality of total population is evaluated. Further evaluating consecutive individuals, once again the sum of values of inverse objective function is calculated until FR is achieved. The individual, at which FR is achieved, is selected for generation of a new population.

The cross-over between individuals creates new individuals with only their parents' genes. This procedure allows obtaining good mixture of genes. Single-point cross-over strategy is used, since individuals represent only 3 parameters. The single-point cross-over principle – to select a random position within the individuals and all genes from this position of one individual is swapped with genes of another individual (Fig. 2).

Individual No. 1

Individual No. 2

Individual No. 1

Individual No. 2
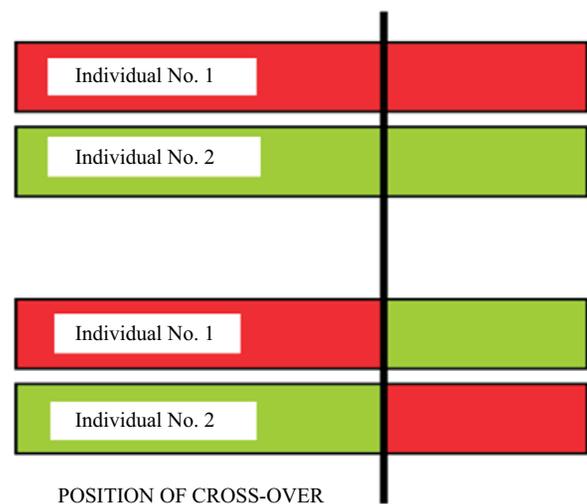
POSITION OF CROSS-OVER

Fig. 2. The cross-over of individuals

In order to make GA more efficient, cross-over coefficient (CC), which evaluates the proportion of individuals to be selected for cross-over, is included. The optimal value of such coefficient depends on particular problem. The analysis revealed the score of CC to be equal to 0.7.

Mutation allows the inclusion of additional genes into the population. During mutation procedure, a gene of an individual changes its value with a certain probability, i. e. very small random number is added or subtracted, the allowed interval of the design variable is not violated. The most efficient results were obtained (see next section) with probability value of 0.4.

The efficiency of the algorithm is increased by choosing the appropriate size of population, i. e. delivering optimal results with a small volume of calculation. Also it is determined, how many number of times the new population will be created. In this paper the population of 30 individuals is used and the number of iterations is equal to 100.

5. Numerical example of optimization problem

In this paper are used the tables of IPE cross-sectional ("I" beam) assortment for beams and the tables of TY cross-sectional (rectangular) assortment for purlins.

The following data is chosen:
- − Length of perimeter: 50 m.
- − Width of perimeter: 30 m.
- − Load: 5000 N/m^2.
- − Price of column's node: 500 kg.
- − Price of beam/purlin node: 10 kg.
- − Distance between columns: 4 – 15 m.
- − Number of purlins per beam: 1 – 8 pcs.

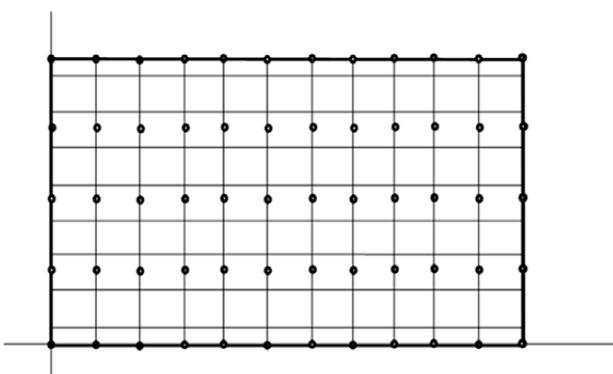The obtained optimal scheme of structure design is shown in Figure 3.

Fig. 3. The optimal scheme of structure

The scheme (Fig. 3) is identified by the following parameters:
- − Mass of the structure: 62944 kg.
- − Number of columns along the length of the perimeter: 12 pcs.
- − Number of columns along the width of the perimeter: 5 pcs.
- − Number of purlins per beam: 2 pcs.
- − Length of beam: 7.5 m.
- − Length of purlin: 4.54545 m.
- − Price of beam: 376.5 kg.
- − Price of purlin: 149 kg.
- − IPE No.: 30.
- − TY No.: 37.

Conclusions

1. The problem of creation of rectangular perimeter structure scheme is reduced to a problem, which can be solved utilizing the equations of material strength.
2. The optimal scheme is obtained by using genetic algorithm. Since the parameters of GA are efficient, the results are obtained instantaneously.

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EKSPERTINĖ SISTEMA STATINIO KONSTRUKCINEI SCHEMAI KURTI

Ž. Steckevičius, D. Mačiūnas, E. Glėbienė, R. Birbalaitė

Santrauka

Šiame darbe apžvelgta optimalios konstrukcinės schemos kūrimo technologija, naudojant genetinį optimizavimo algoritmą. Nagrinėjama stačiakampio perimetro vieno aukšto konstrukcija su tolygiąja apkrova visose jos vietose. Šiuo atveju nebūtina naudoti baigtinių elementų, baigtinių skirtumų ar kitų metodų. Norint įvertinti konstrukcijos elementų įtempius, užtenka medžiagų atsparumo formulių.

Reikšminiai žodžiai: formos optimizavimas, genetiniai algoritmai, struktūrų optimizavimas, medžiagų atsparumas.