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Optimal design of single-story steel building structures based on parametric MINLP optimization

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ABSTRACT

The paper presents an optimal design of single-story industrial steel building structures based on the parametric mixed-integer non-linear programming (MINLP) optimization approach and Eurocode specifications. The optimal design of the structures was investigated for factors which have significant influence on the structure mass: vertical variable load on the structure, horizontal variable load, structure span, structure height, type of standard cross-sections and strength of structural steel.

For this purpose, parametric MINLP optimization was performed for a number of combinations between different parameters, i.e. different values of the mentioned influence factors. The single-story steel building superstructure was generated and the MINLP optimization model developed. The objective function of the structure's mass was defined. The modified outer-approximation/equality-relaxation (OA/ER) algorithm and the three-phase MINLP strategy were used to perform the optimization. The minimal possible structure mass, the optimal topology and the optimal standard cross-sections were obtained through each individual MINLP optimization. Based on the obtained optimal results, the recommended optimal design for single-story/single-bay structures and the comparative mass diagrams were developed.

1. Introduction

The paper discusses an optimal design of single-story industrial steel building structures based on the mathematical programming approach. Single-bay structures are considered here, composed from equal main frames with pitched roof beams, and mutually connected with purlins and rails. The structures investigated in the paper are built up from hot rolled I sections.

The optimization of this simple type of steel structures has frequently been investigated in the past because of their wide use in engineering practice. The first two references, referred to the optimization of frame structures by Maxwell [1] in year 1869 and Michell [2] in 1904, belong to the first references ever referred in the area of optimization. Due to significant developments in computing and computer hardware in the last four decades, a variety of optimization techniques and efficient algorithms has been developed and applied. Recently, O'Brien and Dixon [3] have proposed linear programming for the optimal design of pitched roof frames, Guerlement et al. [4] have introduced a discrete minimum weight design for single-story steel structures by using a DSO algorithm and Kamal et al. [5] have presented a modified method of feasible directions for the optimization of one-bay portal steel frames. Several authors have searched for an optimal design of steel frames by using different algorithms: Saka [6,7] used a genetic algorithm and a harmony search algorithm, Toropov et al. [8] used a genetic algorithm, Foley et al. [9] used the advanced analysis and object-oriented evolutionary computation algorithm and Liu et al. [10] used the genetic evolutionary structural optimization algorithm. Hernández et al. [11] have considered the minimal weight design of steel portal frames with software developed for structural optimization, and Farkas and Jarmai [12] have presented a volume and cost optimization of frames with the help of Rosenbrock's Hillclimb algorithm. Sobieszczanski-Sobieski [13] and Lesniak [14] have presented the optimization of cross-sections in steel structures by using a linear decomposition method. Burns et al. [15] have applied a single termed monomial method to structural design applications. Issa et al. [16] have used a distributed genetic algorithm to perform optimization of haunched rafter pitched roof steel portal frames. It should be noted that all the mentioned authors dealt with discrete sizing optimization at fixed structural topologies. One of the latest studies in this field is the work reported by Žula et al. [17] and Kravanja and Žula [18], which introduces simultaneous topology and standard sizing optimization of single-story steel building structures, performed by the mixed-integer non-linear programming approach. The latter two references consider steel structures with main frames and purlins only. While Ref. [17] handles the mass optimization of the structure, Ref. [18] deals with the cost optimization.

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The present paper is a continuation of works [17,18]. This time, not only the considered single-story superstructure was enlarged with façade rails and façade columns, but the research also reports the multi-parametric MINLP optimization of the superstructure, where a series of MINLP optimizations was performed for a wide range of different design parameters.

The amount of structure mass used is a very important factor in daily engineering practice. The objective of this paper is to find the lightest possible design for this type of structures on the basis of performed MINLP optimizations. An optimal design of the structures was thus investigated for parameters, i.e. for factors which have significant influence on the amount of the material used, such as: load on the structure, the structure's global geometry, the type of standard cross-sections and the strength of the structural steel used (yield strength). For this purpose, the influence of the vertical and horizontal variable loads on the structure mass was investigated together with the structure self-weight. When the structure geometry is considered, the influence of height, span and length should be investigated. Because the treated single-story structures are composed of equal main frames, the structure mass increases proportionally dependent on the structure length. The latter was thus not defined as an influence factor in the study. The following influence factors, however, were proposed to be considered in the parametric MINLP optimization:

- Vertical variable load (e.g. snow),
- Horizontal variable load (e.g. wind),
- Structure span (span of the main frames),
- Structure height (height of the main frames),
- Type of standard cross-sections (HEA, IPE, both HEA and IPE sections), and
- Strength of structural steel (yield strength).

For each combination among parameters, i.e. different values of the above mentioned influence factors, an individual mixed-integer nonlinear programming (MINLP) optimization was applied. The single-story steel building superstructure was generated and the MINLP optimization model developed. The mass objective function was subjected to the set of equality and inequality constraints known from the structural analysis and dimensioning. The dimensioning constraints of steel members were determined in accordance with Eurocode 3 [19]. This MINLP problem is comprehensive, non-convex and highly non-linear. The modified outer-approximation/equality-relaxation (OA/ER) algorithm was thus used to perform the optimization, see Kravanja and Grossmann [20] and Kravanja et al. [21]. Multi-hierarchical MINLP strategies, see Kravanja et al. [22], were applied to accelerate the mentioned algorithm. The task of each optimization was to find the minimal structure mass, the optimal topology (the optimal number of main frames, purlins, rails and secondary façade columns) and the optimal standard cross-sections. Since a number of individual MINLP optimizations was carried out for all combinations of parameters, the parametric MINLP optimization was applied.

All the results obtained from the MINLP optimizations, performed for the combinations of the above parameters, were analyzed and compared. The comparative diagrams, developed and shown at the end of the paper, can usefully be applied for choosing the optimal type of structure. The recommended optimal design for single-story/single-bay steel structures was determined.

2. Single-story industrial steel building structure

The considered single story industrial steel building is designed from identical main frames which are connected with purlins, rails, secondary façade columns and bracing system, see Fig. 1. In this study only pinned column bases are considered, as they present the simplest and cheapest supports designed on pad foundations. Each main frame structure consists of a pair of vertical columns supporting a spanning pitched roof beam. Purlins and rails run continuously over the portal frames. While façade columns appear in the front and rear walls only, rails are constructed in the longitudinal side walls.

The optimization of main frames was performed under the combined effects of the self-weight of the frame members, a uniformly distributed vertical variable load and a concentrated horizontal variable load. The purlins were designed to transfer the permanent load (the self-weight of the purlins and the weight of the roof) and the variable vertical load. The same holds for the secondary façade columns and rails which were subjected to the self-weight, weight of the façade cladding and to the variable horizontal load. The internal forces were calculated by the first-order elastic method. The main frames were classified as non-sway steel portal frames. The dimensioning of the steel members was performed in accordance with Eurocode 3 for the conditions of both the ultimate and the serviceability limit states.

When the ultimate limit states were considered, the elements were checked for the axial, shear and bending moment resistances, for the interaction between the bending moment and the axial force, for the interaction between both bending moments, the interaction between the axial compression/buckling and the buckling resistance moment. When the serviceability limit states were verified, the frame vertical and horizontal deflections were checked for limits recommended by the Eurocodes. While beams and purlins were checked for the vertical deflections, façade columns and rails were verified for the horizontal deflections.

All structural elements are proposed to be built up from European hot rolled I standard sections. Since there is a variety of these sections on the market, three different cross-sectional structure types of the single-story building have been proposed for the optimization:

- Steel building structure consisting of standard HEA sections,
- Steel building structure consisting of standard IPE sections,
- Steel building structure consisting of both HEA and IPE sections:
  - Beams, frame columns and façade columns are made from HEA sections, while purlins and rails are built up from IPE sections (type 1),
  - Frame columns and façade columns are made from HEA sections, while the beams, purlins and rails are built up from IPE sections (type 2),
  - Façade columns are made from HEA sections, while the frame columns, beams, purlins and rails are built up from IPE sections (type 3).

3. MINLP superstructure

The MINLP optimization requires the generation of the MINLP superstructure of different discrete topology and design alternatives which are candidates for an optimal solution. While topology alternatives represent different selections and interconnections of structure elements, design alternatives include different standard cross-sections. The proposed MINLP superstructure for single-story steel buildings thus includes sets of different structural element alternatives (columns, beams, purlins, rails and façade columns) and various hot rolled I section alternatives.

Topology alternatives include:

- n, $n \in N$, alternatives of main frames (i.e. $2n$ number of columns and n number of pitched beams),
- m, $m \in M$, alternatives of purlins (i.e. together $2m$ number of purlins and $2(m-1)$ number of façade columns),
- r, $r \in R$, alternatives of rails (i.e. together $2r$ number of rails).

Standard dimension alternatives comprise:

- i, $i \in I$, standard hot rolled I section alternatives for columns,
- j, $j \in J$, standard hot rolled I section alternatives for beams,
- k, $k \in K$, standard hot rolled I section alternatives for purlins,
- l, $l \in L$, standard hot rolled I section alternatives for rails,
- p, $p \in P$, standard hot rolled I section alternatives for façade columns.