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Automated optimization of steel reinforcement in RC building frames using building information modeling and hybrid genetic algorithm

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ABSTRACT

Design of steel reinforcement is an important and necessary task for designing reinforced concrete (RC) building structures. Currently, steel reinforcement design is performed manually or semi-automatically using computer software such as ETABS, with reference to building codes. These approaches are time consuming and sometimes error-prone. Recent advances in building information modeling (BIM) technology allow digital 3D BIM models to be leveraged for supporting different types of engineering analyses such as structural engineering design. With the aid of BIM technology, steel reinforcement design could be automated for fast, economical and error-free procedures. This paper presents a BIM-based framework using the developed three-stage hybrid genetic algorithm (GA) for automated optimization of steel reinforcement in RC frames. The methodology framework determines the selection and alignment of steel reinforcement bars in an RC building frame for the minimum steel reinforcement area, considering longitudinal tensile, longitudinal compressive and shear steel reinforcement. The first two stages optimize the longitudinal tensile and longitudinal compressive steel reinforcement while the third stage optimizes the shear steel reinforcement. International design code (BS8110) and buildability constraints are considered in the developed optimization framework. A BIM model in Industry Foundation Classes (IFC) is then automatically created to visualize the optimized steel reinforcement design results in 3D thereby facilitating design communication and generation of construction detailing drawings. A three-storey RC building frame is analyzed to check the applicability of the developed framework and its improvement over current

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Abbreviations: A_c, net cross-sectional area of concrete in an RC column; A_s, tensile steel reinforcement area for RC beam/RC column; A_s', compressive steel reinforcement area for RC beam; A_{sc}, compressive steel reinforcement area for RC column; A_{sv}, shear steel reinforcement area for RC beam/RC column; b, width of RC beam/RC column; d, effective depth of the tensile steel reinforcement; d′, depth to the compressive steel reinforcement; $d_{bc,i}$, diameter of compressive steel reinforcement bar *i* for an RC beam; $d_{bs,i}$, diameter of shear steel reinforcement link for subsection *i* of an RC beam; $d_{bt,i}$, diameter of tensile steel reinforcement bar *i* for an RC beam; $d_{cc,i}$, diameter of compressive steel reinforcement bar *i* for an RC column; d_{cs}, diameter of shear steel reinforcement link for an RC column; $d_{ct,i}$, diameter of tensile steel reinforcement bar *i* for an RC column; DL, uniform dead load; e, eccentricity of the applied axial load; f_{cu}, characteristic strength of concrete; f_s, stress in tensile steel reinforcement; f_{sc}, stress in compressive steel reinforcement; f_y, characteristic strength of steel reinforcement; h, depth of the cross-section measured in the plane under consideration; k, normalizing factor for penalty function of maximum diameter steel reinforcement bars; L_{beam}, length of RC beam; L_{col}, length of RC column; $l_{b,i}$, length of each subsection *i* of RC beam/RC column; LL, uniform live load; M, applied revised design moment on the section; N, design ultimate axial load on an RC column; N_{sub}, number of subsections for shear steel reinforcement; N_{bc}, total number of compressive steel reinforcement bars for an RC beam; N_{bt}, total number of tensile steel reinforcement bars for an RC beam; N_{cc}, total number of compressive steel reinforcement bars for an RC column; N_{ct}, total number of tensile steel reinforcement bars for an RC column; $n_{bc,max}$, maximum allowable number of compressive steel reinforcement bars for an RC beam; $n_{bc,min}$, minimum allowable number of compressive steel reinforcement bars for an RC beam; $n_{bs,i}$, total number of shear steel reinforcement links in each stirrup for subsection *i* of an RC beam; $n_{bs,max}$, maximum allowable number of shear steel reinforcement links in each stirrup for an RC beam; $n_{bs,min}$, minimum allowable number of shear steel reinforcement links in each stirrup for an RC beam; $n_{bt,max}$, maximum allowable number of tensile steel reinforcement bars for an RC beam; $n_{bt,min}$, minimum allowable number of tensile steel reinforcement bars for an RC beam; $n_{cc,max}$, maximum allowable number of compressive steel reinforcement bars for an RC column; $n_{cc,min}$, minimum allowable number of compressive steel reinforcement bars for an RC column; n_{cs}, total number of shear steel reinforcement links in each stirrup for an RC column; $n_{cs,max}$, maximum allowable number of shear steel reinforcement links in each stirrup for an RC column; $n_{cs,min}$, minimum allowable number of shear steel reinforcement links in each stirrup for an RC column; $n_{ct,max}$, maximum allowable number of tensile steel reinforcement bars for an RC column; $n_{ct,min}$, minimum allowable number of tensile steel reinforcement bars for an RC column; p, calibration factor for total number of steel reinforcement bars in RC beam/RC column; sc, concrete side cover; $S_{bv,i}$, provided spacing between two shear steel reinforcement stirrups in subsection *i* of an RC beam; $S_{bv,max}$, maximum allowable spacing between two shear steel reinforcement stirrups for an RC beam; $S_{bv,min}$, minimum allowable spacing between two shear steel reinforcement stirrups for an RC beam; S_{cv}, provided spacing between two shear steel reinforcement stirrups in subsection *i* of an RC column; $S_{cv,max}$, maximum allowable spacing between two shear steel reinforcement stirrups for an RC column; $S_{cv,min}$, minimum allowable spacing between two shear steel reinforcement stirrups for an RC column; S_{hc}, provided spacing between compressive steel reinforcement bars; $S_{hc,max}$, maximum allowable spacing between compressive steel reinforcement bars; $S_{hc,min}$, minimum allowable spacing between compressive steel reinforcement bars; S_{ht}, provided spacing between tensile steel reinforcement bars; $S_{ht,max}$, maximum allowable spacing between tensile steel reinforcement bars; $S_{ht,min}$, minimum allowable spacing between tensile steel reinforcement bars; S_{sl}, provided spacing between two shear links in a shear steel reinforcement stirrup; $S_{sl,max}$, maximum allowable spacing between two shear steel reinforcement links in a stirrup; S_{vt}, provided spacing between two layers of tensile steel reinforcement bars; tc, concrete cover to the tensile steel reinforcement; x, depth to the neutral axis; λ, calibration factor for maximum diameter of longitudinal steel reinforcement bars

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design approaches. The results show that the developed methodology framework can minimize the steel reinforcement area quickly and accurately.

1. Introduction

The design of steel reinforcement is an important and necessary task in the structural design of reinforced concrete (RC). Steel reinforcement in RC members of a building should be provided in such a way that RC members are able to resist imposed design loads during their life span [1], and they should be constructible, safe, and economical at the same time. Current practice in the architecture, engineering and construction (AEC) industry involves steel reinforcement design as per enforced regional design codes, either by manual calculations, or by partial automation using computer software such as CSI ETABS [2] and Autodesk Robot Structural Analysis Professional (RSA) [3]. Manual calculations take a long time and sometimes lead to mistakes, over-design and under-design due to the tedious nature of the steel reinforcement design problem and the numerous calculations involved. Current computer software can perform steel reinforcement design in a faster manner, but still requires much human effort to draw the building model in the software interface and to define different kinds of settings such as material properties. In addition, the solutions provided by steel reinforcement design software are often either much higher than the design code requirements or do not satisfy the minimum design code requirements. Furthermore, those software neither consider combination of different diameters of steel reinforcement bars nor all the possible solutions that satisfy design code requirements, leading to an uneconomical design. Moreover, the steel reinforcement design calculation process is time consuming. The more RC members an RC frame contains, the longer time it requires to design all RC members due to specific steel reinforcement design for each RC member. Therefore, full automation and optimization are needed to intelligently calculate the provided steel reinforcement in RC frames in order to obtain a design code compliant steel reinforcement design with the minimum area of steel reinforcement in a faster manner.

In the current AEC industry, a shift has been observed towards building information modeling (BIM) technology due to its capability to reduce wastage [4], reduce error [5], and improved efficiency [6]. Increase in building quality has been observed with the use of BIM in the AEC industry [7,8]. Various types of analyses are also facilitated with the use of BIM such as sustainability analysis [9], thermal analysis [10] and energy analysis [11]. BIM is used in this study because BIM supports integration of different 3D applications as well [12]. In addition, BIM provides a systematic approach for managing building data information in digital format throughout the lifecycle of a building [13,14]. The building data include geometric, loading and end-support information of all RC members in a building. The geometric, loading and end-support information is needed for calculation of steel reinforcement for RC members. This information is available in and can be conveniently extracted from BIM models, thereby reducing the needs for manual handling, which could be time-consuming and error-prone. BIM also helps in representing the building design in a 3D format for better understanding and analysis. Building design data can be seamlessly exchanged between different 3D applications through BIM to achieve automation and construction drawing detailing automation. Therefore, this paper aims to develop an automated and integrated BIM-based integrated steel reinforcement optimization framework for RC frame structures.

This paper is structured as follows. In Section 2, a review of the related literature is presented with research objectives. Section 3 presents the proposed BIM-based framework for automated steel reinforcement optimization for RC frames. Section 3 also describes various constructability aspects and the developed penalty functions to tackle them. Section 4 presents the formulation of the steel reinforcement design problem into a multi-objective optimization function. Section 5 describes the developed hybrid GA-HJ based optimization approach and its advantages over other optimization approaches. Section 6 presents the developed methodology to create BIM models in Industry Foundation Classes (IFC) representation for 3D visualization and construction drawing detailing automation. Section 7 presents an illustrative example for an RC beam and another example for RC frame, which show the applicability of the developed BIM-based framework on real life problems along with improved steel reinforcement results over existing approaches. Summary and future work are discussed in Section 8.

2. Research background

Several studies in the past have tried to optimize the steel reinforcement design process for RC elements [15–20]. For example, Leps and Sejnoha [16] used genetic algorithm (GA) to optimize steel reinforcement design of RC beams in order to minimize the construction cost. However, they always divided an RC beam into three subparts irrespective of the loading conditions, restraining the solution in achieving global optimum. Sahab et al. [17] also used GA to optimize steel reinforcement and to minimize the cost of RC columns. The GA was concluded to be a suitable algorithm to solve steel reinforcement optimization problems in a reasonable amount of time. However, some solutions obtained during optimization violated design code constraints. Lee el al. [21] also used GA to reduce the total construction cost of RC frames, but a lot of assumptions were made while developing the optimization algorithm. Diameters of steel reinforcement bars were pre-defined and fixed (25 mm for RC columns and 22 mm for RC beams). Furthermore, only square RC columns were considered during the optimization process. When tested for a nine-storey RC frame building, the developed optimization algorithm gave infeasible solutions for 4 times out of 15 runs.

Saini et al. [18] used Artificial Neural Network (ANN) to optimize steel reinforcement in singly and doubly reinforced RC beams for minimizing the construction cost. They provided optimal solutions but the solutions were only in the form of percentage of provided steel reinforcement without further detailing, thereby limiting the use of the optimal solutions in actual practice. Hadi [22] also used ANN to optimize the provided steel reinforcement in RC beams. However, same limitations were there in this study also. The solutions were in the form of percentage of provided steel reinforcement without further detailing. Ahmadkhanlou and Adeli [23] used developed neural dynamics model to minimize the construction cost of one-way RC slabs. The developed model provided the steel reinforcement design with less construction cost for the considered RC slabs. However, the spacing between steel reinforcement bars was limited to integers thereby restraining the solutions to achieve global optimum. Moreover, all the above mentioned efforts did not consider combination of steel reinforcement bars of different diameters. These efforts also lack full automation in obtaining input data (e.g., the loading conditions, end-support conditions and geometries of RC structural members) directly to perform the steel reinforcement optimization. 3D visualization and construction drawing detailing automation were not considered in all these research efforts as well.

Therefore, objective of the current research is to develop a methodology framework based on the BIM technology for automated optimization of steel reinforcement in RC frames. The framework combines geometric and functional information from BIM models together with design code requirements, to calculate design code compliant steel