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Automated specification of steel reinforcement to support the optimisation of RC floors

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ABSTRACT

A Building Information Modelling (BIM)-enabled computational approach was presented in this paper for the automated specification of steel reinforcement to support the optimisation of reinforced concrete (RC) flat slabs. After importing slab geometries from BIM, the proposed procedure utilised internal forces output from Finite Element Model (FEM) to map required reinforcement in two stages. In the first stage, the reinforcement specifications matched the spatial resolution of the FEM. In the second, the reinforcement was adjusted by imposing constructability functions to limit the number of arrangements in terms of zones and bar spacing. The aim of the paper was to investigate the parametric capabilities of the proposed approach in the context of an optimisation model for the generation of material-efficient structural designs. Numerical examples were presented to demonstrate the efficiency of the automated specification procedure. The material efficiency and the design complexity of the developed reinforcement configurations were also assessed against a conventional solution under realistic design conditions.

1. Introduction

Cast in situ reinforced concrete (RC) structures are prevalent in small and medium residential and office buildings. However, their detailed design and construction remain relatively low-tech and labour intensive. The design of these structures involves specifying the placement and size of reinforcing bars within the concrete matrix. This phase of the design usually follows an iterative process, in which structural engineers use a manual trial-and-error approach to find a sufficiently safe and economical structural solution [1,2].

However, the trial-and-error method often demands considerable amount of time and effort [3,4]. Most structural engineering problems could be formulated as optimisation problems that achieve optimum structural performance whilst satisfying conflicting design constraints [5]. Reinforcement design is no exception and designing it this way would achieve both automation and optimisation at the same time [4]. This paper proposes a numerical process to achieve this.

Structural optimisation techniques [6] have been applied in many fields of engineering [7–12] however their uptake in engineering practices is sometime met with some resistance. Common reasons for this reluctance include issues such as training and attitude, modelling development and post-processing procedures, data sharing in multidisciplinary frameworks and algorithm selection among others according to a recent study that surveyed to what extend engineering companies in the UK use computational optimisation approaches [13].

Despite practicing engineers' expertise and experience, conventional structural design processes often result in sub-optimal solutions [14]. New design processes that increase the adoption of practical optimisation techniques by structural engineering practitioners are still necessary [15]. Developments within Building Information Modelling (BIM) technologies and computational systems are expected to enhance the integration of optimised structural designs with more efficient design [16] and construction [17–19] procedures. More specifically, Chi et al. [20] recognised five areas that will become more relevant with the development of BIM technologies in the context of structural engineering:

- Adoption of structural optimisation during the early design stages
- Parametric design specifications for enhanced sustainability performance
- Intuitive decision-making models supported by advanced visualisation techniques

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- Numerical applications in realistic engineering examples
- Amplified collaboration and communication between design teams

The current study investigates how Chi et al.'s [20] insights could be implemented in the context of RC building structures with flat slabs, which are a very commonly used floor system with reinforced concrete structures.

In the optimisation of flat slabs [21], the focus is on the careful selection of slab thicknesses as the concrete in the slab constitutes the largest proportion of the floor material [22]. However, slab thickness optimisation is often limited by constructability constraints, which dictate a small finite set of slab thickness options. On the other hand, the optimisation of reinforcement could be achieved in various ways by engineering practitioners, and could lead to significant material savings. In a recent flat slab optimisation study, the reinforcement accounts for approximately 25% of the total material and construction costs in the floor [21]. Similar figures have also been reported in other studies conducted by Sahab et al. [23] and Eleftheriadis et al. [22,24] with flat slab systems.

Previous studies have focused on the reinforcement optimisation of different structural frames mainly without the implementation of BIM technologies [25–27]. However, in a recent study by Mangal & Cheng [4] the reinforcement (longitudinal and shear) of RC frames (beams and columns) was optimised using a BIM-based approach. Little attention was given on the automation of reinforcement specifications to support the optimisation of RC flat slabs.

In this study an automated reinforcement specification process is proposed to effectively support the optimisation of RC flat slabs, which is a structural system that is used extensively in the UK and many other countries. Section 2 describes the computational processes used in this study to automate the specification of steel reinforcement. Numerical applications and the validation of the proposed computational model are presented in Section 3. The paper concludes with discussion in Section 4 and conclusions in Section 5.

2. Methods and models

2.1. Optimisation framework and context

The BIM-based approach that was initially proposed by Eleftheriadis et al. [22] for the optimisation of RC flat slabs and columns using single objective functions for cost and embodied carbon, was extended to simultaneously evaluate multiple objectives deploying a bespoke NSGA-II algorithm with a FEM engine [24]. In this paper, special attention is given to the computational modules and processes of the optimisation approach described in [24] that are responsible for the automated reinforcement specification of RC floor structures. The specification of the reinforcement is an important component of the optimisation analysis enabling the computation of structural material quantities necessary for the cost and embodied carbon calculations. Typically, the specification of reinforcement in RC floors is completed by structural engineers during the early design stages using aggregate reinforcement rates (the quantities are given kg/m^3). The main aim of the proposed reinforcement specification procedure was to ensure that detailed yet practical reinforcement topologies (layouts) and schedules (quantities) are utilised not only for optimisation purposes but also for the refinement of construction drawings and design information at detailed design stages by the structural engineers through dedicated BIM interoperability [24]. Because the optimisation of a structure involves multiple iterations until a set of optimised solutions is adequately obtained (in some cases thousands of iterations might be required depending on the complexity of the building case [24]), the detailed analysis of the slab reinforcement should be automated in an efficient and robust way. The general workflow of the optimisation is shown in Fig. 1.

The optimisation procedure begins by querying building and geometric information directly from a BIM model into the FEM engine. To support the reinforcement analysis for the slab component a set of customised algorithms was constructed in juxtaposition with the FE engine. If the relevant code constraints and limit states are satisfied after the FE analysis, material schedules for the concrete and the steel reinforcement as well as the reinforcement zones in the slab are specified. The same reinforcement specification procedure is repeated multiple times for the design optimisation of the slab using the NSGA-II until a set of optimised solutions is obtained and visualised in the Pareto front. Thorough review of the optimisation principles as well as results from numerical examples can be found in [24].

2.2. Automated reinforcement analysis

The proposed automated design specification process comprises three main stages:

1) Processing data from BIM so that the floor system can be analysed with a finite element (FE) model;
2) Generating refined reinforcement maps that match the mesh size of the finite element model;
3) Simplification and smoothing of the refined mesh to ensure it is practical to build.

In this paper, Autodesk Robot Structural Analysis (RSA) 2016 was used for the FE calculations and Autodesk Revit for BIM as these are currently very commonly used in the industry [16]. The entire computational process is driven automatically through code developed in C# using the Application Programme Interface (API) of RSA and Revit. The project requirements define the material properties, load cases and support coordinates which are directly transferred from BIM to the FE model via the API. The slab-column connections are modelled in the FE model assuming pinned supports. The limit state checks are specified based on national or international codes. In this study, all structural limit states were checked according to Eurocode 2 (EC2) [28,29].

Once the structural model is established in RSA, the calculations leading to the estimation of the slab reinforcement begin. Firstly, detailed required reinforcement maps are calculated at the resolution of the finite element mesh size. These refined maps are then smoothed out and simplified into practical reinforcement bar specifications. At the end of this process, the reinforcement schedule as well as the detailed reinforcement weight of the slab are obtained. Fig. 2 shows the general computational workflow including the necessary processes for the calculation of the required and the specified reinforcement.

2.3. Required reinforcement calculations

Using the FEM output, the required reinforcement is calculated as an area of steel per unit length for top and bottom reinforcement in both directions at each node of the finite element mesh. An example of a map showing this required reinforcement is presented in Fig. 3 for a generic slab component.

The map in Fig. 3 highlights the areas where no reinforcement is required as well as the areas where reinforcement is needed based on the code restrictions. As the reinforcement follows the FE mesh, this map represents the smallest amount of steel that must be provided for a given FE mesh size. Punching shear reinforcement has not been specified at this stage of the project and thus, it is not included in the scope of this study.

Coons' method [30] is used to generate the finite mesh in the slab, and the Wood & Armer method [31] is used in the calculation of the moment for the required reinforcement in the slab. The finite element mesh size can be adjusted by the user based on the project requirements. Herein it was initialised using the value the structural engineers used (0.5 m) in the tested building scenario under examination. This allowed a direct comparison and assessment of the conventional designs with the computer-generated scenarios presented in Section 3. Details