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Optimum design of reinforced concrete plane frames based on predetermined section database

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Abstract

For the optimum design of reinforced concrete (RC) structures, predetermined section databases of RC columns and beams are constructed and arranged in order of resisting capacity. Because all the design variables of an RC section are interconnected by a representative design variable of the section identification number, regression equations representing the relation between the section identification number and section resisting capacity are derived to effectively handle all the design variables and to use in determining a continuous solution. An introduction to effective discrete optimization algorithms, which can search for an optimum solution quickly using a direct search method, is followed. Moreover, the investigation for the applicability and effectiveness of the introduced design procedure is conducted through a correlation study for typical example structures. Because of an absence of restrictions on the construction of objective functions, together with very simple optimization processes and fast convergence, the introduced method can effectively be used in the preliminary design of RC frame structures. Especially, the obtained solutions selected from the section database can be applied applicable in practice, because these sections are constructed to satisfy all design code requirements and practical limitations.

Keywords: Optimum design; Reinforced concrete; Database; Section identification number; Regression equation; Direct search method

1. Introduction

Design in any engineering discipline is a complex process in which a product is generated to satisfy perceived requirements. When designing a structure, the engineer has a choice of two basic strategies: a traditional design procedure or an "optimal" design procedure. A traditional design procedure consists of first adopting intuitively the geometry and materials of the structure and then calculating the specified design loads as well as values of behavioural or state variables such as the resisting capacities and displacements to check the safety and functionality of the structure. Along with successive modifications of the geometry, this procedure is repeated until the calculated behavior satisfies certain prescribed requirements, which are usually expressed in the form of inequalities representing the upper limits of the resisting capacities and displacements or a lower limit on the load capacity. The obvious disadvantages of this procedure are as follows: (1) much computational effort may be wasted on successive analyses and (2) the design can be highly uneconomical even when an intuitively selected solution satisfies the behavioural constraints.

To eliminate these drawbacks, the traditional procedure may be somewhat revised. In what is termed optimal design, the required structural behaviour together with the design loads and geometrical constraints are initially specified and then the quantity, termed cost [11] or objective function are also defined. The aim of this computational effort is to select the geometry and possibly the materials of the structure so that the required behaviour is achieved at the lowest possible cost or with the smallest possible member sizes. Accordingly, design optimization has been a fundamental objective of virtually every structural engineer who has striven to create a structural system to meet a need.

During the past two decades, considerable progress has been made in the area of the optimum design of reinforced concrete (RC) structures via mathematical programming methods such

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as the Lagrangian multipliers method, convex programming, linear programming [5,17] and sequential unconstrained minimization techniques [17]. The fundamental assumption of these analytical methods is that the design variables are continuous. In reality, however, most RC members in building structures have dimensions of discrete sizes. The dimensions of concrete sections are usually increased by a certain size, e.g. 5 cm (2 in.) a step [8], thus making the section dimensions discrete. The amount of reinforcement is also determined by the number of bars put into the RC section. Therefore, from a practical point of view, the problem may be defined as optimizing RC members with discrete variables rather than with continuous variables. A number of methods have been developed as general methods for the discrete optimization of structures [5,17]. The application of these methods, however, is limited to small or simple structures, as most of the methods involve numerous design variables. It is difficult to apply these methods to the optimization of large or complex structures; thus, such methods are seldom used in practice.

Recently, new approaches using genetic algorithms have been introduced [6,12,13,18–20]. Although genetic algorithms have been applied to discrete optimization problems, such as the design of RC frames, and usually give a global minimum, the direct use of classical genetic algorithms remains limited due to the very slow convergence. The reliability of result deteriorates, as it does not reach a converged optimum solution within the practical limits of iterative executions [4].

In this paper, a simplified and effective algorithm for the practical application of optimum design techniques for RC member design is proposed. Instead of utilizing the more sophisticated optimization model that requires many design variables and complicated descriptive functions, the proposed algorithm uses a more effective direct search method to find the optimum member sections from a predetermined section database. After constructing a database of predetermined reinforced concrete sections, which are arranged in the order of increasing resisting capacities, the relationship between the section identification numbers and the resisting capacities of sections is established by regression and is used to obtain an initial solution (section) that satisfies the imposed design constraints. Assuming that an optimum section exists near that initially selected by the regression formula, a direct search is conducted to determine the discrete optimum solution. The optimization of the entire structure is accomplished through the optimization of individual members.

2. Construction of database

Even though an infinite number of RC sections can theoretically be designed to resist applied forces, it is easily observed from practical design that the dimensions of concrete sections usually have practical limitations; in many cases, the ratios of widths to depths range from 1.5 to 2.5 in. beams and from 1.0 to 2.0 in. columns; the dimensions of concrete sections are usually increased by 5 cm (2 in.) a step; and the sizes of reinforcing bars most frequently used in RC building structures are D19 (#6), D22 (#7), and D25 (#8). Complying with the aforementioned restrictions and current design code requirements [1], such as the maximum and/or minimum steel ratio in a section and the minimum cover thickness of 3 cm, it is possible to construct a database of RC sections that are frequently used in current practice.

Once the minimum dimensions of a section, i.e. width B and depth H, are decided as 30 cm × 30 cm in a column and 20 cm × 35 cm in a beam, the number of reinforcing bars to be put into the section increased by 5 cm a step is determined with the restrictions by the design code in use [1,3] up to the maximum dimensions of 60 cm × 90 cm in a column and 50 cm × 90 cm in a beam, which are considered in this paper. Providing different levels of reinforcement in a section ranging from minimum to maximum steel ratios stated in the design codes, it is possible to construct a number of different sections, with each having identical overall dimensions. The reinforcing bars used in beam sections are D19 (#6) and D22 (#7), and those used in column sections are D19 (#6), D22 (#7), and D25 (#8). The combinative use of different steel bar sizes, e.g. the combination of D19 (#6) and D22 (#7) in a beam section, is not considered in this paper since such a combinative use is not common in practice and only makes the problem unnecessarily complex. In advance, the placement of steel bars is also limited to two layers.

For the abovementioned RC sections, the resisting capacity of each section in terms of the ultimate bending moment $M_u = \phi M_n$ for the beam and the normalized area of the P–M interaction diagram (see Fig. 1) for the column is calculated on the basis of the ultimate strength design method adopted in the design code [1,14], where ϕ refers to the strength reduction factor. Selections from the column and beam databases constructed in this study are given in Tables 1 and 2, respectively, to show the general contents of the data, where the cost per unit length of a member is calculated for each section by the following equations.

$$\text{Column: } A_{\cos t} = C_s \times A_s + C_c \times B \times H + C_f \times (2B + 2H) \quad (1)$$

$$\text{Beam: } A_{\cos t} = C_s \times A_s + C_c \times B \times H + C_f \times (B + 2H) \quad (2)$$

where C_s, C_c, and C_f denote the unit cost of steel, concrete and formwork, including the related labour, and B and H are the selection width and height, respectively. These costs are based on the market prices and may differ from time to time and also from place to place in a country. Therefore, the price data can never be fixed and should be updated constantly as the market prices change. The section costs mentioned in Tables 1 and 2 was constructed using the following values of $C_s = 19{,}700$ Won/ton, $C_c = 28{,}800$ Won/m^3, and $C_f = 8{,}300$ Won/m^2.

These sections are arranged in the database in order of increasing moment resisting capacities for beams and of increasing normalized areas of the P–M interaction diagram for columns, respectively. In total, approximately 2240 beam sections and 2450 column sections are constructed.

For a case in which the calculated member force exceeds the resisting capacity of a section in the database and the desired