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Cost optimisation of reinforced concrete flat slab buildings

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Abstract

Cost optimisation of reinforced concrete flat slab buildings according to the British Code of Practice (BS8110) is presented. The objective function is the total cost of the building including the cost of floors, columns and foundations. The cost of each structural element covers that of material and labour for reinforcement, concrete and formwork. The structure is modelled and analysed using the equivalent frame method. The optimisation process is handled in three different levels. In the first level, the optimum column layout is achieved by an exhaustive search. In the second level, using a hybrid optimisation algorithm, the optimum dimensions of columns and slab thickness for each column layout are found. In this hybrid algorithm, a genetic algorithm is used for a global search, followed by a discretised form of the Hook and Jeeves method. In the third level, an exhaustive search is employed to determine the optimum number and size of reinforcing bars of reinforced concrete members. Cost optimisation for three reinforced concrete flat slab buildings is illustrated and the results of the optimum and conventional design procedures are compared.

Keywords: Flat slab buildings; Reinforced concrete; Structural optimisation; Genetic algorithm; Hybrid optimisation algorithm

1. Introduction

In reinforced concrete flat slab buildings, floors are directly supported by columns as shown in Fig. 1 without the use of intermediary beams. Flat slab systems are popular for use in office and residential buildings, hospitals, schools and hotels. They are quick and easy to formwork and build. The architectural finish can be directly applied to the underside of the slab. Absence of beams allows lower storey heights and, as a result, cost saving in vertical cladding, partition walls, mechanical systems, plumbing and a large number of other items of construction especially for medium and high rise buildings. They provide flexibility for partition location and allow passing and fixing services easily. Windows can be extended up to the underside of the ceiling. The absence of sharp corners gives better fire resistance and less danger of concrete spalling and exposing the reinforcement. Moreover, a flat slab can result in more storeys being accommodated within a restricted height of the building [1–3].

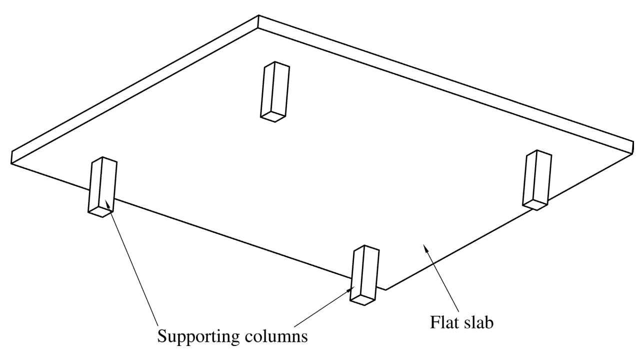

Fig. 1. Flat slab system.

Cohn and Dinovitzer [4] demonstrated the state of practice in structural optimisation with a comprehensive catalogue of 501 examples extracted from textbooks,

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monographs, articles and conference proceedings. This survey showed that the majority of research in the field of structural optimisation deals with the design optimisation of isolated elements or simple structures, which may not be practically important. They concluded that optimisation would become more attractive to practising designers if more optimisation examples were available, especially for realistic structures, loading conditions and limit states. It is also to be noted that of the 501 examples in the catalogue, 460 are relevant to steel structures and only 21 and 20 deal with reinforced concrete and composite structures, respectively. This study clearly indicates that the amount of research in the field of optimisation of reinforced concrete structures is much less than that for steel structures. In 1998, Sarma and Adeli [5] reviewed major papers on cost optimisation of reinforced concrete structures published in the past three and a half decades. They concluded that there is a need for research on cost optimisation of realistic reinforced concrete three-dimensional large scale structures. The current paper presents cost optimisation of reinforced concrete flat slab buildings according to the British Code of Practice (BS8110) for design and construction of reinforced concrete structures [6]. The objective function is the total cost of the building including the cost of material and labour for concrete, reinforcement and formwork for floors, columns and foundations.

2. Structural analysis of flat slab buildings

The structural analysis of flat slab systems can be carried out using the finite element method, strip method, grillage analogy, yield line theory or equivalent frame method. Among these techniques, the equivalent frame method (EFM) has been developed as a practical method of analysis of flat slab buildings and adopted by several codes of practice such as the British (BS8110-1997), American (ACI 318-02), Australian (AS3600-2001) and Canadian (CSA A23.3-94) codes [6–9].

In the EFM, a flat slab building having a rectangular column layout is divided into a series of longitudinal and transverse plane frames as shown in Fig. 2. Each frame consists of a row of equivalent columns and beams representing columns and strips of slabs bounded laterally by centrelines of panels adjacent to columns. In each direction, edge and middle equivalent frames are structurally analysed to obtain the total bending moments and shear forces at different sections of slabs. These frames are loaded with the full uniform gravity dead and imposed loads over the width of equivalent frames. It is assumed that lateral loads are resisted by other structural systems such as shear walls. Since the bending moment over the width of slab strips (equivalent beams) in equivalent frames is variable therefore, the width of equivalent beams is divided into two strips, namely column and middle strips. The average bending moment over each strip is obtained as a percentage of the total bending moment at each section of equivalent beams using the values recommended by the Code of Practice (BS8110). The required reinforcement in each slab section is calculated according to the design bending moment obtained in each section of column and middle strips as shown in Fig. 3.

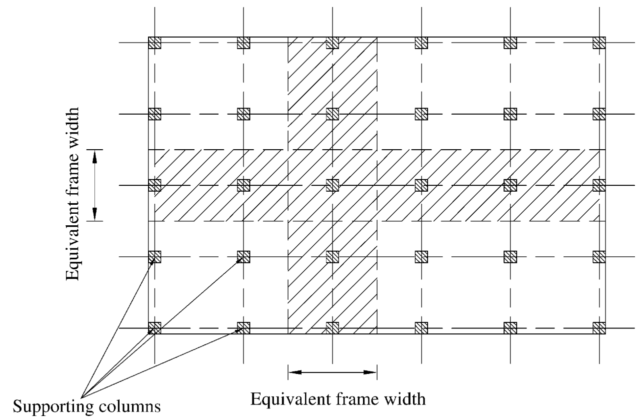

Fig. 2. A plan of the middle equivalent frames of a flat slab building.

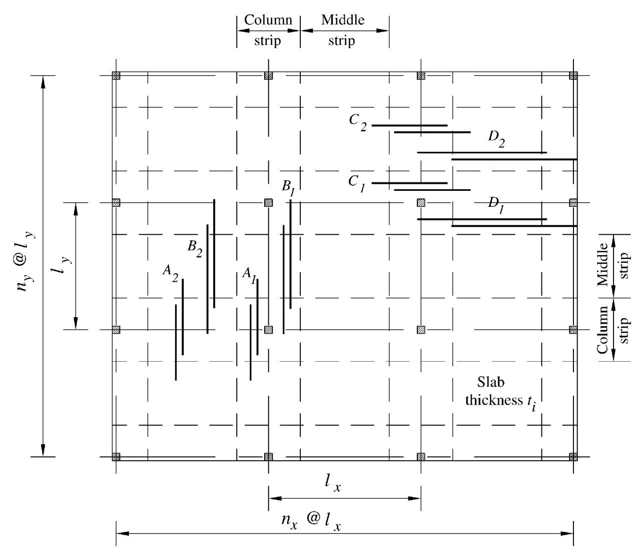

Fig. 3. Design variables in a typical floor slab.

It should be noted that the current analysis is restricted to rectangular planform buildings. In case of an irregular planform, the EFM cannot be used and other more accurate techniques such as the finite element method should be applied instead. In addition, geometrical non-linearity in the form of interaction between axial loads and deflections of columns is negligible as the height of flat slab buildings considered in the present study is small.

3. Statement of the problem

3.1. Design variables

Fig. 3 illustrates the design variables for a typical floor of a flat slab building having n_f storeys with arbitrary heights, and n_x and n_y spans of equal lengths l_x and l_y in the x and y directions, respectively. The number of spans in the longitudinal and transverse directions of the building, the thickness t_i of the floor slab and the number and size of reinforcements in different positions over the floor slab are considered as design variables. In Fig. 3, A_1 and A_2 are hogging reinforcements, B_1 and B_2 are sagging reinforcements in the y direction in column and middle strips, C_1 and C_2 are hogging reinforcements, and D_1 and D_2 are sagging reinforcements in the x direction in column and middle strips, respectively.

Fig. 4 shows a typical layout of shear reinforcement around a column recommended by BS8110. In practice, it is not desirable to use different composition of bar sizes in different layers of shear reinforcement around a column. Therefore, it is assumed that all required shear reinforcements for a column–slab connection have the same diameter. The number of required layers of shear reinforcement for each column–slab connection depends on the magnitude of punching shear stresses around columns. The number of reinforcements in each layer is considered as a design variable. Four types of column–slab connection have been considered in each floor. These are a corner connection, two edge connections for columns located in longitudinal and transverse sides of the building and an intermediate connection. Design details, such as column head or column capital, can be used in the top region of columns to enhance the punching shear resistance of slab–column connections. The main disadvantage of providing a column head is the additional formwork and consequent increase in construction time and cost. They may also obstruct the installation of services. Therefore, they are not considered in the present optimisation algorithm.

Fig. 5 shows design variables for a column. To simplify the problem, it is assumed that all columns have rectangular cross-sectional shape; however, the optimisation algorithm can be extended to accommodate other column cross-sections such as circular or polygonal. All reinforcements have the same diameter and they are concentrated in four corners of the column section. Since it has been assumed that lateral loads are resisted by shear walls or another system capable of withstanding lateral forces, there is no considerable shear force in the column section. Hence the size and spacing of the column links are calculated in terms of the longitudinal bar diameter according to the Code recommendations to prevent outward buckling of the longitudinal bars and to provide ductility [10,11]. Four different typical columns are considered in each storey, which are a corner column, two edge columns in longitudinal and transverse sides of the building and an intermediate column.

3.2. Objective function

The objective function, C, is the cost of labour and material for concrete, reinforcement and formwork for n_f

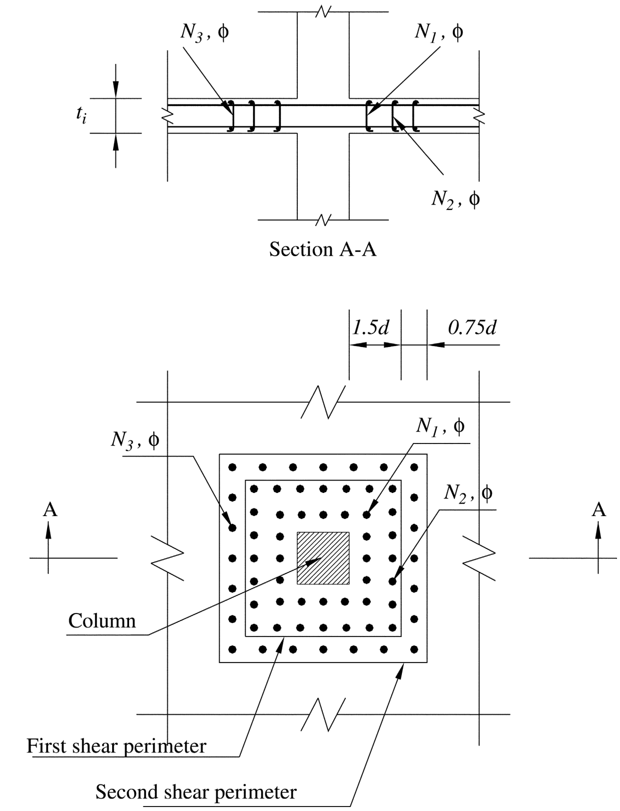

Fig. 4. Design variables for shear reinforcement around columns.

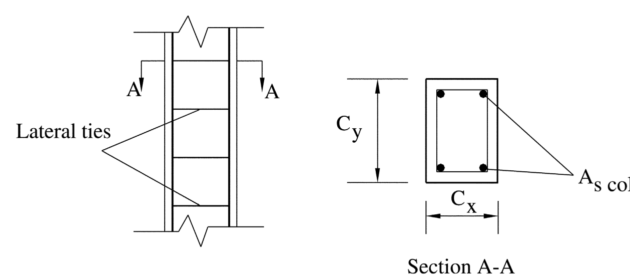

Fig. 5. Design variables for a reinforced concrete column.

floors, n_c typical columns and foundations for a quarter of the building as follows:

$$C = \sum_{i=1}^{n_f} C_i(x_f) + \sum_{j=1}^{n_c} C_j(x_c) + C_f(x) \quad (1)$$

subject to

$$G_i(\boldsymbol{x}_f, \boldsymbol{x}_c) \le 1 \qquad i = 1, 2, \ldots, n_g \quad (2)$$

$$\boldsymbol{x}_j^l \le \boldsymbol{x}_j \le \boldsymbol{x}_j^u \qquad j = 1, 2, \ldots, n_s \quad (3)$$

$$\boldsymbol{x} = (\boldsymbol{x}_f, \boldsymbol{x}_c) \quad (4)$$

where $C_i(x_f)$, $C_j(x_c)$ and $C_f(x)$ represent the total costs of floors, all typical columns and foundations including the cost of foundation excavation for a quarter of the building, respectively. G_i given in Eq. (2) is the i-th non-dimensional behavioural constraint function. Eq. (3) gives side constraints on design variables x_j, where x_j^l and x_j^u are the lower and upper limits of the design variable x_j, respectively. In Eqs. (2) and (3), n_g and n_s are the number of behavioural and side constraints, respectively. The foundation cost is approximately calculated by assuming that all foundations are identical reinforced concrete pad footings. The cost of shear reinforcement around columns is also included in the total cost of floors. The vector of design variables comprises two components: $\boldsymbol{x}_f$ are the design variables of flat slab floors and $\boldsymbol{x}_c$ are the design variables of columns as indicated by Eq. (4).

3.3. Design constraints

Design constraints represented by Eqs. (2) and (3) are formulated according to BS8110 [6] Code requirements. The constraints for slabs can be expressed as follows:

$$M/M_n \leq 1 \quad (5)$$

$$K/K' \leq 1 \quad (6)$$

$$\rho_{\max} \geq A_s/A_c \geq \rho_{\min} \quad (7)$$

$$s_{\min} \leq b/N_b \leq s_{\max} \quad (8)$$

$$t \geq 125 \text{ mm} \quad \text{(no shear reinforcement used)} \quad (9)$$

$$t \geq 200 \text{ mm} \quad \text{(shear reinforcement used)} \quad (10)$$

where M is the design ultimate moment, M_n is the sectional moment of resistance, K and K' are two parameters which are calculated from bending moments after and before moment redistribution, properties of the section and the characteristic strength of concrete. In practice, it is preferred to design slabs without compression reinforcement; therefore K should be less than K'. Also in the above constraints, A_s is the area of tension reinforcement, b is the width of the section, A_c is the area of concrete section, $\rho_{\min}$ and $\rho_{\max}$ are the minimum and maximum allowable reinforcement ratios in slabs, respectively, N_b is the number of steel bars in a width b of the slab, and $s_{\min}$ and $s_{\max}$ are minimum and maximum allowable spacings between bars, respectively.

The required area of bending reinforcement for the slab is often calculated on the basis of strength requirements. However, increasing reinforcement in some spans to satisfy deflection requirements, which are adequate for bending strength, can be much more economical than increasing the slab thickness over the whole floor. Therefore, the required amount of reinforcement at the middle of slab spans may also be obtained from the deflection limit, as follows:

$$A_s \geq \min(A_{sd}, A_{s\ \max}) \quad (11)$$

where A_{sd} and $A_{s\ \max}$ are the required area of tension reinforcement at the middle of spans to satisfy deflection limits and maximum allowable area of tension reinforcement for a singly reinforced bending section, respectively.

The constraints for shear reinforcement around columns are summarised as

$$v_{c\,\text{eff}}/\min\left(0.8\sqrt{f_{cu}}, 5 \text{ N/mm}^2\right) \leq 1 \quad (12)$$

$$V_{\text{eff}}/V_n \leq 1 \quad (13)$$

$$sh_{\min} \leq N_{sh}/p \leq sh_{\max} \quad (14)$$

$$A_{sh1} \geq 0.4(A_{sh1} + A_{sh2}) \quad (15)$$

where $v_{c\,\text{eff}}$ is the effective design shear stress at the column face, V_n and V_{eff} are the shear strength and effective design shear stress provided in each punching shear zone around columns, respectively, p is the length of each perimeter around columns, on which N_{sh} links are distributed, $sh_{\min}$ and $sh_{\max}$ are minimum and maximum allowable spacings between links, respectively, and A_{sh1} and A_{sh2} are the areas of shear reinforcement in the first and second perimeters in each assumed failure zone (see Fig. 4).

The constraints for columns include:

$$P/P_n \leq 1 \quad (16)$$

$$M/M_n \leq 1 \quad (17)$$

$$\rho_{\max} \geq A_{sc}/A_c \geq \rho_{\min} \quad (18)$$

$$4 \leq N \leq 20 \quad (19)$$

$$\phi \geq 12 \text{ mm} \quad (20)$$

$$C_x, C_y \geq 250 \text{ mm} \quad (21)$$

$$\phi_s \geq \text{Max}(\phi/4, 6 \text{ mm}) \quad (22)$$

$$s_l \leq 12\phi \quad (23)$$

where P_n, P, M_n and M are the calculated axial strength, the design axial force, the calculated bending strength and the design bending moment, respectively, A_{sc} is the area of steel in the column, $\rho_{\min}$ and $\rho_{\max}$ are minimum and maximum allowable reinforcement ratios in the column, respectively, N is the number of steel bars in the column and ϕ is the main longitudinal reinforcement diameter and C_x and C_y are the cross-sectional dimensions of the column. ϕ_s and s_l are the diameter and spacing of lateral links in columns, respectively. P_n and M_n are obtained from interaction diagrams for reinforced concrete column design.

There is also an additional constraint for maximum design moment transferable between the slab and edge or corner column, $M_{t\ \max}$:

$$M/2M_{t\ \max} \leq 1 \quad (24)$$

where M is the value of the bending moment for an edge or corner column which is obtained from the structural analysis of equivalent frames using EFM and $M_{t\ \max}$ is calculated according to the features of the slab–column connection and the characteristic strength of concrete as given in BS8110 [6].

In addition to these constraints, which are extracted from the code provisions, some constraint can be established regarding practical considerations. For example bar sizes are limited to those available in the market and also column dimensions may decrease or be kept the same from lower to upper floors.

4. Design optimisation procedure

Fig. 6 shows the algorithm of the computer program developed for the design optimisation of reinforced concrete

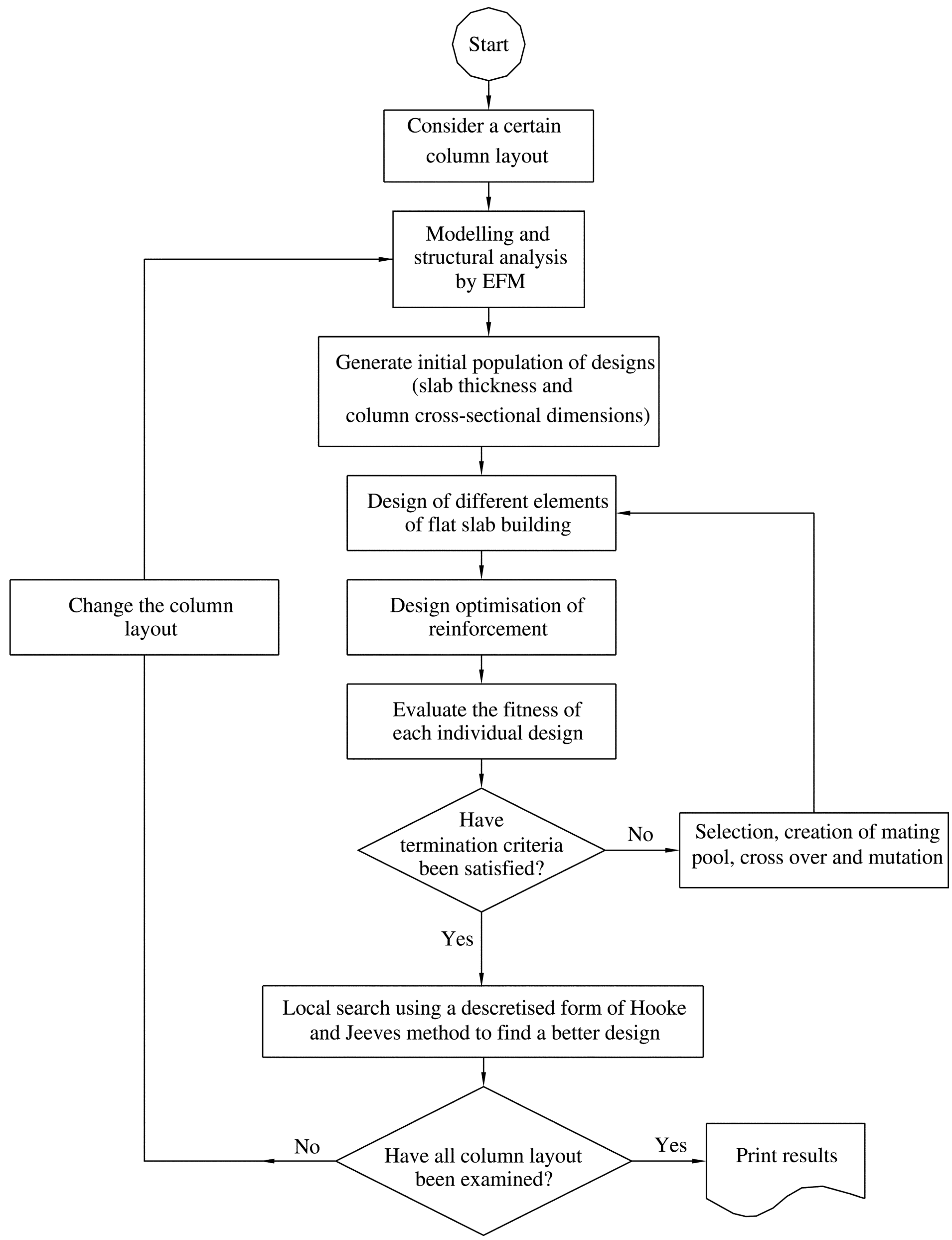

Fig. 6. The flowchart of the optimisation procedure.

flat slab buildings. The optimisation procedure is handled in three different levels. In the first level, different practical column layouts for a building of a given number of storeys, length and width of rectangular plan are compared against each other in order to find the optimum number of spans in the longitudinal and transverse directions. For each column layout, the program creates a model for the structural analysis using the EFM. Design optimisation of the structure is then carried out and the total cost of the optimum structure for the defined column layout is calculated. The minimum total cost among all the results obtained for different column layouts corresponds to the optimum column layout.

Design variables for each column layout have been divided into two groups. The first group is the cross-sectional dimensions of columns and thickness of floors, which influence the structural analysis and the second group is the size and number of bars in member cross-sections. The optimum values of the second group of design variables are calculated for each element separately from design forces and cross-sectional dimensions of the element according to BS8110. Therefore the first group of design variables are considered as independent design variables and the second group of design variables are dependent design variables.

In the second level, the optimum cross-sectional dimensions of the columns and thickness of slabs for each assumed column layout are found. The number of possible solutions of design variables could be large; therefore a hybrid optimisation algorithm [12] based on a genetic algorithm (GA) is employed. The algorithm includes two stages. In the first stage a modified GA is initially used for a global search to find the optimum or a near-optimum solution for the cross-sectional dimensions of structural elements as explained below. In the second stage, the GA solution is improved using a complementary process, similar to the Hooke and Jeeves method [13] but adapted for discrete design variables. Thus the solution obtained by a GA process is considered as a base point for a local exploration. The objective function is calculated at a point obtained by a positive or negative increment in the direction of the first coordinate (design variable). If any of these new points gives a better design, this new point is considered as a new base point. This process is repeated for all coordinates until there is no point in the neighbourhood of the base point that gives a better design.

In the third level, using an exhaustive search method [14], the optimum amount of reinforcement (number and diameter of bars) for each group of members with given dimensions is determined.

4.1. Basic GA and modifications implemented

The nature of the design variables has a major influence on the selection of the appropriate optimisation technique. In the current research, all design variables are discrete, although a floor thickness and cross-sectional dimensions of columns may theoretically take any real number value—but practically they are restricted to a set of discrete values. Number of bars is inherently a discrete variable and size of bars is also restricted to those of rolled steel bars available in the market. The discrete nature of the design variables of the problem under consideration limits the choice of solution techniques to the group of discrete optimisation methods to which GA belongs. Although integer programming methods may be used for discrete optimisation problems, other features of the current problem such as it being multimodal justify the use of the GA.

GAs are numerical optimisation techniques inspired by the natural evolution laws. A GA starts searching design space with a population of designs which are created over the design space at random. In the basic GA, every individual of population is described by a binary string. GA uses three main operators: selection (reproduction), crossover and mutation to direct the density of the population of designs towards the optimum point [12].

In the selection process, some individuals of a population are selected by some randomised method as parents to create the next generation. The fitter individuals (designs) have a greater chance of being selected.

Crossover allows the characteristics of the designs to be altered, depending on the crossover probability, P_c, for creation of a better generation of designs. In this process, different digits of binary strings of each parent are transferred to their children (new designs produced by the crossover operation).

Mutation is an occasional random alteration of the value of some digits in a design's binary code. The mutation operation changes each bit of string from 0 to 1 or vice versa depending on the mutation probability, P_m. Mutation can be considered as a factor preventing premature convergence [12].

Two modifications have been implemented in the basic GA. The first modification is that the GA starts with a large size of randomly created individuals (designs) over the design search space [15] and then best designs are selected to carry on the rest of the GA process. The second modification limits the number of copies of each group of designs with the same fitness to one. In this manner, the population size is decreased during the process but not to less than a predefined minimum allowable population size [15]. Full details of the hybrid optimisation technique are given in another paper [15].

4.2. Constraint handling

The constraints reflect design requirements in the optimisation problem. In other words, they limit the range of acceptable designs in the problem. As GAs are unconstrained optimisation techniques, it is necessary to transform the constrained optimisation problem to an unconstrained one. Several methods [16] for handling constraints by means of GAs have been proposed. In the current research, the constraints relevant to the first group of design variables, namely cross-sectional dimensions of reinforced concrete elements, are applied using a penalty function and those relevant to the second group of design variables, namely the number and diameter of reinforcing bars, are applied by limiting the search range to the feasible domain. The penalisation techniques are very popular because they can be implemented without significant modification of the standard genetic algorithm. However, to be efficient, they require an adequate tuning of different parameters. In the penalty method [17], a constrained optimisation problem is converted to an unconstrained problem by adding a penalty term for each constraint violation to the objective function, $C(\boldsymbol{x})$, as follows:

$$\tilde{C}(\boldsymbol{x}) = C(\boldsymbol{x}) + r \sum_{i=1}^{m} \Phi_i(\boldsymbol{x}) \tag{25}$$

where $\tilde{C}(\boldsymbol{x})$ is the penalised objective function, r is the penalty multiplier, m is the number of constraints and Φ_i is the i-th penalty function which can be expressed in a general form as follows:

$$\Phi_i(\boldsymbol{x}) = [\max(G_i(x), 0)]^n \tag{26}$$

where n is the power of penalty function and $G_i(\boldsymbol{x})$ is the value of the i-th constraint. In this paper, linear, quadratic

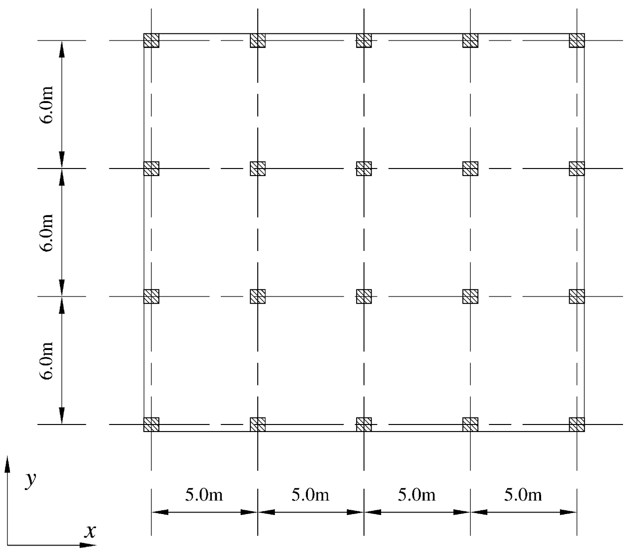

Fig. 7. A plan of the flat slab building in Examples 1 and 2.

and square root forms of the penalty function are used. Proximity of the GA solution to the real optimum solution depends heavily on the values of the penalty multiplier, r. If the penalty coefficient is small, the algorithm may converge to an unfeasible solution. On the other hand, if the penalty coefficient is too large, this method becomes equivalent to the rejecting strategy method. In the reinforced concrete flat slab examples presented below, the penalty multiplier r is fixed at 10.

5. Design examples and discussions

5.1. Example 1: a one-storey reinforced concrete flat slab building

A one-storey reinforced concrete flat slab building with a plan as shown in Fig. 7 is optimised. In this example, the column layout is assumed fixed as shown in Fig. 7. The live load is 5.0 kN/m^2 and the dead load, excluding the self-weight of concrete, is 2.5 kN/m^2. The unit prices of materials and labour for concrete, steel and formwork are 55 £/m^3, 0.5 £/kg and 20 £/m^2, respectively as given in Spon's Architects' and Builders' Price Book 2001 [18] and Harris [19]. Other design parameters used in this example are the characteristic strength of the main reinforcement $f_y = 460$ N/mm^2, the characteristic strength of the shear reinforcement $f_{yv} = 250$ N/mm^2, the characteristic strength of concrete $f_{cu} = 35$ N/mm^2; the top and bottom covers of steel bars are 20 and 25 mm for slabs, respectively and the cover of bars in columns is 40 mm. Maximum and minimum bar diameters for flexural reinforcement are 25 and 10 mm and for shear reinforcement they are 14 and 6 mm, respectively.

Table 1 shows the floor thickness and cross-sectional dimensions of columns obtained from the current optimisation technique. The corresponding values obtained from a conventional design that satisfies all BS8110 code requirements for reinforced concrete flat slabs are also presented in Table 1. Table 2 compares cost components for different elements of the optimum and conventional designs. It is important to note that, for the optimum thickness of 220 mm, the required area of reinforcement at the middle of the two spans is governed by the deflection constraint; i.e. the amount of reinforcement in these spans has been increased as compared with that obtained from bending strength requirements. In other words, increasing the amount of longitudinal reinforcement at the middle of a few spans is more economical than increasing the thickness of the slab to satisfy deflection requirements. As Table 1 shows, the slab thickness for the optimum design is 30 mm smaller than that for the conventional design. Therefore, in order to prevent punching shear failure in the optimum design the cross-sectional dimensions of the edge columns in the x direction are increased as compared with that of the conventional design and, as a consequence, the total cost of columns for the optimum design is 3.3% greater than that for the conventional design as given in Table 2. However, 2.8% total cost saving has been achieved using the optimisation technique presented here compared with the conventional design. Table 2 indicates that the cost of the floors constitutes the major part of the total cost of the building.

5.2. Example 2: a four-storey reinforced concrete flat slab building

A four-storey reinforced concrete flat slab building is optimised. The building has the same plan and loading on the first, second and third floors as those given in Example 1. The live and dead loads on the fourth floor are 1.5 and 2.0 kN/mm^2, respectively. The main goal in presenting this example is to compare the total cost of a structure when different member groupings are considered for reinforced concrete elements. Moreover, in this example the importance of optimisation and cost saving for a large structure of a larger number of storeys as compared with the previous example is investigated.

In practice, a typical design is usually adopted for many floors of similar conditions and column dimensions are changed every few storeys. Two cases were examined for grouping of structural members. In Case 1, it is assumed that column dimensions and slab thickness can change from one floor to another subject to the defined constraints. In Case 2, it is assumed that column dimensions can change every two storeys. Considering that loading over the first, second and third floors is similar, it is also assumed that these three floors have the same thickness and reinforcement detailing which could be different from those of the fourth floor. It should be noted that no reduction in the unitary cost of repetitive structural elements as in Case 2 is included in the objective function. Table 3 presents the dimensions obtained for the optimum (Cases 1 and 2) and conventional designs. It indicates that the optimum size of structural

Table 1
Comparison of the results obtained from optimum and conventional designs for a one-storey flat slab building

Design method	t (mm)	Corner columns C_x (mm)	C_y (mm)	Steel bars	Edge columns in the x direction C_x (mm)	C_y (mm)	Steel bars	Edge columns in the y direction C_x (mm)	C_y (mm)	Steel bars	Intermediate columns C_x (mm)	C_y (mm)	Steel bars
Optimum design	220	250	250	4T12	250	300	4T12	250	250	4T12	250	250	4T12
Conventional design	250	250	250	4T12	250	250	4T12	250	250	4T12	250	250	4T12

elements in the case of member grouping is the same as or larger than that in the case of member ungrouping. Table 4 compares cost components of the optimum (Cases 1 and 2) and conventional designs. Tables 3 and 4 show that, on increasing the number of storeys or, in other words, the number of structural elements, the amount of saving achieved by design optimisation of the structure has increased compared with the one-floor flat slab building case presented above. These results show the importance of optimisation of large scale structures. The results show that the total cost in Case 2 is slightly greater than that in Case 1. However, from a practical point of view, having a typical design for many floors gives a simpler design and leads to saving in design and supervision costs.

Table 2
Comparisons of cost components of the optimum and conventional designs

Design method	Total cost of floors (£/m^2)	Total cost of columns (£/m^2)	Total approximate cost of foundation (£/m^2)	Total cost of building (£/m^2)
Optimum design	38.411	5.944	5.2	49.556
Conventional design	39.811	5.756	5.411	50.978
Cost saving (%)	3.5	−3.3	3.9	2.8

5.3. Example 3: a comparative design example

This design example has been chosen from a report on comparative costs of concrete and steel framed office buildings [20] that has been recommended as a benchmark for future studies. The conventional design of this example has been carried out by a team of professional engineers [20]. The building includes three identical storeys, each of 3.95 m height. The total length and width of the building are 37.5 m. The live load on intermediate floors is 5.0 kN/m^2 and on the roof is 1.5 kN/m^2. Dead loads are self-weight and the imposed dead load of 1.5 kN/m^2. In the report [20], different unit prices have been considered for each of the materials depending on the type of the structural element. In this study, the average unit prices of materials and labours for concrete, shear and main longitudinal reinforcement, and formwork have been considered as $u_c = 53.5$ £/m^3, $u_r = 0.4$ £/kg and $u_f = 18.5$ £/m^2, respectively. The cost of foundation excavation, which has been presented in the report, is composed of different items; therefore, an average unit cost of 18.5 £/m^3 is considered for foundation excavation including the cost of disposal and backfill of soil. The characteristic strengths of the main longitudinal and shear reinforcement, and concrete are $f_y = 460$ N/mm^2, $f_{yv} = 250$ N/mm^2 and $f_{cu} = 35$ N/mm^2, respectively. The cover of steel bars for the floors is 25 mm and for the columns is 40 mm. The minimum and maximum bar diameters for main longitudinal reinforcements of floors and columns, and shear reinforcement are 10, 25 and 10, 32 and 6, 12 mm, respectively.

5.4. Fixed span lengths

In the first stage of this example, the span lengths are assumed to be fixed in both directions; l_x and l_y are 7.5 m, i.e. n_x and n_y are 5 as given in [20]. Fig. 8 shows the comparison of the cost components of concrete, reinforcement and formwork of the structure obtained from conventional design [20] and the current optimum design. The breakdown of costs of the floors and columns is also shown in this figure. The total costs of the superstructure obtained from the conventional and optimum designs are 55.46 £/m^2 and 42.57 £/m^2, respectively. As a result, design optimisation of the structure has produced 23.3% cost saving. Fig. 8 indicates that the cost of floors and columns is about 89% and 11% of the total cost for the conventional design and 91% and 9% of the total cost for the optimum design, respectively. Therefore, the cost of floors constitutes the major part of the structural cost and emphasises the importance of the optimisation of floors in the flat slab buildings, as concluded by other researchers [20,21]. It can be observed that the largest component of the overall cost is the formwork cost (39% and 51% for the conventional and optimum designs, respectively). The concrete cost contributes 33% and 36% of the structural cost for the conventional and optimum designs, respectively. The smallest component is the cost of reinforcement, being 28% and 13% for the conventional and optimum designs, respectively. The least cost saving is obtained for the formwork (0.5% cost saving) as the formwork cost relates to the soffits for floors which are identical to the conventional and optimum designs.

5.5. Optimum span lengths

In addition to the optimum sizes of structural elements, the optimum number of spans was also determined in

Table 3
Comparison of the optimum and conventional designs for a four-storey flat slab building

Floor	Design	t	Corner columns			Edge columns in the x direction			Edge columns in the y direction			Intermediate columns		
		(mm)	C_x (mm)	C_y (mm)	Steel bars	C_x (mm)	C_y (mm)	Steel bars	C_x (mm)	C_y (mm)	Steel bars	C_x (mm)	C_y (mm)	Steel bars
First	Optimum (ungrouping)	215	250	250	4T12	250	250	4T16	300	250	4T12	300	350	4T20
	Optimum (grouping)	215	250	250	4T12	250	250	4T16	300	350	4T12	300	350	4T25
	Conventional	250	250	250	4T12	300	300	4T12	300	300	4T12	400	400	4T16
Second	Optimum (ungrouping)	215	250	250	4T12	250	250	4T16	250	250	4T12	250	250	4T25
	Optimum (grouping)	215	250	250	4T12	250	250	4T16	300	350	4T12	300	350	4T12
	Conventional	250	250	250	4T12	300	300	4T12	300	300	4T12	400	400	4T16
Third	Optimum (ungrouping)	215	250	250	4T12	250	250	4T12	250	250	4T12	250	250	4T12
	Optimum (grouping)	215	250	250	4T12	250	250	4T12	250	250	4T16	250	250	4T12
	Conventional	250	250	250	4T12	250	250	4T12	250	250	4T12	300	300	4T12
Fourth	Optimum (ungrouping)	200	250	250	4T16	250	250	8T12	250	250	4T16	250	250	4T12
	Optimum (grouping)	200	250	250	4T16	250	250	8T12	250	250	4T16	250	250	4T12
	Conventional	230	250	250	4T16	250	250	4T12	250	250	4T12	300	300	4T12

Table 4
Comparisons of cost components of the optimum and conventional designs

Design	Total cost of floors (£/m^2)	Total cost of columns (£/m^2)	Total approximate cost of foundation (£/m^2)	Total cost of building (£/m^2)
Optimum (Ungrouping)	37.558	5.100	3.947	46.605
Optimum (Grouping)	37.633	5.281	3.983	46.897
Conventional	39.136	5.661	4.322	49.119
Cost saving (%)	4.0[a]/3.8[b]	9.9[a]/6.7[b]	8.7[a]/7.8[b]	5.1[a]/4.5[b]

[a] Cost saving in comparison with the optimum design in the case of member ungrouping.
[b] Cost saving in comparison with the optimum design in the case of member grouping.

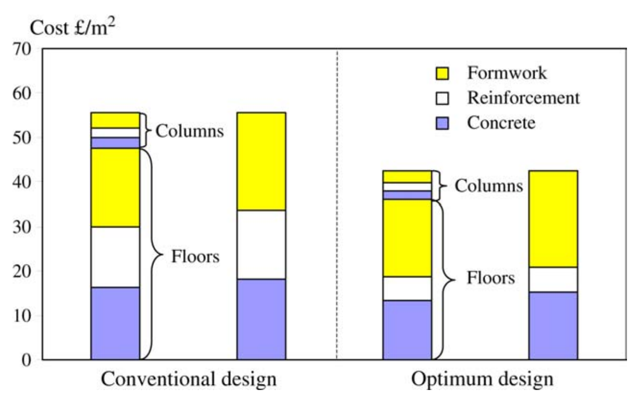

Fig. 8. Comparisons of cost components obtained from conventional and optimum designs.

this example. The optimum column layout is achieved by comparing the minimum structural cost of different column layouts of the building. Fig. 9 shows the variation of the minimum structural cost of the building with respect to the span lengths. The most economical span lengths are $l_x = l_y = 5.357$ m (i.e. $n_x = n_y = 7$). The total cost per unit area of the flat slab building for the optimum column layout and the optimum and conventional designs of the previously assumed column layout ($l_x = l_y = 7.5$ m) are 40.62 £/m^2, 46.89 £/m^2 and 63.56 £/m^2, respectively. Therefore, the optimum column layout can produce 36% and 13% cost saving as compared with the conventional and optimum designs with fixed spans equal to $l_x = l_y = 7.5$ m, respectively.

6. Conclusions

Cost optimisation of reinforced concrete flat slab buildings using a multi-level optimisation procedure has been presented. The procedure includes finding the optimum column layout, cross-sectional dimensions and reinforcement of different reinforced concrete elements. The design optimisation of three reinforced concrete flat slab buildings with different structural features and number of storeys was illustrated and the following conclusions may be drawn:

- The greater the number of storeys in the reinforced concrete flat slab building, in other words, the greater

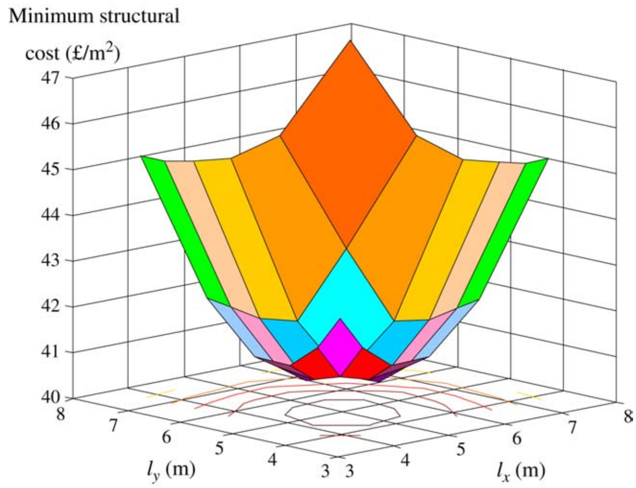

Fig. 9. The minimum structural cost versus length of spans.

the number of structural elements, the greater the cost savings achieved using design optimisation.

- Column layout optimisation of flat slab buildings can produce substantial savings as regards the total structural cost of the building.
- Cost of floors constitutes the major part of the total structural cost of reinforced concrete flat slab buildings.

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