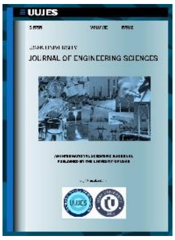

Usak University

Journal of Engineering Sciences

An international e-journal published by the University of Usak

Journal homepage: dergipark.gov.tr/uujes

Research article

DESIGN OPTIMIZATION OF RECTANGULAR RC BEAMS USING GENETIC ALGORITHM

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Received: 13 May 2021 Revised:19 October 2021 Accepted: 9 November 2021 Online available:30 December 2021

Handling Editor: Jülide Öner

Abstract

The study presents an optimal design of simply supported rectangular reinforced concrete beams based on the ultimate limit state philosophy of BS8110 and using genetic algorithm as optimization tool. An optimization model was formulated. The model consists of an objective function which focuses on minimizing the steel ratio of the beams and constraint equations which are focused on checking that all the requirements of BS8110 for the design of reinforced concrete beams are satisfied. Results obtained showed a difference of up to 46% and 12.6% in steel ratios obtained using the traditional approach and those obtained using the optimization model for singly and doubly reinforced concrete beams respectively, depending on the magnitude of the applied moment. The model has proved to minimize the final dimensions of rectangular reinforced concrete beams and by implication, the steel ratio even though all the requirements of the code were satisfied.

Keywords: *Optimization, rectangular beams, reinforcement ratio, Genetic Algorithm.*

1. Introduction

Reinforced concrete (RC) structures have significant compressive strength when compared to other construction materials. Besides possessing a reasonably high compressive strength, reinforced concrete structures are durable, multi-functional and cost much lower when it comes to maintenance as compared to other structures. RC structures are also, generally very good in resisting the effect of fire and damages due to water, and have been characterised to have long service life [1].

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DOI: 10.47137/uujes.936917

The conventional approach in the design of RC members does not completely optimize the use of materials. Most designs are based on the experience or technical know-how of the designer. The designer chooses grades of materials and cross-section dimensions by comparing it to his/her own personal past experience. This gives space to fixed rules of thumb for preliminary designs [2]. In the process of designing structural elements, the engineers makes assumptions at every step in view of structural and non-structural features such as atheistic, stiffness, element strength, serviceability and how easy or otherwise it can be constructed. In other words, the designer formulates optimal design criteria to achieve their best designs; therefore, this process of structural design may be considered as an optimum design. As a result, for a structural element (member) which is subject to the same support and loading condition, different reinforcement areas and member sizes are used by different Engineers. These reinforcement areas and member sizes have different implications in terms of cost and some may be highly un-economical when used even though they have met code (design) requirements [3]. This traditional approach, which is entirely dependent on assumptions with the effectiveness of the resulting design (which are never the same for different designers) directly linked to the experience of the designer is strenuous as it requires a lot of effort, costs more and encourages waste of construction materials. Therefore, the use of genetic algorithm in structural design optimization is a better alternative to "design based on engineer's past experience" [4].

Optimization is purely a mathematical aspect that deals with the finding of minimum or maximum of an established objective function that still satisfy the prevailing design constraints. Structural optimization on the other hand, entails using available optimization methods in deigning structures. The structural optimization problem is made up of an objective function which is formulated to minimize the cost, dimension, volume or area of a structure under some given constraints which are mostly based on limits set by the design code. These constraints may be in the form of serviceability limit states or mechanical properties of the structure. It is important to note that, even when the optimization is not directly related to the cost, it should be able to come up with a solution that satisfies all design requirements [5].

Optimization of reinforced concrete members is an intricate problem, due to the large number of variables and associated rigorous constraint that control the design process. The structural design process may be divided into four different stages: formulating the functional requirements, conceptual design, optimization and detailing [6]. An iterative procedure is often needed for each stage before the final solution is accomplished; a process that is normally carried out without considering the relative costs of steel, concrete, formwork, or other relevant costs or any other auxiliary information in case of genetic or evolutionary algorithms. In an optimal design the structural behaviour, design loads and geometrical constraints are specified and then the objective function is defined. The aim of this computerized procedure is to ascertain the geometry to attain the desired behaviour at the lowest possible section leading to lowest cost. Computer programmes have therefore, become very important tools in structural optimization.

In recent time, genetic algorithms (GA) have been widely used in solving various structural optimization problems [2]. GA is a technique that is classified under stochastic heuristic optimization techniques. As the name implies, it mimics Darwin's theory of evolution, where the individuals having the best traits in the population have greater chance of survival and are responsible for producing new off springs [7]. David [8] applied genetic programming in solving design problems in civil engineering. The author was able to obtain improved solutions by applying genetic algorithms in solving

structural design problems. GA modifies the traits of individuals that are chosen from a present generation to produce new individuals that form a new generation. With GA, the population approaches optimality as the number of generations increases [3].
Structural elements designed to carry transverse loads are generally referred to as Reinforced Concrete Beams. As a result of this load, the beam is made to resist shear forces, bending moments and sometimes torsion across its span. Generally, concrete is known to be weak in tension and strong in compression. Compared to compressive strength, the tensile strength of concrete is only about 10% and as a result, the designs of reinforced concrete structures are done with the assumption that the concrete offers no resistance to tensile forces [9]. Hence, steel reinforcements are combined with concrete to resist the tensile forces. In a framed structure, beams transfer loads (from slabs, walls and other beams) to the columns they are resting on. Beams can be of different shapes and support conditions. They can be continuous, cantilevered or simply supported, depending on the number, type and position of the supports. The depth of the beam is dependent on the magnitude of the moment it is designed to resist, this consequently, determines whether a beam is to be designed as singly or doubly reinforced. [10].
This paper presents an optimal design of rectangular reinforced concrete beams using GA as an optimization tool. The study is motivated by the promising technique of genetic algorithm in optimization and the continuous search for optimum solutions to structural engineering design problems.

1.1 Optimization of Structural Elements

Several research works on structural optimization have been carried out in the past. Some of the pertinent literatures in the field of structural optimization; specifically, in the area of RC beams are summarized here. Using geometric programming as optimization tool, Chakrabarty [11] carried out a minimum cost design for singly reinforced rectangular concrete beams. Khaleel and Itani [12] automated the design of partially pre-stressed concrete girders. Sequential quadratic programming (SQP) was used as optimization tool. The author achieved an optimized volume of pre-stressing and non-prestressing steel reinforcement, and also, optimized dimensions and spacing between stirrups. Adamu*et al* [13] used the European Code to optimize the cost of singly reinforced concrete beams using the continuum type optimality criteria. The author successfully optimized, by an iterative process, a RC beam that is simply supported at one end and fixed at the other. Al-Salloum and Siddiqi [14] carried out design optimization of singly reinforced rectangular beams. The authors focused on minimizing the cost of the beam on the basis of the principles of the American Code (ACI 318-89). They were able to achieve an optimal solution with an objective function that includes the costs of steel reinforcement, concrete and formwork for a unit length of the beam. In a related study, Yousif and Najim [15], with the application of genetic algorithm optimized the cost design of reinforced concrete beams. The study however, used the ACI standard specification. Alex and Kottali [16] developed a program based on genetic algorithm to optimize the dimensions of a beam. The study however, considered the design of a cantilever beam only.

2. Formulation of the Optimization Model

2.1 Singly Reinforced Concrete Beam

2.1.1 Objective Function for Singly Reinforced Beam

The objective function, which is the steel ratio, is derived using the stress block (through compatibility of strains) for singly reinforced concrete beam as shown in Fig. 1. The analysis using compatibility of strains relates the reinforcement strain, to the strain at crack, and also the internal forces acting in the concrete and reinforcement [17].

The design variables are the width of the beam (x_1) and the effective depth (x_2).

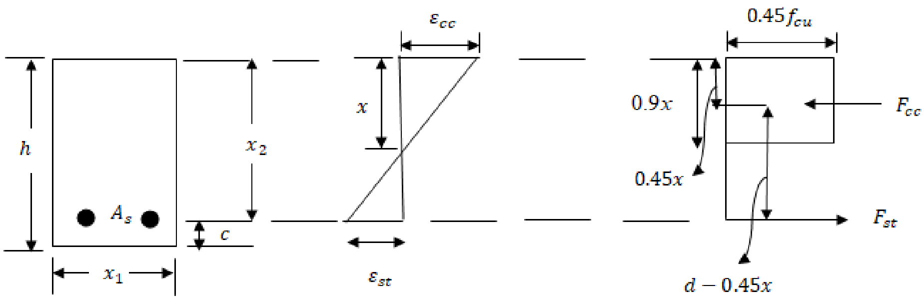

Fig. 1 Stress block for singly reinforced concrete beam

Let
M=ultimate moment of beam section
f_{cu} = Concrete grade
f_y = Steel grade
x_1 = Width of beam
x_2 = Effective depth of beam
c = Concrete cover + half reinforcement diameter
h = Overall depth of beam
A_s = Area of tension reinforcement for singly reinforced beam
f_{cc} = Force in the compression zone
f_{st} = Force in the tension zone
ε_{cc} = Strain in the compression zone
ε_{st} = Strain in the tension zone
ρ = Steel reinforcement ratio

$$\frac{\varepsilon_{st}}{x_2 - x} = \frac{\varepsilon_{cc}}{x}$$

$$x\varepsilon_{st} = \varepsilon_{cc}(x_2 - x)$$

$$x(\varepsilon_{st} + \varepsilon_{cc}) = x_2\varepsilon_{cc}$$

$$x = \frac{x_2\varepsilon_{cc}}{(\varepsilon_{st} + \varepsilon_{cc})} = \frac{x_2}{1 + \frac{\varepsilon_{st}}{\varepsilon_{cc}}} \quad (1)$$

but

$$\varepsilon_{cc} = 0.0035 \text{ and } \varepsilon_{st} = \frac{0.95f_y}{E_s} = 0.00219$$

Substituting these values in (1),
The neutral axis, $x = \frac{x_2}{1+\frac{0.00219}{0.0035}} = 0.615x_2$ (2)

The forces developed within the cross-section must be balanced by the applied force, P.

$$P = F_{cc} + F_{st} = \sigma_{cc}A_{cc} - \sigma_s A_s$$

$$P = \sigma_{cc}A_{cc} - E_s A_s \varepsilon_{st}$$

$$P = (0.45f_{cu} \times 0.9xx_1) - (E_s \times 0.00219 \times A_s)$$

From (2), $x = 0.615x_2$

$$P = 0.25f_{cu}x_1x_2 - 0.00219E_sA_s \quad (3)$$

Taking moment through the middle of the section,

$$M = F_{cc}(0.5h - 0.45x) + F_{st}(x_2 - 0.5h)$$

$$\text{But } h = x_2 + c \text{ and } x = 0.615x_2$$

$$M = F_{cc}[0.5(x_2 + c) - 0.45(0.615x_2)] + F_{st}[x_2 - 0.5(x_2 + c)]$$

$$M = F_{cc}(0.2232x_2 + 0.5c) + F_{cc}(0.5x_2 + 0.5c)$$

But $F_{cc} = \sigma_{cc}A_{cc} = 0.25f_{cu}x_1x_2$ and $F_{st} = \sigma_s A_s = 0.00219E_sA_s$

$$M = 0.25f_{cu}x_1x_2(0.2232x_2 + 0.5c) + 0.00219E_sA_s(0.5x_2 + 0.5c) \quad (4)$$

From (4),

$$Area\ of\ steel\ reinforcement, A_s = \frac{M - 0.25f_{cu}x_1x_2(0.2232x_2 + 0.5c)}{0.00219E_s(0.5x_2 + 0.5c)} \quad (5)$$

$$Steel\ ratio, \rho = \frac{Area\ of\ steel}{Area\ of\ concrete} = \frac{A_s}{x_1(x_2 + c)} \quad (6)$$

The objective function for singly reinforced beam is therefore,

$$\rho(x_1, x_2) = \left[\frac{M - 0.25f_{cu}x_1x_2(0.2232x_2 + 0.5c)}{0.00219E_s(0.5x_2 + 0.5c)}\right] \div [x_1(x_2 + c)] \quad (7)$$

2.1.2 Design Constraints for Singly Reinforced Beams

The design constraint equations are formulated based on the limits set by BS8110. The limitations of the optimization process are generally defined by the constraints. These constraints are conditions that govern the mechanical behaviour of the material, making sure that the conditions that guarantee the safety of the structural element are accounted for. BS 8110 has set limits for moment, minimum and maximum reinforcement ratios, cover-effective depth ratio and deflections for the safety and stability of the beam. These limits have been converted to constraint equations for the optimization problem.

Moment constraint

BS8110 provides that the ultimate moment, M should be less than $0.156 f_{cu} bd^2$ for the beam to be considered as singly reinforced.

$$M \leq 0.156 f_{cu} x_1 x_2^2 \tag{8}$$

Minimum and maximum reinforcement constraint

BS 8110 provides that the reinforcement ratios for beams must be between 0.13 and 6%. This limit has been used to generate the following constraint equations

$$0.13 - \left[\left(100 \times \frac{\left(M - 0.25 f_{cu} x_1 x_2 (0.2232 x_2 + 0.5c)\right)}{0.00219 E_s (0.5 x_2 + 0.5c)}\right) \div \left(x_1 (x_2 + c)\right)\right] \leq 0 \tag{9}$$

$$\left[\left(100 \times \frac{\left(M - 0.25 f_{cu} x_1 x_2 (0.2232 x_2 + 0.5c)\right)}{0.00219 E_s (0.5 x_2 + 0.5c)}\right) \div \left(x_1 (x_2 + c)\right)\right] - 6 \leq 0 \tag{10}$$

2.2 Doubly Reinforced Concrete Beams

2.2.1 Objective Function for Doubly Reinforced Beam

The objective function, which is the steel ratio, is derived using the stress block (through compatibility of strains) for doubly reinforced concrete beam as shown in Fig. 2. The design variables are the width of the beam (x_1) and the effective depth (x_2).

Let

A_{st} = Area of tension reinforcement

A_{sc} = Area of compression reinforcement

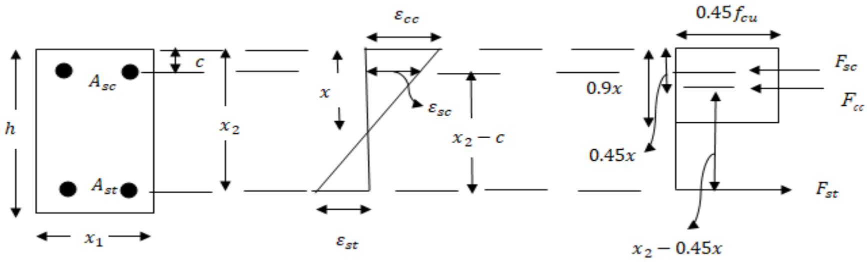

Fig. 2 Stress block for doubly reinforced concrete rectangular beam optimization

From compatibility of strains

$$x = \frac{x_2}{1+\frac{0.00219}{0.0035}} = \frac{x_2}{1.6257} = 0.615x_2$$

$$F_{cc} = \sigma_{cc}A_{cc} = 0.45f_{cu} \times 0.9x_1x = 0.45f_{cu}x_1 \times 0.9 \times 0.615x_2$$

$$F_{cc} = 0.25f_{cu}x_1x_2 \tag{11}$$

$$F_{st} = \sigma_sA_{st} = E_s\varepsilon_sA_{st} = 0.00219E_sA_{st} \tag{12}$$

$$F_{sc} = 0.00219E_sA_{sc} \tag{13}$$

Taking moment about the F_{st} axis

$$M = F_{cc}(x_2 - 0.45x) + F_{sc}(x_2 - c)$$

$$M = 0.25f_{cu}x_1x_2(x_2 - 0.45 \times 0.615x_2) + A_{sc} \times 0.00219E_s(x_2 - c) \tag{14}$$

From (14),

$$A_{sc} = \frac{M - 0.1808f_{cu}x_1x_2^2}{0.00219E_s(x_2 - c)} \tag{15}$$

Taking Moment at the neutral axis, at $x = 0.615x_2$

$$M = F_{st}(x_2 - 0.9 \times 0.615x_2) + F_{cc}(0.615x_2 - 0.45 \times 0.615x_2) + F_{sc}(0.615x_2 - c) \tag{16}$$

By substituting the values of F_{st}, F_{cc} and F_{sc} in (16),

$$A_{st} = \frac{M - 0.0845f_{cu}x_1x_2^2 - A_{sc}(0.615x_2 - c) \times 0.00219E_s}{0.00219E_s \times 0.446x_2}$$

$$A_{st} = \frac{M - 0.0845f_{cu}x_1x_2^2}{0.000978x_2E_s} - A_{sc} \times \frac{(0.615x_2 - c)}{(0.446x_2)}$$

$$A_{st} = \frac{M - 0.0845f_{cu}x_1x_2^2}{0.000978x_2E_s} - \left(\frac{M - 0.1808f_{cu}x_1x_2^2}{0.00219E_s(x_2 - c)}\right)\frac{(0.615x_2 - c)}{(0.446x_2)} \tag{17}$$

Total reinforcement area, $A_s = A_{st} + A_{sc}$

$$A_s = \frac{M - 0.0845 f_{cu} x_1 x_2^2}{0.000978 x_2 E_s} - \left(\frac{M - 0.1808 f_{cu} x_1 x_2^2}{0.00219 E_s (x_2 - c)}\right) \frac{(0.615 x_2 - c)}{(0.446 x_2)} + \frac{M - 0.1808 f_{cu} x_1 x_2^2}{0.00219 E_s (x_2 - c)} \quad (18)$$

$$Steel\ ratio, \rho = \frac{Area\ of\ Steel}{Area\ of\ Concrete} = \frac{A_s}{x_1 (x_2 + c)}$$

The objective function for doubly reinforced beam is therefore,

$$\rho(x_1, x_2) = \left[\frac{M - 0.0845 f_{cu} x_1 x_2^2}{0.000978 x_2 E_s} - \left(\frac{M - 0.1808 f_{cu} x_1 x_2^2}{0.00219 E_s (x_2 - c)}\right) \frac{(0.615 x_2 - c)}{(0.446 x_2)} + \frac{M - 0.1808 f_{cu} x_1 x_2^2}{0.00219 E_s (x_2 - c)}\right] \div x_1 (x_2 + c) \quad (19)$$

2.2.2 Design Constraints for Doubly Reinforced Beams

Cover-effective depth ratio

$$\frac{c}{x_2} \leq 0.2 \quad (20)$$

Ultimate moment

$$0.156 f_{cu} x_1 x_2^2 - M \leq 0 \quad (21)$$

Minimum and maximum compression reinforcement ratio

$$0.2 - \left[\left(100 \times \frac{M - 0.1808 f_{cu} x_1 x_2^2}{0.00219 E_s (x_2 - c)}\right) \div \left(x_1 (x_2 + c)\right)\right] \leq 0 \quad (22)$$

$$\left[\left(100 \times \frac{M - 0.1808 f_{cu} x_1 x_2^2}{0.00219 E_s (x_2 - d')}\right) \div \left(x_1 (x_2 + c)\right)\right] - 6 \leq 0 \quad (23)$$

Minimum and maximum total reinforcement ratio

$$0.13 - \left[\left(100 \times \frac{M - 0.0845 f_{cu} x_1 x_2^2}{0.000978 x_2 E_s} - \left(\frac{M - 0.1808 f_{cu} x_1 x_2^2}{0.00219 E_s (x_2 - c)}\right) \frac{(0.615 x_2 - c)}{(0.446 x_2)}\right) \div \left(x_1 (x_2 + c)\right)\right] \leq 0 \quad (24)$$

$$\left[\left(100 \times \frac{(M - 0.0845 f_{cu} x_1 x_2^2)}{0.000978 x_2 E_s} - \left(\frac{M - 0.1808 f_{cu} x_1 x_2^2}{0.00219 E_s (x_2 - c)}\right) \frac{(0.615 x_2 - c)}{(0.446 x_2)}\right) \div \left(x_1 (x_2 + c)\right)\right] - 6 \leq 0 \quad (25)$$

Deflection
Applied deflection,

$$\alpha = \frac{5wL^4}{384E_cI_{cr}}$$

$$\frac{5wl^4}{384E_cI_{cr}} - \frac{L}{250} \leq 0 \tag{26}$$

where

I_{cr} = Moment of inertia of cracked section is found using parallel axis theorem from the transformed section shown Fig. 3

w =Unfactored live load

$E_{c=}$ Elastic strength of concrete

I_{cr} =Moment of inertia of cracked section

L = Length of beam

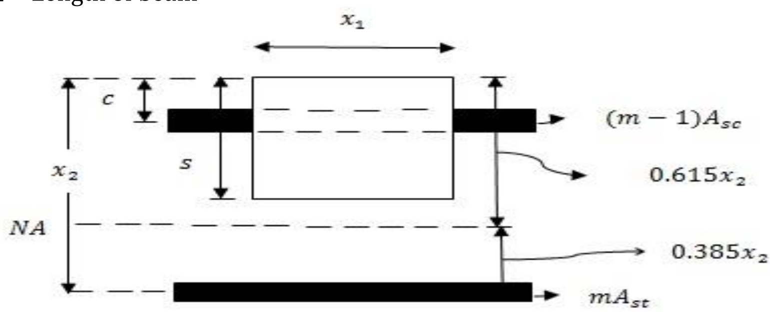

Fig. 3 Transformed concrete section

$$I_{cr} = \sum(I_i + A_id^2)$$

$$I_{cr} = (0.385x_2)^2 m\left[\frac{M - 0.0845f_{cu}x_1x_2^2}{0.000978x_2E_s} - \left(\frac{M - 0.1808f_{cu}x_1x_2^2}{0.00219E_s(x_2 - c)}\right)\frac{(0.615x_2 - c)}{(0.446c)}\right] + (m-1)(0.615x_2 - c)^2\left(\frac{M - 0.1808f_{cu}x_1x_2^2}{0.00219E_s(x_1 - c)}\right) + 0.0774x_1x_2^3$$

3. Results and Discussion

After the designs were done for both manual (BS8110) and optimum (Genetic algorithm), it was observed that the following were optimized:

- Beam width(x_1)
- Effective Depth (x_2)
- Reinforcement Ratio (ρ).

For this optimization, the following parameters were fixed

$f_{cu} = 30\text{N/mm}^2$

$f_y = 460\text{N/mm}^2$

$E_S = 200 \times 10^3 \text{ N/mm}^2$

$E_C = 26 \times 10^3 \text{ N/mm}^2$

$c = 50\text{mm}$

3.1 Singly Reinforced Concrete Beams

Table 1 shows a comparison of results obtained using the optimization model (with genetic algorithm) and those obtained using the traditional approach. It will be observed that the cross-sectional dimensions as well as the steel ratio for the beams are reduced when the optimization model is used even though the beams are subjected to the same moment. Fig. 4 shows a pictorial representation of the steel ratios. The steel ratios are reduced when the optimization model is used but are not directly proportional to the magnitude of the applied moment. This also applies to the beam cross-sections (the width and depth).

Table 1 The comparison between manual and optimization results for singly reinforced beam

Applied Moment(kNm)	**Traditional Approach**			**Optimization model**			**Difference in ρ (%)**
	x_1 (mm)	x_2 (mm)	ρ	x_1 (mm)	x_2 (mm)	ρ	
116	270	465	0.0051	250	450	0.0046	9.8
119	260	510	0.0058	250	500	0.0037	36.2
133	240	470	0.0072	230	450	0.0065	9.7
134	265	470	0.0053	250	450	0.0036	32.1
141	210	420	0.0075	200	400	0.0069	8
144	205	415	0.01	200	400	0.0098	2
151	265	460	0.0054	250	450	0.0032	40.7
163	260	510	0.0056	250	500	0.0036	35.2
166	240	465	0.005	230	450	0.0027	46
169	250	410	0.0079	230	400	0.0073	7.6

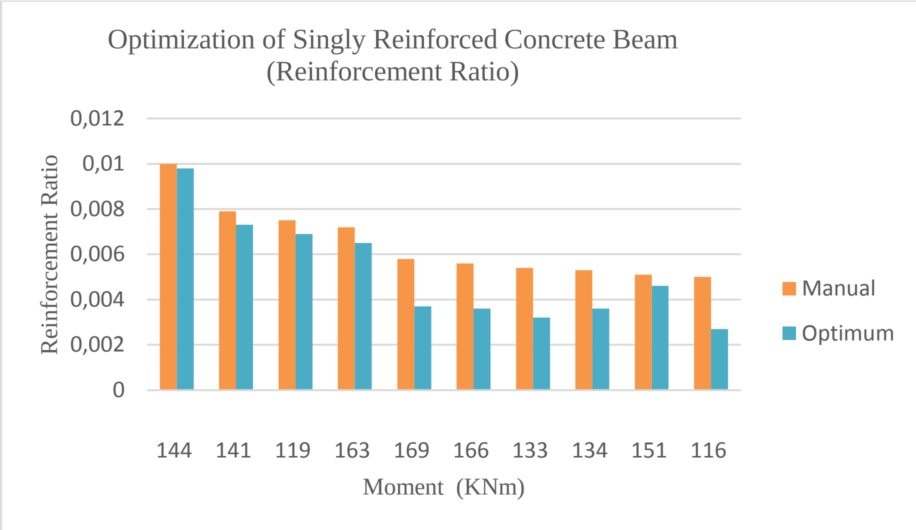

Fig. 4 The variation of the reinforcement ratios obtained using traditional and optimization approaches for considered moments (singly reinforced beam)

3.2 Doubly Reinforced Concrete Beams

A comparison was made between optimized and manual design and in each case, the optimized result was less than the manual result for reinforcement ratios as shown in Table 2 and Fig. 5

The length, elastic modulus of concrete (Ec), characteristic strength of concrete (fcu), width (x_1) and effective depth(x_2) of the beam were taken to be constant for both manual and optimized design and tried for random values of moment. The reinforcement ratios were found to be minimal with the optimization model with difference of up to 12.6% when compared with the manual (traditional) approach.

Table 2 The comparison between manual and optimization results for doubly reinforced beam

x_1 **(mm)**	x_2 **(mm)**	ρ **(manual)**	ρ **(optimization)**	**Difference in** ρ **(%)**
250	300	0.063	0.0569	9.7
230	300	0.0538	0.0488	9.3
250	350	0.0484	0.0434	10.3
250	400	0.0399	0.0356	10.7
250	450	0.0319	0.0282	11.6
250	450	0.0359	0.0319	11.14
200	400	0.035	0.031	11.42
230	450	0.0277	0.0243	12.27
250	400	0.0305	0.0268	12.13
250	450	0.0262	0.0229	12.6

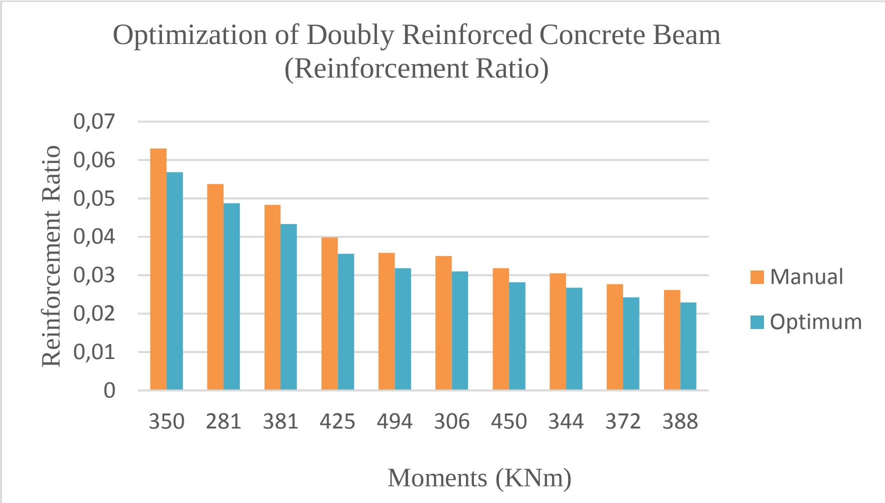

Fig. 5 The variation of the reinforcement ratios obtained using traditional and optimization approaches for considered moments (doubly reinforced beam)

4. Conclusion

The paper presents a design optimization model for simply supported reinforced concrete beams using Genetic Algorithm (GA) as an optimization tool. The model has proved to minimize the steel ratio for both singly and doubly reinforced concrete beams while satisfying design requirements of BS8110. Percentage difference in steel ratio as high as 46% and 12.6% for singly and doubly reinforced concrete beams respectively were obtained when the optimization model was compared with manual method in the design of reinforced concrete beams. By using the model, the cost of constructing simply supported beam is reduced significantly. However, the model can only be applied to simply supported rectangular reinforced concrete beams, other beam end conditions and shapes were not considered. The model is also almost ineffective in terms of minimizing the cross-sectional dimensions for doubly reinforced beams when compared to the traditional approach. It is only effective in minimizing the final reinforcement ratio. This indicates that only the area of reinforcement is minimized.

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