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# COST OPTIMIZATION OF REINFORCED CONCRETE ELEMENTS

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## ABSTRACT

A computer-based systematic approach for optimizing material cost in reinforced concrete elements is presented. This approach considers the current material cost in the trade-off and selection of member dimensions and reinforcement design of concrete elements such as beams and columns. The theoretical framework is to design reinforced concrete structure based on the cost of available materials and not just on the availability of materials. The windows-oriented computer program developed for this purpose would also be beneficial to owners, designers and contractors interested in cost optimization of reinforced concrete elements.

**Keywords:** cost optimization, reinforced concrete, reinforcement ratio



## BACKGROUND

Optimization in concrete design, as a main building material component, attracted attention of researchers and professional engineers. Literature on concrete design shows considerable efforts in the optimization of concrete constituents and mixture proportions [1], [2] and [3]. Early concrete design procedures, including the mixture proportions, were based on consecutive trials from which an acceptable design and composition were selected. The relationships established for optimization were mainly between the mix composition and the compressive strength, Ref. [2].

Although optimization methods are often applied in concrete design and mixture proportions, few of these methods consider the costs of both plain concrete and reinforcement as functions.

Cost optimization remains one of the major factors in construction projects. It is the responsibility of all members of the design-construction team to consider analytical procedures for optimizing cost. Maximum impact to be gained on cost is available at the earliest parts in the life-cycle of a project, Ref. [4]. A major area has a great contribution to achieve cost optimization is the reinforced concrete system; specifically during the design phase.

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Cost considerations are lacking in many of these processes. A high influence on cost can be achieved at the earliest parts in the life-cycle of a project, mainly the design phase. One aspect of controlling cost during design comes with introduction of the Design-To-Cost concept [5]. The basis of Design-To-Cost is to make design converge on cost, instead of the other way around. Design-To-Cost has drawbacks of extra time and cost of redesigning/re-bidding in the case of value engineering, and the compromise of quality in the case of Design-To-Cost. In Kuwait, no systematic procedure has been adopted for cost optimization in reinforced concrete design.

Most design offices do not advocate realistic estimate of material costs, even though all the specifications set forth by design codes are adequately incorporated. The practical applications of cost optimization in concrete design are still relatively rare, and they are usually carried out based on manual consecutive trials of design. Design offices have the difficult task of convincing their clients (owners) of the cost efficiency of their designs. Value engineering measures are beginning to be considered and carried out by major consultant offices for large public projects as an avenue for cost reduction, but these offices usually ignore the reinforced concrete systems of the facility under hand, Refs. [4 and 6].

Recent advancement and availability of cheap computing technology have provided powerful tools for analysis and design of concrete structures and computer model for optimization problems. Coupled with the extensive power of today's personal computers, the available design software are capable of efficiently performing rapid interactive graphics and databases operations in reinforced concrete design.

The advantages of computer technology have been incorporated in the optimization of concrete design and mixture proportions; most notably is the use of spreadsheets. Spreadsheets are user friendly and exceedingly powerful but are not being exploited as much as they could be in structural engineering design, Ref. [7]. Spreadsheets and intelligent databases are being used for mix designs, Refs. [8] and [9], and automation of concrete design, Refs. [1] and [10]. Other approaches used for reinforced design and mixture proportions such as object-oriented, Ref. [11], and constraint-based reasoning, Ref. [12], can use the powerful programming tools such as Visual Basic and C++.

A quick and accurate systematic optimization approach based on the function of cost in concrete design would reduce the cost of construction and enhance the design process. This research is concerned with developing a tool that considers the costs of reinforced concrete materials along with the specifications of the design codes. The tool would integrate the processes of reinforced concrete design, quantity take-off and cost estimating. A change in any of the parameters in one process would have its effects on the other parameters of the other processes. The suggested optimization approach could set the ground for further research in predicting optimal design dimensions, mixture proportions and structural designs and systems.

The end product is an easy to use window-oriented tool that is beneficial to owners, designers and contractors interested in reinforced concrete cost optimization.

## OBJECTIVE

The objective of this article is to present a computer-based systematic approach for optimizing materials cost in reinforced concrete elements.

## PROPOSED SYSTEM FOR REINFORCED CONCRETE ELEMENTS DESIGN AND COST OPTIMIZATION

The quantities of material for any structural system can be either computed on the past records of completed buildings or alternatively from first principles by analysis, design and computation of quantities, Ref. [13]. The accuracy in the case of the first method depends on whether the various structural components of completed buildings were designed using methods being adapted to present. The proposed system is dependant on the second method. This is especially with the availability of the advanced computer systems that can carry out the design process easily such as STAADIII©. In addition, the proposed system considers the updated material costs in the trade-off and selection of member dimensions and reinforcement design of concrete elements such as isolated footings, beams, columns and slabs. The theoretical framework is to design reinforced concrete elements based on the cost of available materials and not just on the availability of materials, Figure 1.

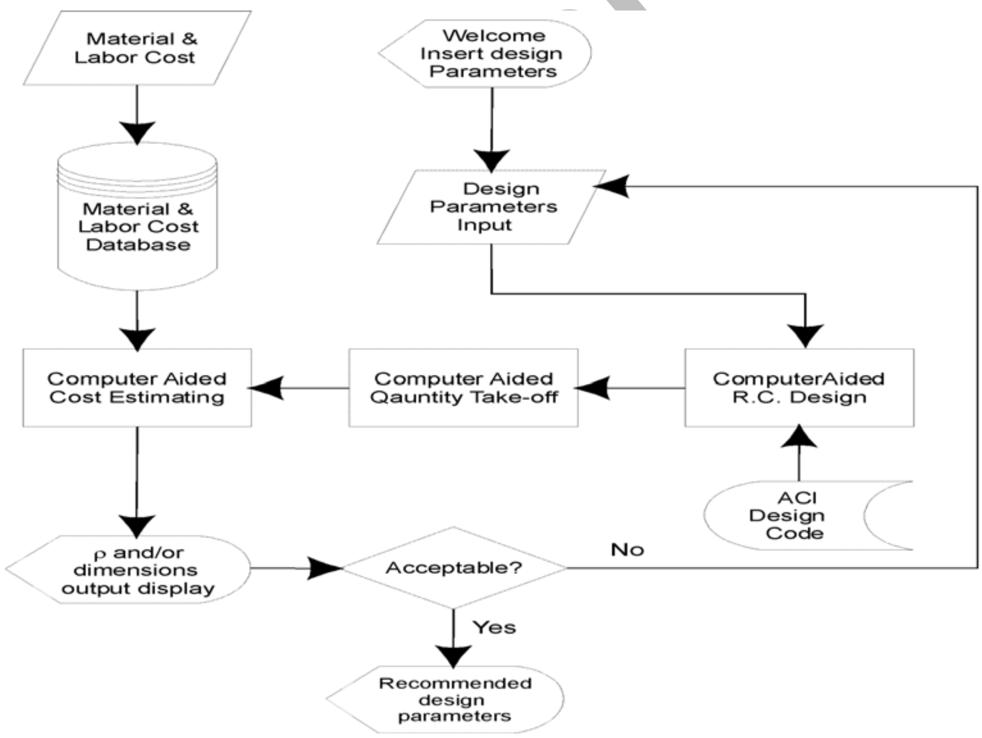


Figure 1. Diagram of the proposed systematic for cost optimization in reinforced concrete design

## RESEARCH METHODOLOGY

The methodology of this research consists of five sequential stages as follows:

*Literature review*
Establish the concepts of reinforced concrete and its current design applications specified in the ACI Building code [14]. Then, the relevant equations, parameters and methods of calculation for the reinforced concrete systems are established. This study is focusing on the two structural elements, namely columns and beams, to demonstrate the approach of the proposed system.

*Cost data*
Conduct a study of the materials cost of reinforced concrete for the past two years, and establish change indicators for these costs. This would require cost data collection from previous projects (from Kuwait as a practical example), current projects and reinforced concrete materials suppliers. The collected data will be developed in a database to be used for cost references.

*Cost Parameters*
Define the parameters in the reinforced concrete design process that affect the cost of materials. This would include the dimensions (X, Y, Z) of the different reinforced concrete elements, the area of reinforcements and $\rho$ limit values, and the different types of concrete and reinforcement available in the market.

*Design phase*
The design phase utilizes the automatic calculations and programming powers of the spreadsheet environment with its Macros capabilities. The design phase consists of four stages as follows:

i. Structural design computer program. This compute-aided design program incorporates the reinforced concrete design procedures and equations as per the ACI code. It automates the design process for accuracy and speed purposes.
ii. Quantity take-off computer program. This program measures the total quantities of the reinforced concrete systems on the basis and their units of measure through given set of dimensions and number of elements (inputs).
iii. Cost estimating computer program. The program uses the cost data from the material cost database and the quantity take-off system to estimate total cost of materials.
iv. Cost optimization support system. The three programs of reinforced concrete design, quantity take-off and cost estimating, are integrated into a single system that would provide different costs for different reinforced concrete designs.

*Validation and Implementation*
The functionality of the cost optimization support system is then tested in an iterative mode to ensure reliability prior to final implementation. Upon successful testing, parametric cost studies are conducted to determine the relationship between the structural element dimensions and their costs.

## ANALYSIS AND RESULTS

The cost of reinforced concrete consists of two main elements, which includes the concrete cost and the reinforcement cost. A design process aims to determine the values of concrete element dimensions and steel area in addition to the steel ratio $\rho$. Recommended steel ratio $\rho$ is that ensures the minimum total cost. This section describes the calculation steps to obtain the recommended steel ratio $\rho$ and then a sensitivity analysis is introduced to demonstrate the system range of applicability.

## CALCULATION STEPS

1. Suppose the concrete structure element is exposed to external forces.
2. Use STAAD III to design the safe cross sections with variable sections elements (b-section breadth, d-depth of the concrete cross section and steel ratio $\rho$). All the designed sections will be safe under the supposed external forces based on ACI code.
3. Calculate the required concrete and steel quantities using spread sheet (Microsoft Excel).
4. Calculate the cost of concrete and steel using the recent available database for construction material costs.

A sample of the summarized calculations for getting the minimum cost for a beam exposed to external bending moment of 300 kN.m is presented in Table 1. All the eight sections are safe based on $f'_c$= 25MPa and $f_y$ = 400 MPa. The calculation of total cost is the summation of longitudinal steel bars cost and ready mix concrete for 100 meters of beam lengths of prismatic section. Section number 2 has the least total cost which means that section of 300mm breadth and 700 mm in depth is the optimum section for this external bending moment of 300 kN.m.

Table 1. Sample of spread sheet calculation for beams

| No. | Moment (kN.m) | B (mm) | H (mm) | Ac ($m^2$) | $\rho$ | As ($mm^2$) | Conc. Qty ($M^3$) | Steel Qty (Kg) | Conc. unit Price (KD/$m^3$) | Steel unit Price (KD/kg) | Conc. Cost (KD) | Steel Cost (KD) | Total Cost (KD) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 300 | 600 | 300 | 0.18 | 0.04 | 5853 | 18 | 4595 | 18 | 0.1 | 324 | 459.5 | 783.5 |
| 2 | 300 | 700 | 300 | 0.21 | 0.03 | 4856 | 21 | 3812 | 18 | 0.1 | 378 | 381.2 | 759.2 |
| 3 | 300 | 800 | 300 | 0.24 | 0.02 | 4498 | 24 | 3531 | 18 | 0.1 | 432 | 353.1 | 785.1 |
| 4 | 300 | 900 | 300 | 0.27 | 0.02 | 4293 | 27 | 3370 | 18 | 0.1 | 486 | 337.0 | 823.0 |
| 5 | 300 | 1000 | 300 | 0.3 | 0.02 | 4157 | 30 | 3263 | 18 | 0.1 | 540 | 326.3 | 866.3 |
| 6 | 300 | 1100 | 300 | 0.33 | 0.02 | 4059 | 33 | 3186 | 18 | 0.1 | 594 | 318.6 | 912.6 |
| 7 | 300 | 1200 | 300 | 0.36 | 0.01 | 3984 | 36 | 3128 | 18 | 0.1 | 648 | 312.8 | 960.8 |
| 8 | 300 | 1300 | 300 | 0.39 | 0.013 | 3898 | 39 | 3060 | 18 | 0.1 | 702 | 306.0 | 1008. |

## RECOMMENDED STEEL RATIO FOR COLUMN

Column concrete section is tested under four different compressive loads varying from 1500 kN to 3750 kN, which are common in residential (not high rise) buildings. Different safe cross section can be obtained from STAAD III, for example different combinations of b, d, $\rho$ can safely resist a 1500 kN compressive force.

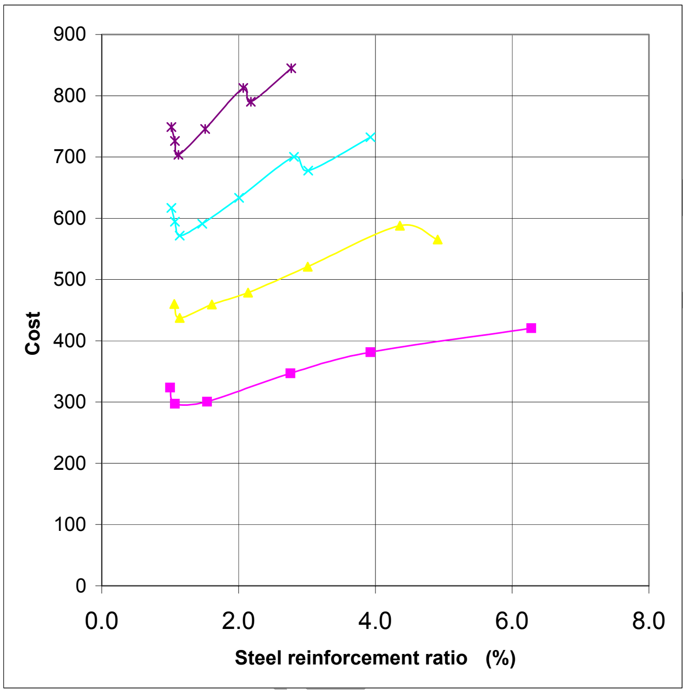


Figure 2. Depicts the relationship between the steel ratio and the total cost of concrete section

Figure (2) Relationship Between Steel Ratio % and Total Cost for Columns Subjected to Different Compressive Loads

The steel ratio that ascertains the minimum cost for all sections is about 1.2 % of the concrete cross section (average steel ration is 1.216, min, 1.07, max 1.61).

The trend at different levels is similar, where the total cost of the element increases with increasing steel ratio. This trend is caused by the fact that the cost of steel is higher than that of concrete.

## SENSITIVITY ANALYSIS FOR COLUMNS

A sensitivity analysis is performed to assess the impact of variation in the cost of the concrete and steel. In Figure 3, the range of steel and concrete cost varies between + 30% to

–30% from the initial estimate cost. It is noticed in general that there is no remarked impact of changes of steel and concrete cost on the recommended steel ratio ρ.

The steel recommended steel ratio for compressive load 1500 kN were increased to be 1.58 instead of 1.1 if the concrete cost increased by 20% and 30%. This can be due to the percentage of cost contribution to the total cost in small compressive loads.

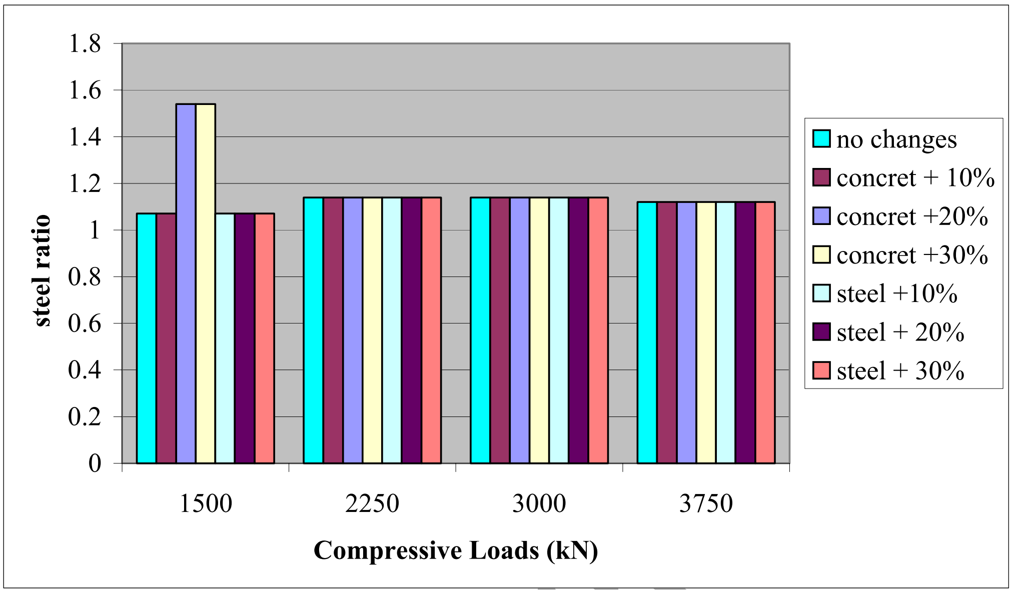


Figure 3. Changes in original cost estimate

## RECOMMENDED STEEL RATIO FOR BEAMS

Four bending moments of 300, 500, 700 and 900 kN.m were chosen as external forces to check which of the safe sections will ascertain the minimum cost. The range of moments from 300 kN.m to 900 kN.m is representing the range of forces that most of residential building beams can expose to. The beam sections that can be safe under each of these external forces were calculated. Beam breadths ranged from 200 to 900 mm.

The total cost was calculated for varied cases of moment, breadth, steel ratio ρ and depth. Figures (4 to 7) show the relationship between total cost of the cross section and the steel ratio ρ. The figures show a similar trend for all sections that total cost is high for small values of steel ratio, and then decreases to the minimum at the recommended steel ratio, and then increases again.

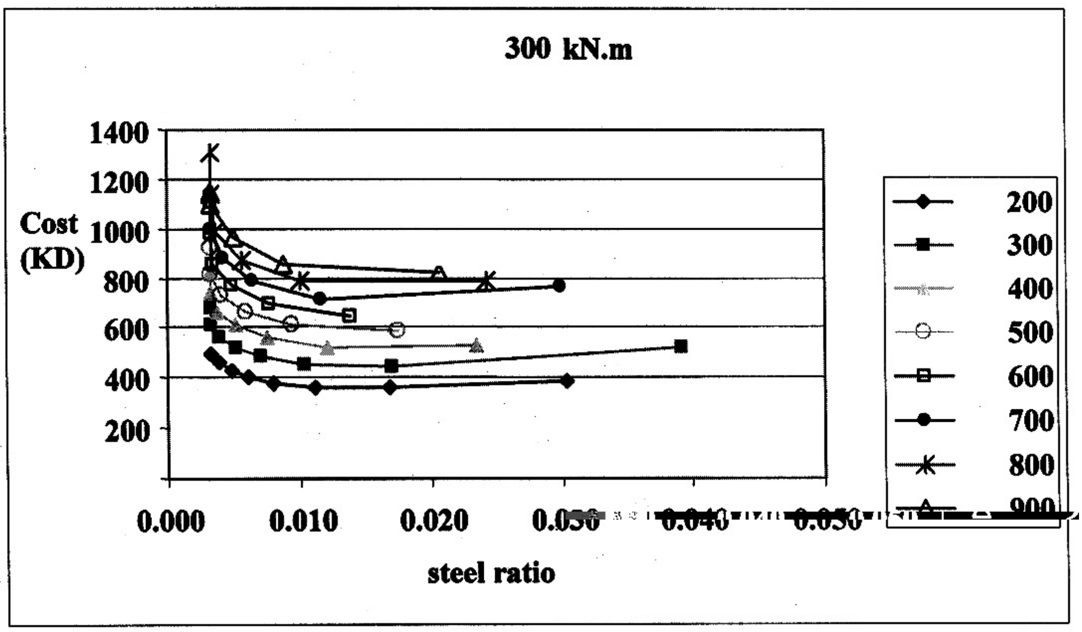


Figure 4. Total costs for different breadths for beam cross sections exposed to 300 kN.m the minimum total cost for each checked moment is represented in Table (2).

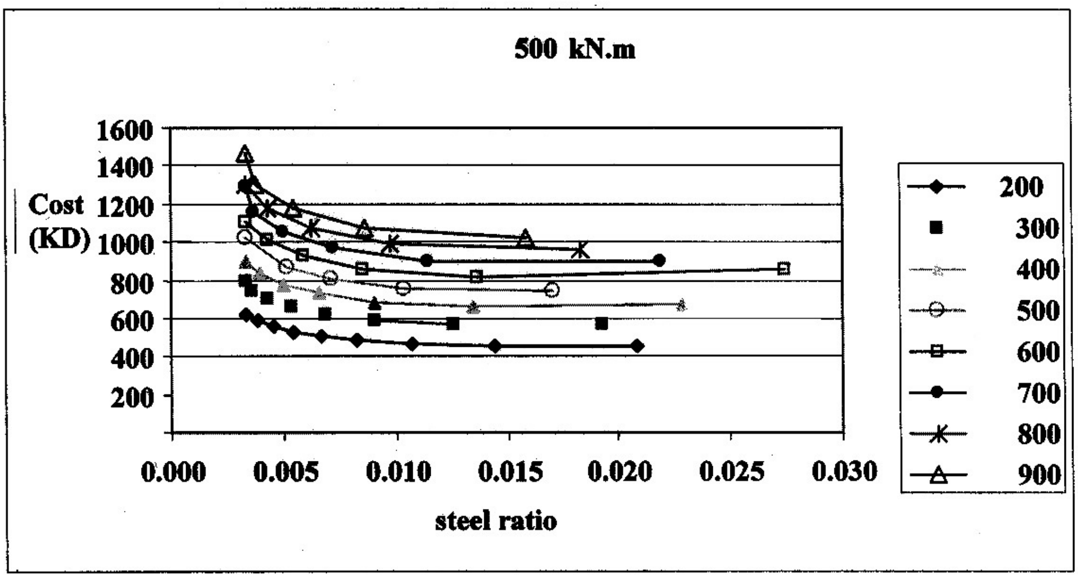


Figure 5. Total costs for different breadths for cross sections exposed to 500 kN.m

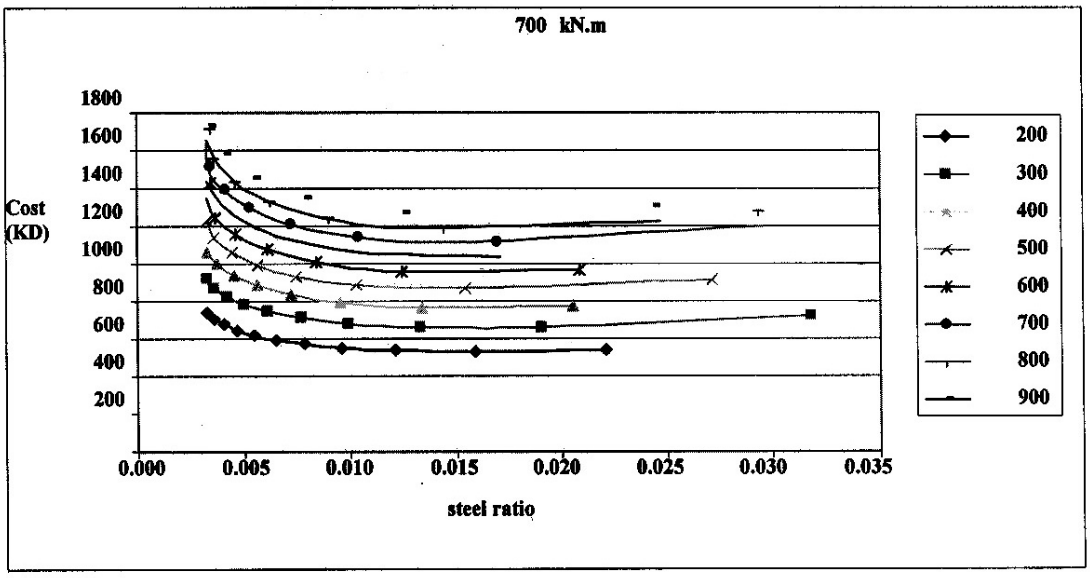


Figure 6. Total costs for different breadths for cross sections exposed to 700 kN.m

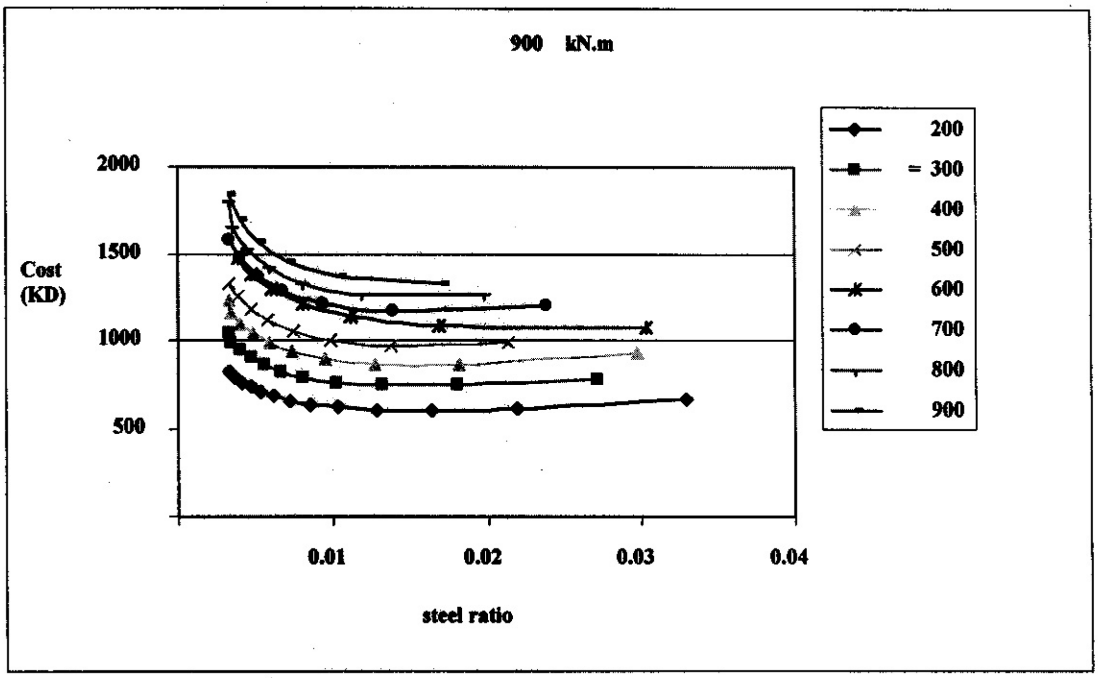


Figure 7. Total costs for different breadths for cross sections exposed to 900 kN.m

The Average recommended ρ from all sections that can establish the optimum cost is 0.01535; maximum recommended is 0.02056 and the minimum is 0.01. In other words the recommended ρ range from 0.01 to 0.02.

Table 2 represents the recommended design criteria. Designers can use this table to establish the optimum beam cross section that can achieve the minimum cost for each external load. The designer may choose another section to match with architecture or any other requirements, it can use another section and determine the percentage of cost increase due to minimum cost by using figures such as Figure 8 for moment 900 MN.

The recommended value for ρ may be sensitive for the current cost of steel and concrete, so sensitivity analysis was conducted to test the effect of changes of these estimate values.

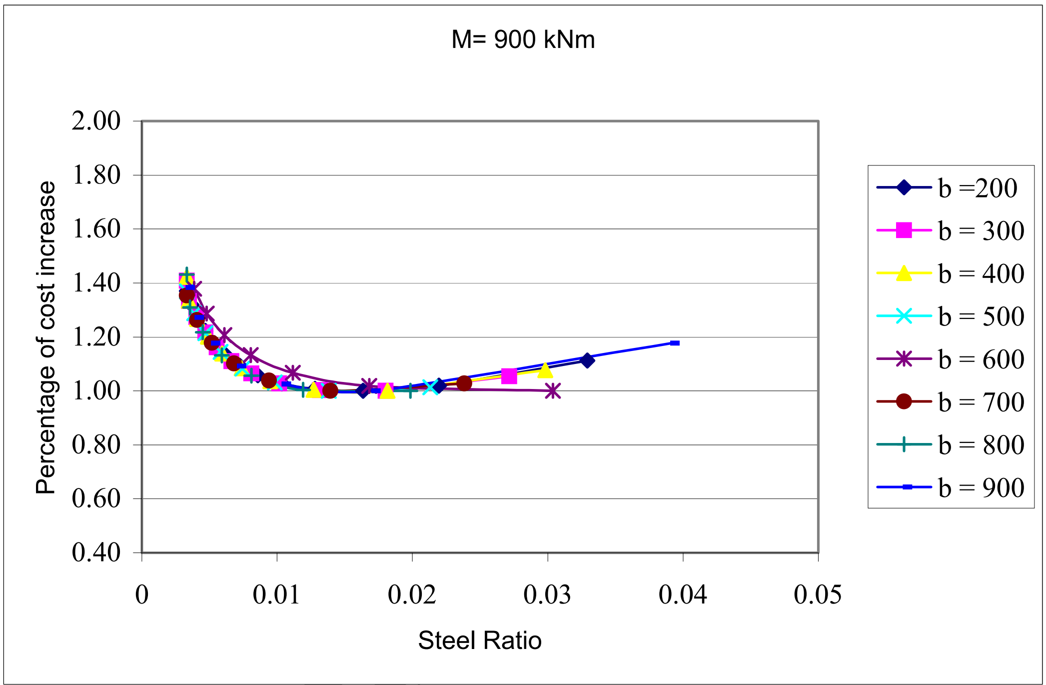


Figure 8. Percentage of total cost increase over the optimum cost

## SENSITIVITY ANALYSIS FOR BEAMS

The total cost is recalculated due to changes in the estimate cost of steel and concrete by-30% to +30%.

As shown in Figure 9, there is no impact for changing steel and concrete cost if the inflation affects the cost of both materials by the same percentage.

If the steel cost changed and the cost of concrete does not change, the average recommended steel ratio $\rho$ is between 0.012 to 0.0198, while, if the concrete and steel costs change in opposite directions, the average recommended steel ratio $\rho$ will be between 0.0129 to 0.0185.

The recommended steel ratio is averaged between 0.01 and 0.02 in all cases.

Table 2. Recommended design criteria for external bending moment

| Moment (kN.m) | Beam breadth (mm) | Beam Height (mm) | Steel Ratio (ρ) |
|---|---|---|---|
| 300 | 200 | 600 | 0.01682 |
| | 300 | 500 | 0.01705 |
| | 400 | 500 | 0.01207 |
| | 500 | 400 | 0.01739 |
| | 600 | 400 | 0.01391 |
| | 700 | 400 | 0.01162 |
| | 800 | 400 | 0.00999 |
| | 900 | 300 | 0.02056 |
| 500 | 200 | 800 | 0.01439 |
| | 300 | 600 | 0.01924 |
| | 400 | 600 | 0.01348 |
| | 500 | 500 | 0.01705 |
| | 600 | 500 | 0.01366 |
| | 700 | 500 | 0.01141 |
| | 800 | 400 | 0.01832 |
| | 900 | 400 | 0.0158 |
| 700 | 200 | 900 | 0.01586 |
| | 300 | 800 | 0.01326 |
| | 400 | 700 | 0.01335 |
| | 500 | 600 | 0.01544 |
| | 600 | 600 | 0.01243 |
| | 700 | 500 | 0.01705 |
| | 800 | 500 | 0.01447 |
| | 900 | 500 | 0.01259 |
| 900 | 200 | 1000 | 0.01635 |
| | 300 | 800 | 0.01802 |
| | 400 | 700 | 0.01816 |
| | 500 | 700 | 0.01381 |
| | 600 | 600 | 0.01682 |
| | 700 | 600 | 0.01394 |
| | 800 | 500 | 0.01984 |
| | 900 | 500 | 0.01705 |

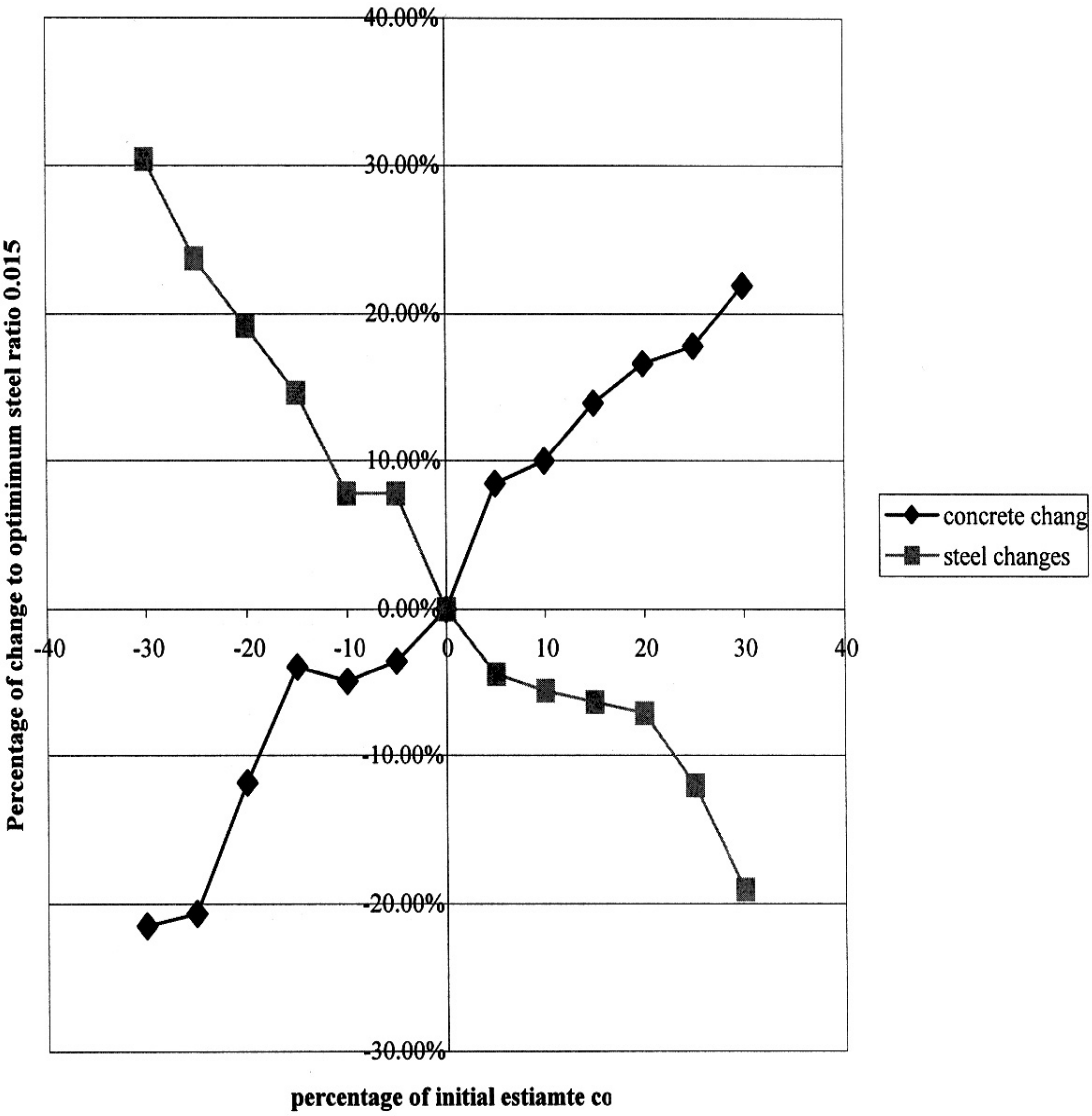


Figure 9. Sensitivity analysis for steel ratio ρ

## CONCLUSIONS

Cost indicators are important during the design phase to minimize the construction cost. Excellent designers must have the capacity for organization and management to conduct the process of design so that it includes cost consideration during the design process. This research presented a model for cost optimization of reinforced concrete design. The focus has been on the reinforced concrete elements since they represent about one third of the total cost of the constructed facility.

Implementation of the suggested reinforced concrete cost optimization model for material cost data obtain from Kuwait's market resulted in the following steel ratio recommendations:

Recommended steel ratio ρ for column design is 1.216 % of the concrete cross section.

Recommended steel ratio ρ for beam design is about 0.015% of the concrete cross section.

The above design recommendations will vary with any changes in the cost of reinforced concrete materials. The developed system is updated with most recent market cost of reinforced concrete materials; thus ensuring valid, meaningful and up-to-date results of design recommended ratios.

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## REFERENCES

1. Balling and Richard, J., How to optimize reinforced concrete systems. *Proceedings of the Symposium on Structural Engineering in Natural Hazards Mitigation.* ASCE (1993), Irvine, CA, USA.
2. Brandt, A. M. Optimization Methods for Material Design of Cement-Based Composites. *Modern Concrete Technology 7.* E& FN SPON, (an imprint of Rout ledge), USA, 1998.
3. Mather, K. and Rashwan, Sh., Model for ready-mix concrete optimization, *Proceedings of the 1997 Annual Canadian Society for Civil Engineering.* Part 2, Canada, 1997.
4. Young III and James, A. Design phase cost control. Transactions of American Association of Cost Engineers, Morgantown. ISSN: 10747397 (1997) Page 24-27.
5. Vitaliano, Wm. J. Three design-to-cost myths. *SAVE Annual Proceeding. New Orleans.* USA, 1994.
6. Kwakye, A. A *Construction Project Administration in Practice*. (Addison Wesley Longman), USA, 1997.
7. Goodchild, C. H. and Lupton, J. (1999) Spreadsheets and the structural engineer. *The Structural Engineer*, 77(1999)326-334.
8. de Larrard, F. and Sedran, T. Computer-Aided Mix Design: Predicting Final Results *The Magazine of the American Concrete Institute* **18(**1996)178-186.
9. Ganju, T. N. Spread sheeting Mix Designs. *The Magazine of the American Concrete Institute* **18**(1996)187-198.
10. Walden, N. Lee and Wilkerson, Steve. Automation of Concrete Design. *The Magazine of the American Concrete Institute*. **18**(1996)148-156.
11. Kulkarni, A. B. and Rojiani, K. B. Object-oriented approach for reinforced concrete design. *Proceedings of the 1st Congress on Computing in Civil Engineering.* Part 1 of 2. ASCE., pp. 161-168. New York, USA, 1994.

12. Lucas, W. K.; Roddis, W.M. Kim. Constraint-based reasoning for optimal concrete design and detailing. *Proceedings of the 12th Conference on Analysis and Computation.* ASCE, pp. 154-165, New York, USA, 1996.
13. Singh, S., Cost Model for approximate cost estimation of structure systems in commercial high rise buildings, thesis submitted to the National University of Singapore, un fulfillment of the requirements for the degree of Doctor of Philosophy, Singapore, 1986.
14. ACI, 318/98, Code of the American Concrete Institute. Detroit: American Concrete Institute, USA, 1999.