

Economical Simply Supported Reinforced Concrete Rectangular Beam Design Using STAAD Pro

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ABSTRACT: This study aims to minimize the cost of simply supported reinforced concrete(RC) rectangular beam and approach the economical beam design which has total cost close to lowest value for that beam, with a standard beam cross section. The total cost of beam includes cost of concrete, reinforcement, and formwork, whereas the stirrups cost incorporated in the reinforcement cost. The design variables considered in this study are the loading, width of beam, height to width ratio, length of beam, compressive strength of concrete, unit cost of concrete and unit cost of formwork. STAAD Pro which is one of widespread engineering software for structural analysis and design has been used to design the beams for moment and shear. All calculations are done based on elastic analysis and the ultimate strength method of design as per ACI 318M-14 code requirements.

The results of economical beams total costs database indicate that the average cost ratio of concrete, reinforcement and formwork to total cost are 32%, 32% and 36% respectively, whereas stirrups cost constitutes 9% of the total cost. Economical beam design can be attained from several iterations in total cost calculations, and more attempts for section dimensions of the beam provide more economical beam design. Numerical equations for the economical beam design have been developed and can be used swiftly to estimate the beam width and height without prior understanding of optimization.

KEYWORDS: Economical Beam, Cost, Simply Supported Beam, Reinforced Concrete, Design for Moment and Shear, STAAD Pro

NOTATIONS

A_f	= area of formwork, m ²
A_v	= minimum area of shear reinforcement, mm ²
b	= width of beam, mm
b_w	= web width, mm
C_c	= cost of concrete, US\$
C_f	= cost of formwork, US\$
C_s	= cost of steel reinforcement, US\$
C_t	= total cost of the beam, US\$
c_t	= total cost per unit length of the beam, US\$/m
F	= moment factor
f'_c	= specified compressive strength of concrete, MPa
f_y	= specified yield strength of reinforcement, MPa

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f_{yt}	=specified yield strength of transverse reinforcement, MPa
h	= height of beam (total depth), mm
l	= span length of beam, m
M_e	= external ultimate bending moment, kN.m
M_u	= ultimate bending moment, kN.m
RC	= Reinforced Concrete
s	=spacing of stirrups, mm
S_c	= complete section modulus (bh^2), mm^3
U_c	= unit cost of concrete, $\text{US\$/m}^3$
U_f	= unit cost of formwork, $\text{US\$/m}^2$
U_s	= unit cost of steel reinforcement, $\text{US\$/kg}$
V_c	= nominal shear strength of concrete, N
V_{co}	= volume of concrete, m^3
V_s	= nominal shear strength of shear reinforcement, N
V_u	= ultimate shear strength, N
W_s	= weight of steel reinforcement, kg
W_{ls}	= weight of longitudinal steel reinforcement, kg
W_{ts}	= weight of transverse steel reinforcement (stirrups), kg
w_d	= unfactored dead load per unit length of the beam, kN/m
w_l	= unfactored live load per unit length of the beam, kN/m
ϕ	=strength reduction factor, which is equal 0.90 for bending with tension controlled or equal 0.75 for shear
ρ	=ratio of A_{st} to bd
ρ_w	=ratio of A_{st} to $b_w d$
ϵ_c	= maximum usable strain at extreme concrete compression fiber
ϵ_s	= net tensile strain in extreme layer of longitudinal tension reinforcement at nominal strength

I. INTRODUCTION

Economy plays an important role in the chosen of reinforced concrete (RC) for construction of buildings and other projects [1]. Through the last few decades there is emphasis on the *economy and aesthetics* of structural design, so that to ensure the cost of the structure may not be exorbitant and far from aesthetics [2]. *Cost indicators are important during the design phase to minimize the construction cost*, as the RC elements represent about one third of the total cost of the construction [3].

Optimal sizing and reinforcing for beam and column members in RC structures results in cost savings over typical-practice design solutions[4].

As noted in the earlier literature, the structural design should satisfy the design codes requirements, and the optimum design is an iterative technique and economic design[5]. Different studies have been study the optimum design of RC beams using different mathematical software programs[4, 5, 6, 7, 8, 9, 10, 11...etc].

The economical beam design can be obtained for shorter beams (up to 25 ft or around 7.5 m) when the ratio d/b is in the range of 1.5 to 2. For longer beams, better economy is usually found if *deep, narrow sections* are used with d/b in the range of 3 to 4[12].

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For different spans of singly RC beams in the range of 4 m to 32 m, uniformly distributed live load of 25 kN/m, steel reinforcement of grade M60 and different grades of concrete, there is small change in the cost when the d/b is 1.5 to 2.5, but the ratio of 2.5 gives the most economical beam design[11].

It is recommended to use beams with h/b in the range of 1.5 to 2 [2, 13]. It may be higher (up to 3 or even more) for beams subjected to heavy loads. Increasing the height of the beam is always useful to improve moment resisting capacity, flexural stiffness, and hence, less deflections, curvatures and crack-widths[2].

Increasing the concrete section of the beam may save the steel and the beam will be more economical and would be preferred, except beam section dimensions must be minimized for architectural or functional reasons[14].

Steel is quite expensive [12], and using over-reinforcing will lead to uneconomical beam design[15]. For economical beam design, the reinforcement ratios will typically vary between 50% ρ_{max} and 75% ρ_{max} [14], whereas these ratios vary between 50% ρ_{max} and 67% ρ_{max} [16], so that to keep the concrete strain at or above the tension-controlled limit of 0.005. For optimum cost of beams subjected to external bending moment of 300, 500, 700 and 900 kN.m, $f'_c = 25$ MPa and $f_y = 400$ MPa, the recommended reinforcement ratio was found in the range of 0.01 to 0.02 with an average of 0.015. The study used STAAD III software and Excel spread sheet to calculate the total cost of beams including concrete unit price and steel unit price[3].

Formwork constitutes about 40% [17], and can be as high as 60% of total cost of a cast-in place concrete structure. For this reason it is important to create a structural system that will minimize the cost of formwork, and it is essential that costs of formwork to be included in the cost evaluation of concrete structural frames. [18].

Formwork cost can be reduced through reusing the same forms from area to area and floor to floor. It is usually uneconomical to use least amount of concrete and steel by *exactly calculating the size of every beam and column* to fit the loads exactly. Furthermore, changing section sizes often leads to increased design complexity and consequently error through construction. Economic structure can be achieved by adopting the design requirements and saving the time of design and construction [16].

Economical beam design should be based on cost of the beam rather than its weight optimization [5, 19, 20], as the weight constitutes a significant part of the cost [21]. Also, the unit costs of concrete, steel, and formwork play a significant role in determining of the *optimum beam and column section dimensions*[22].

The beams *database* [23] were studied using different unit costs of concrete, steel and formwork of 105 \$/m³, 0.9 \$/kg and 92 \$/m² respectively *to make the total cost component the minimum* based on two meta-heuristic algorithms using Matlab software [24].

Also, beams *database* were studied using different unit costs of concrete, steel and formwork of 100 \$/m³, 1 \$/kg and 25 \$/m² respectively in the first case, 110 \$/m³, 2.1 \$/kg and 27 \$/m², respectively in the second case to minimize the beam total cost based on the harmony search algorithm using Fortran programming language [22].

As the optimum section will not necessarily provide an optimum design for the entire structure [5, 25], and using uniform width and depth of beams throughout the frame [16] or may be through the building [18] has been recommended for economy, this study has been performed in order to minimize the cost of simply supported RC rectangular beam and approach swiftly the economical beam design without prior understanding of optimization by using a wide range of unit costs of concrete and formwork.

STAAD Pro software [26] and EXCEL spreadsheet [12] have been used for the calculations based on the elastic analysis and the ultimate strength method of design as per ACI 318M-14 code requirements for moment and shear [27]. STAAD Pro software is one of the popular and widespread structural software program [28], very easy to learn and work, accurate for both analysis and design *practically all types of structures*, more preferred because of its flexibility and ease of workability used to find the shear forces, bending moments, deflections and reinforcement details for the

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structural components of building (such as beams, columns & slabs) to develop the economic design [29]. StAAD Pro software has been used to determine iteratively [30] the total cost of different simply supported RC rectangular beams.

II. SCOPE AND METHODOLOGY

A. OBJECTIVE

This study aims to minimize the cost of simply supported RC rectangular beam and approach the economical beam design which has total cost per unit length of the beam [20, 31] close to lowest value for that beam, with a standard beam cross section and without prior understanding of optimization.

The total cost of beam includes cost of concrete, reinforcement, and formwork, whereas the stirrups cost incorporated in the reinforcement cost. Total cost of beam includes material, labor and equipment costs of concrete, reinforcement, formwork, overhead and profit [4, 7]. The total cost per unit length can be calculated by the following equations,

$$C_t = C_c + C_s + C_f(1a)$$

$$C_t = V_{co} \cdot U_c + W_s \cdot U_s + A_f \cdot U_f(1b)$$

$$C_t = (b \cdot h \cdot l) U_c + (W_{ls} + W_{rs}) U_s + l(b+2h) U_f(1c)$$

$$c_t = C_t / l(1d)$$

B. FORMULATION OF THE PROBLEM

B.1 SOLUTION PROCEDURE

Both longitudinal and transverse reinforcement (stirrups) of each beam can be found by using STAAD Pro structural software in design the beams. All calculations are done based on elastic analysis and the ultimate strength method of design as per ACI 318M-14 code requirements for moment and shear.

B.2 DESIGN VARIABLES

The various variables considered in this study are the loadings (w_d and w_l), width of beam (b), height to width ratio (h/b), length of beam (l), compressive strength of concrete (f'_c), unit cost of concrete (U_c) and unit cost of formwork (U_f).

B.3 DESIGN FOR MOMENT

The ACI code provides two factors of safety, one is called the load factors and equal to 1.2 and 1.6 for dead and live load respectively, and the other is called the strength reduction factor (ϕ). The strength reduction factor (ϕ) varies from 0.90 to 0.65. Applying the conditions of equilibrium and compatibility of strains with maximum concrete compressive strain at crushing of the concrete equal to ($\epsilon_c = 0.003$) and other assumptions of the code for tension controlled beams where the strength reduction factor (ϕ) is equal 0.90 [14, 30],

$$a = \frac{A_s f_y}{0.85 f'_c b} (2)$$

$$M_u = 0.9 A_s f_y \left(d - \frac{a}{2} \right) (3)$$

The limitation of the area of tension reinforcement (A_s) for the maximum reinforcement ratio and the minimum reinforcement ratio is given by:

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$$\rho_{max}(\epsilon_s=0.005) = 0.31875\beta l \frac{f'_c}{f_y} \quad (4)$$

$$\rho_{min} = \frac{0.25\sqrt{f'_c}}{f_y} \geq \frac{1.4}{f_y} \quad (5)$$

where βl is equal to 0.85 for f'_c up to and including 28 MPa and 0.05 less for each 7 MPa of strength in excess of 28 MPa, but βl shall not be taken less than 0.65. Also, the strains of concrete and steel are ($\epsilon_c = 0.003$) and ($\epsilon_s = 0.005$) respectively.

For f'_c equals 21, 24 and 28 MPa and f_y equals 420 MPa which are widely used and studied in the following numerical examples, the tension reinforcement ratio (ρ) should satisfy the following constraints for the maximum reinforcement ratio and the minimum reinforcement ratio [12, 32]:

$$0.0033 \leq \rho \leq 0.0135 \quad \text{for } f'_c \text{ equals 21 MPa (6a)}$$

$$0.0033 \leq \rho \leq 0.0155 \quad \text{for } f'_c \text{ equals 24 MPa (6b)}$$

$$0.0033 \leq \rho \leq 0.0181 \quad \text{for } f'_c \text{ equals 28 MPa (6c)}$$

where ρ is equal to:

$$\rho = \frac{A_s}{bd} \quad (7)$$

B.4 DESIGN FOR SHEAR

The ACI code provides larger safety factor (ϕ) against shear failure than that provided for bending to have ductile members with warning of sudden failure [12].

The ultimate shear strength (V_u) is consisting of shear strength of concrete (ϕV_c) and shear strength of shear reinforcement (ϕV_s):

$$V_u = \phi V_c + \phi V_s \quad (8)$$

The ACI code provides the following requirements in the Eqs. (9) through (13) for shear design :

The concrete shear force (V_c) shall be calculated by:

$$V_c = 0.17\sqrt{f'_c} b_w d \quad (9)$$

For more detailed calculation, the least of following equations can be taken to calculate the shear strength of concrete (V_c) for normal weight of concrete:

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$$V_c = (0.16\sqrt{f'_c} + 17\rho_w \frac{V_u d}{M_u}) b_w d \quad (10.a)$$

$$V_c = (0.16\sqrt{f'_c} + 17\rho_w) b_w d \quad (10.b)$$

$$V_c = 0.29\sqrt{f'_c} b_w d \quad (10.c)$$

The minimum area of shear reinforcement ($A_{v,min}$) shall be provided using stirrups in all regions where:

$$V_u > 0.5 \phi V_c \quad (11)$$

To avoid brittle failure [33], the ACI code stipulates the minimum area of shear reinforcement ($A_{v,min}$) shall be satisfied the greater of:

$$A_{v,min} = 0.062\sqrt{f'_c} \frac{b_w s}{f_{yt}} \quad (12.a)$$

$$A_{v,min} = 0.35 \frac{b_w s}{f_{yt}} \quad (12.b)$$

Also, the ACI code stipulates the maximum spacing of stirrups (s) shall be :

$$\text{For } V_s \leq 0.33\sqrt{f'_c} b_w d, \text{ the least of } d/2 \text{ nor } 600 \text{ mm} \quad (13.a)$$

$$\text{For } V_s \geq 0.33\sqrt{f'_c} b_w d, \text{ the least of } d/4 \text{ nor } 300 \text{ mm} \quad (13.b)$$

Whereas, the theoretical spacing of stirrups (s) can be calculated by the following equation [12]:

$$\text{Theoretical } s = \frac{A_v f_{yt} d}{V_s} \quad (14)$$

III. NUMERICAL EXAMPLES

A. SELECTION OF BEAMS

A series of 2880 beams database with different variables are selected to investigate the simply supported RC rectangular beam total cost per unit length and approach the economical beam design. Various variables are deemed in this study as shown in Table (1).

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Table (1) – Range of variables

Type	Values			Number	Remarks
	Min.	Between Min. & Max.	Max.		
w_d , kN/m	10	20, 25, 30	40	12	Two uniform loadings are applied each case as shown in Table 2
w_l , kN/m	10	20, 25, 30	40		
b , mm	200	250, 300, 350, 400	450		
h/b ratio	1.5	2, 2.5, 3, 3.5	4		
l , m	3	4.5, 6, 7.5	9	5	Shorter and longer beams
f_c' , N/mm ²	21	24	28	3	Normal strength concretes [12]
Unit cost of concrete (U_c), US\$/m ³	80	100, 120	140	4	Unit cost for concrete of $f_c' = 21$ N/mm ²
	90	110, 130	150		Unit cost for concrete of $f_c' = 24$ N/mm ²
	100	120, 140	160		Unit cost for concrete of $f_c' = 28$ N/mm ²
Unit cost of formwork (U_f), US\$/m ²	5	10, 20	30	4	
Total number of var. (beams) = 12 x 5 x 3 x 4 x 4				2,880	

The loading schedule for all beams is clarified in Table (2), where the unfactored dead load (w_d) and unfactored live load (w_l) are 10 kN, 20 kN, 25 kN, 30 kN and 40 kN, the standard widths (b) are 200 mm, 250 mm, 300 mm, 350 mm, 400 mm and 450 mm, the height to width ratios (h/b) are (1.5, 2.0, 2.5 and 3.0) and (2.5, 3.0, 3.5 and 4.0) for shorter beams of length (3.0 m, 4.5 m, 6 m) and longer beams of length (7.5 m, 9 m) respectively, and concrete strengths are 21, 24 and 28 MPa.

All beams heights (h) are selected in such a way that satisfy the serviceability requirements of the ACI code for deflection. For all beams, the yield stress of steel (f_y), clear cover of reinforcement, unit weight of RC, unit weight of steel reinforcement, cost of reinforcement (U_s) are 420 MPa, 40 mm [20, 24], 24 kN/m³ [4, 12], 7850 kg/m³ [3, 31] and 1 US\$/kg [22] respectively. The sizes of the longitudinal bars are : 12mm, 16mm, 20mm, 25mm and 32mm , while the size of transverse bar (stirrups) is 10 mm, which are commonly used and available at the market.

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Table (2) – Loading schedule

Loading case	Loading value			f_c' , N/mm ²	Width of beam (b), mm			h/b ratio			Sequence of beams	Remarks
	w_d , kN/m	w_l , kN/m	l , m		Min.	Between Min. & Max.	Max.	Min.	Between Min. & Max.	Max.		
1	10	10	3	21	200	250	300	1.5	2, 2.5	3	1 to 192	No. of beams = 192 for each case including 3 widths, 4 h/b ratios, 4 concrete unit rates and 4 formwork unit rates
2	20	20	4.5		200	250	300				193 to 384	
3	25	25	6		250	300	350				385 to 576	
4	30	30	7.5		300	350	400	2.5	3, 3.5	4	577 to 768	
5	40	40	9		350	400	450				769 to 960	
6	10	10	3	24	200	250	300	1.5	2, 2.5	3	961 to 1152	
7	20	20	4.5		200	250	300				1153 to 1344	
8	25	25	6		250	300	350				1345 to 1536	
9	30	30	7.5		300	350	400	2.5	3, 3.5	4	1537 to 1728	
10	40	40	9		350	400	450				1729 to 1920	
11	10	10	3	28	200	250	300	1.5	2, 2.5	3	1921 to 2112	
12	20	20	4.5		200	250	300				2113 to 2304	
13	25	25	6		250	300	350				2305 to 2496	
14	30	30	7.5		300	350	400	2.5	3, 3.5	4	2497 to 2688	
15	40	40	9		350	400	450				2689 to 2880	
Total number of beams = 192 x 15 = 2,880												

B. RESULTS AND DISCUSSIONS

STAAD Pro software and EXCEL spreadsheet as per ACI 318M-14 code design requirements for bending and shear have been used to calculate the beams costs. Eqs.(1), (2) through (7) and (8) through (14) provide the beams total costs, design for bending and design for shear respectively.

STAAD Pro software includes the beam *self-weight* [10] based on the input values for the span length (l), width (b) and height (h) in order to calculate the accurate loading and accordingly bending moment and shear will have the exact values. The reinforcement arrangement is *simple, easily achievable solution* [19] and *economical patterns* [12] for both longitudinal and transverse reinforcement (stirrups). The longitudinal bars are fit in a single layer or placed in two layers [12], so that lowest amount of reinforcement is used to satisfy the design requirements and also the specified sizes of the steel bars are utilized. All the beams have been designed for tension controlled requirements for both required and provided longitudinal reinforcement. Also, STAAD Pro software provides the quantities of concrete and

reinforcement for whole beam length through the take off command. The quantities of longitudinal and transverse reinforcement (stirrups) have been used in the EXCEL spreadsheet to calculate the beam total cost per unit length.

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B.1 ECONOMICAL BEAM DESIGN

Table (3) presents the database of all beams total costs per unit length and for all unit costs of concrete and formwork. The total cost includes concrete, reinforcement for both longitudinal and transverse (stirrups) and formwork costs. For each beam of same loading, compressive strength of concrete (f'_c), unit cost of concrete (U_c) and unit cost of formwork (U_f), there is *several iterations* [12] to find the total cost per unit length for different widths (b) and heights (h) of the beams, due to different amount of concrete, reinforcement and formwork belong to each section, and more trials lead to more economical beam design.

Table (3) – Database of beams total costs per unit length

Beam No.	Load. Case	Beam dimensions				Concrete				Steel reinforcement					Formwork			c, \$/m
		l , m	b , mm	h , mm	h/b	V_{co} , m ³	U_c , \$/m ³	C_c , \$	ρ	W_{ls} , Kg	W_{ts} , Kg	W_s , Kg	U_s , \$/kg	C_s , \$	A_f , m ²	U_f , \$/m ²	C_f , \$	
1	1	3	200	300	1.5	0.18	80	14.4	0.0082	9.5	13.5	23.0	1	23.0	2.4	5	12.0	16.5
2	1	3	200	400	2	0.24	80	19.2	0.0040	8.0	11.8	19.8	1	19.8	3	5	15.0	18.0
196	2	4.5	200	600	3	0.54	80	43.2	0.0075	34.6	15.7	50.3	1	50.3	6.3	5	31.5	27.8
926	5	9	350	1050	3	3.31	140	463.1	0.0115	276.9	51.7	328.6	1	328.6	22.05	10	220.5	112.5
985	6	3	200	300	1.5	0.18	90	16.2	0.0081	9.5	13.5	23.0	1	23.0	2.4	20	48.0	29.1
1527	8	6	250	625	2.5	0.94	150	140.6	0.0140	92.3	21.5	113.8	1	113.8	9	30	270.0	87.4
1537	9	7.5	300	750	2.5	1.69	90	151.9	0.0146	173.0	31.0	204.0	1	204.0	13.5	5	67.5	56.5
1754	10	9	350	1050	3	3.31	90	297.7	0.0113	276.9	48.2	325.1	1	325.1	22.05	20	441.0	118.2
1933	11	3	200	300	1.5	0.18	100	18.0	0.0080	9.5	13.5	23.0	1	23.0	2.4	10	24.0	21.7
2677	14	7.5	300	750	2.5	1.69	160	270.0	0.0142	173.0	28.4	201.4	1	201.4	13.5	30	405.0	116.9
2869	15	9	350	875	2.5	2.76	160	441.0	0.0174	346.1	60.3	406.4	1	406.4	18.9	30	567.0	157.2
2880	15	9	450	1800	4	7.29	160	1166.4	0.0033	181.4	44.3	225.7	1	225.7	36.45	30	1093.5	276.2

For a beam with specific length, loading, unit cost of concrete and unit cost of formwork, there is an economical total cost for that beam depending on the beam section dimensions, and contribution of unit cost of concrete, unit cost of steel reinforcement and the unit cost of formwork in the beam total cost.

Table (4) shows the *upper and lower bounds* [4] of the economical beams total costs per unit length and for all unit costs of concrete and formwork. The bounds are formulated for heavy loads and long beam – i.e large moments, light loads and short beam – i.e small moments.

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Table (4) – Upper and lower bounds of economical beams total costs per unit length

Beam No.	Load. Case	Beam dimensions				Concrete			Steel reinforcement					Formwork			c _t \$/m	
		l, m	b, mm	h, mm	h/b	V _{co} , m ³	U _c , \$/m ³	C _c \$	ρ	W _{ls} , Kg	W _{rs} , Kg	W _s , Kg	U _s , \$/kg	C _s \$	A _f , m ²	U _f , \$/m ²		C _f \$
1	1	3	200	300	1.5	0.18	80	14.4	0.0082	9.5	13.5	23.0	1	23.0	2.4	5	12.0	16.5
181	1	3	200	300	1.5	0.18	140	25.2	0.0082	9.5	13.5	23.0	1	23.0	2.4	30	72.0	40.1
770	5	9	350	1050	3	3.31	80	264.6	0.0115	276.9	51.7	328.6	1	328.6	22.05	5	110.3	78.2
950	5	9	350	1050	3	3.31	140	463.1	0.0115	276.9	51.7	328.6	1	328.6	22.05	30	661.5	161.5
961	6	3	200	300	1.5	0.18	90	16.2	0.0081	9.5	13.5	23.0	1	23.0	2.4	5	12.0	17.1
1141	6	3	200	300	1.5	0.18	150	27.0	0.0081	9.5	13.5	23.0	1	23.0	2.4	30	72.0	40.7
1730	10	9	350	1050	3	3.31	90	297.7	0.0113	276.9	48.2	325.1	1	325.1	22.05	5	110.3	81.4
1910	10	9	350	1050	3	3.31	150	496.1	0.0113	276.9	48.2	325.1	1	325.1	22.05	30	661.5	164.7
1921	11	3	200	300	1.5	0.18	100	18.0	0.0080	9.5	13.5	23.0	1	23.0	2.4	5	12.0	17.7
2101	11	3	200	300	1.5	0.18	160	28.8	0.0080	9.5	13.5	23.0	1	23.0	2.4	30	72.0	41.3
2690	15	9	350	1050	3	3.31	100	330.8	0.0111	265.8	44.8	310.6	1	310.6	22.05	5	110.3	83.5
2869	15	9	350	875	2.5	2.76	160	441.0	0.0174	346.1	60.3	406.4	1	406.4	18.9	30	567.0	157.2

Table (5) shows the cost ratio of concrete, reinforcement, formwork and stirrups to total cost can be up to 44%, 48%, 60% and 27% while the average cost ratio are 32%, 32%, 36% and 9% respectively whereas the stirrups cost is a part of steel cost, for concrete unit costs in the range of 80 \$/m³ to 160 \$/m³ and formwork unit costs in the range of 5 \$/m² to 30 \$/m².

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Table (5) – Cost ratio of economical beams total costs per unit length

Beam No.	Load. Case	Concrete	Formwork	Cost ratio				Remarks
		$U_c, \$/m^3$	$U_f, \$/m^2$	Concrete/ Total	Steel/ Total	Formwork /Total	Stirrups/ Total	
1	1	80	5	29%	47%	24%	27%	$f_c' = 21 \text{ N/mm}^2$
181	1	140	30	21%	19%	60%	11%	$f_c' = 21 \text{ N/mm}^2$
388	3	80	5	39%	38%	23%	9%	$f_c' = 21 \text{ N/mm}^2$
758	4	140	30	31%	18%	51%	3%	$f_c' = 21 \text{ N/mm}^2$
1335	7	150	30	23%	20%	56%	5%	$f_c' = 24 \text{ N/mm}^2$
1348	8	90	5	42%	37%	22%	8%	$f_c' = 24 \text{ N/mm}^2$
1537	9	90	5	36%	48%	16%	7%	$f_c' = 24 \text{ N/mm}^2$
1717	9	150	30	29%	24%	47%	4%	$f_c' = 24 \text{ N/mm}^2$
2295	12	160	30	25%	20%	55%	5%	$f_c' = 28 \text{ N/mm}^2$
2307	13	100	5	38%	44%	18%	9%	$f_c' = 28 \text{ N/mm}^2$
2690	15	100	5	44%	41%	15%	6%	$f_c' = 28 \text{ N/mm}^2$
2869	15	160	30	31%	29%	40%	4%	$f_c' = 28 \text{ N/mm}^2$
Maximum of economical beams total costs				44%	48%	60%	27%	Stirrups cost is a part of steel cost
Average of economical beams total costs				32%	32%	36%	9%	Stirrups cost is a part of steel cost

B.2 EFFECT OF REINFORCEMENT RATIO

Table (4) shows the longitudinal reinforcement ratios (ρ) for various economical beams in the range of 0.0082 to 0.0115, 0.0081 to 0.0113 and 0.0080 to 0.0174 with an average of 0.0099, 0.0097 and 0.0127 for concrete strengths 21, 24 and 28 MPa respectively. All the longitudinal reinforcement ratios for both required and provided area of steel reinforcement are within the ACI code limits for tension controlled of Eq. (6).

The lower limits of longitudinal reinforcement ratio are almost the same for various concrete strengths while the upper limits are increased as the maximum reinforcement ratio increased in the Eq. (6). The lower reinforcement ratio will lead to increase the height of the beam and attain the ductile failure. The ductile failure is gradual, giving ample prior warning of the impending collapse by way of increased curvatures, deflections and cracking, while brittle failure occurs explosively without warning [30, 34]. Also, using small reinforcement ratio will fix the steel bars smoothly without complex and congestion [16].

Different researches emphasize that the ductility of singly (RC) beams decreases when the percentage of reinforcement increases [35, 36, 37].

Structural designers believe that keeping steel percentages fairly low will result in good economy [12]. Also, saving the quantity of reinforcement will reduce the carbon footprint, and improve the sustainability of RC construction [38, 39].

B.3 EFFECT OF HEIGHT TO WIDTH RATIO

Table (4) indicates that economical beam design may occur when h/b ratio in the range of 1.5 to 3 for beams up to and including 9 m in length and concrete strengths 21, 24 and 28 MPa. It seems that there is no direct relationship between the height to width ratio (h/b) and the economical beam design due to the contribution of unit cost of concrete, unit cost of steel reinforcement and the unit cost of formwork in the beam total cost per unit length.

In general, using deep and narrow beams leads to satisfy both design requirements and economy, while sometimes and from standpoint of economy small reduction in that deep height leads to better economy when the cost of concrete and formwork is expensive as shown in Table (4).

B.4 EFFECT OF FORMWORK UNIT COST

The formwork unit cost (U_f) for different beams are 5 \$/m², 10 \$/m², 20 \$/m² and 30 \$/m² for all unit costs of concrete. Fig. (1) demonstrates the relationship between economical beam total cost per unit length and formwork unit cost.

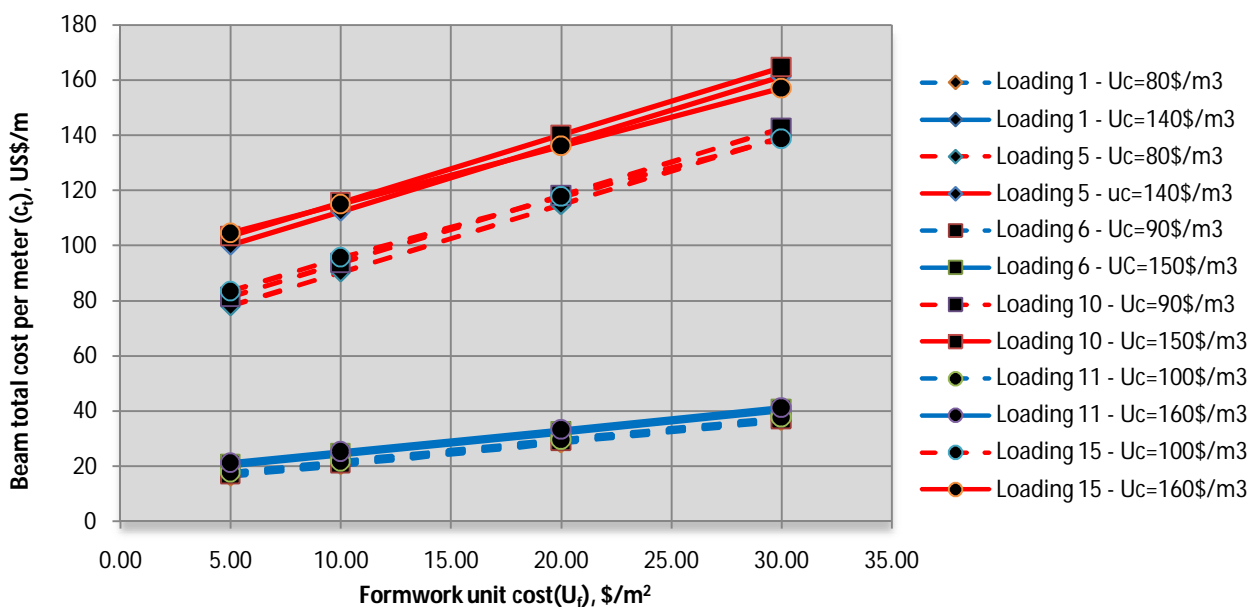


Fig. 1 - Relationship between economical beam total cost per unit length and formwork unit cost

The average increases in the economical beams total costs per unit length are in the range between 21% and 111% for small moments, and in the range between 12% and 70% for large moments when the formwork unit cost (U_f) increases in the range between 5 \$/m² and 30 \$/m². The formwork is *more cost effective* [18] than concrete due to the formwork unit cost is increased quickly compared with the concrete unit cost whereas the formwork unit cost is increased up to six times while the concrete unit cost is increased up to two times only during the cost comparison between the upper bounds of large moments and the lower bounds of small moments. For economy in beam design using usual and standard beam section dimensions, *increased speed of construction and saving in formwork will save more than the cost of the excess concrete* [1].

B.4 EFFECT OF CONCRETE UNIT COST

The concrete unit cost (U_c) for different beams are (80 \$/m³, 100 \$/m³, 120 \$/m³ and 140 \$/m³), (90 \$/m³, 110 \$/m³, 130 \$/m³ and 150 \$/m³) and (100 \$/m³, 120 \$/m³, 140 \$/m³ and 160 \$/m³) for concrete strengths 21, 24 and 28 MPa respectively and for all unit costs of formwork. Fig. (2) demonstrates the relationship between economical beam total cost per unit length and concrete unit cost.

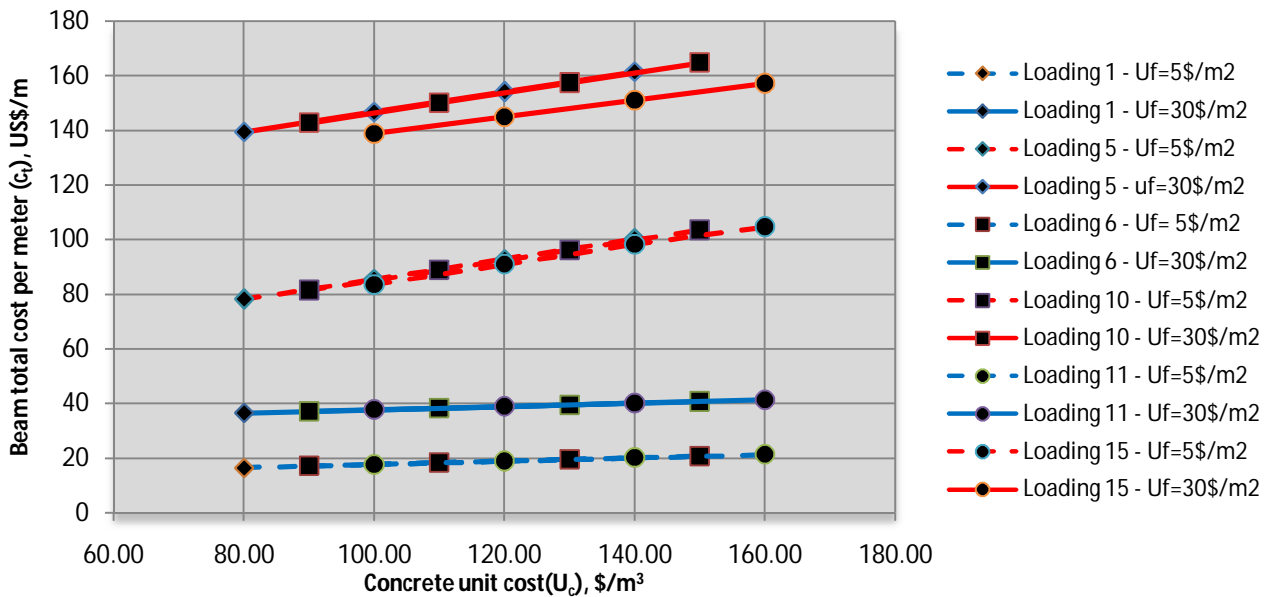


Fig. 2 - Relationship between economical beam total cost per unit length and concrete unit cost

The average increases in the economical beams total costs costs per unit length are in the range between 5% and 16% for small moments, and in the range between 7% and 22% for large moments when the concrete unit cost (U_c) increases in the range of 80 $\$/m^2$ and 160 $\$/m^2$.

The concrete is less cost effect than formwork due to small increase in concrete unit cost compared with large increase in formwork unit cost.

B. 5 EFFECT OF CONCRETE STRENGTH

From a cost point of view, it seems that it is preferable to use low concrete strength in the economical beam design [40]. Table (4) indicates that reduce the concrete strength may lead to more economical beam design for the beam which has the same dimensions, ultimate moment (M_u) and formwork unit cost (U_f), although generally there is a little increase in the reinforcement due to decrease of the concrete unit cost (U_c) which leads to reduce the cost of concrete – i.e. comparison between beams number 950 and 1910. The average reduction in the economical beams total costs per unit length is about 3% and 4% when concrete strengths are 24 and 28 MPa compared with 21 MPa respectively.

B. 6 ULTIMATE MOMENT FACTOR

The final value for the maximum bending moment (M_u) at midspan of the beam cannot be defined until the beam cross section is determined and the self-weight is included within the dead load applied to the beam [16]. Table (6) shows that the moment factor (F) for the external ultimate bending moment (M_e) - i.e. without the beam the self-weight [30], is found in the range between 1.05 and 1.09 with an average of 1.07 for various loadings, beams length and concrete strengths.

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Table (6) – Economical beams details with ultimate bending moment (M_u) and complete section modulus (bh^2)

Beam No.	Load Case	w_d , kN/m	w_l , kN/m	f_c' , N/mm ²	Beam dimensions				M_u , kN.m	M_c , kN.m	F = M_u/M_c	$bh^2 \times 10^5$, mm ³
					l , m	b , mm	h , mm	h/b				
1	1	10	10	21	3.0	200	300	1.5	33.44	31.50	1.06	180.00
378	2	20	20	21	4.5	250	500	2.0	150.86	141.75	1.06	625.00
388	3	25	25	21	6.0	250	750	3.0	339.30	315.00	1.08	1406.25
570	3	25	25	21	6.0	300	600	2.0	338.33	315.00	1.07	1080.00
950	5	40	40	21	9.0	350	1050	3.0	1241.16	1134.00	1.09	3858.75
1155	7	20	20	24	4.5	200	500	2.5	149.04	141.75	1.05	500.00
1527	8	25	25	24	6.0	250	625	2.5	335.25	315.00	1.06	976.56
1537	9	30	30	24	7.5	300	750	2.5	636.19	590.63	1.08	1687.50
1717	9	30	30	24	7.5	300	750	2.5	636.19	590.63	1.08	1687.50
2307	13	25	25	28	6.0	250	625	2.5	335.25	315.00	1.06	976.56
2690	15	40	40	28	9.0	350	1050	3.0	1241.16	1134.00	1.09	3858.75
2869	15	40	40	28	9.0	350	875	2.5	1223.30	1134.00	1.08	2679.69

B.7 APPROACH TO ECONOMICAL BEAM DESIGN

The pertinent Fig. (3) and Fig. (4) have been developed based on Table (6), to have a good guide in estimation the beam section dimensions and then attain the economical simply supported RC rectangular beam design without prior understanding of optimization.

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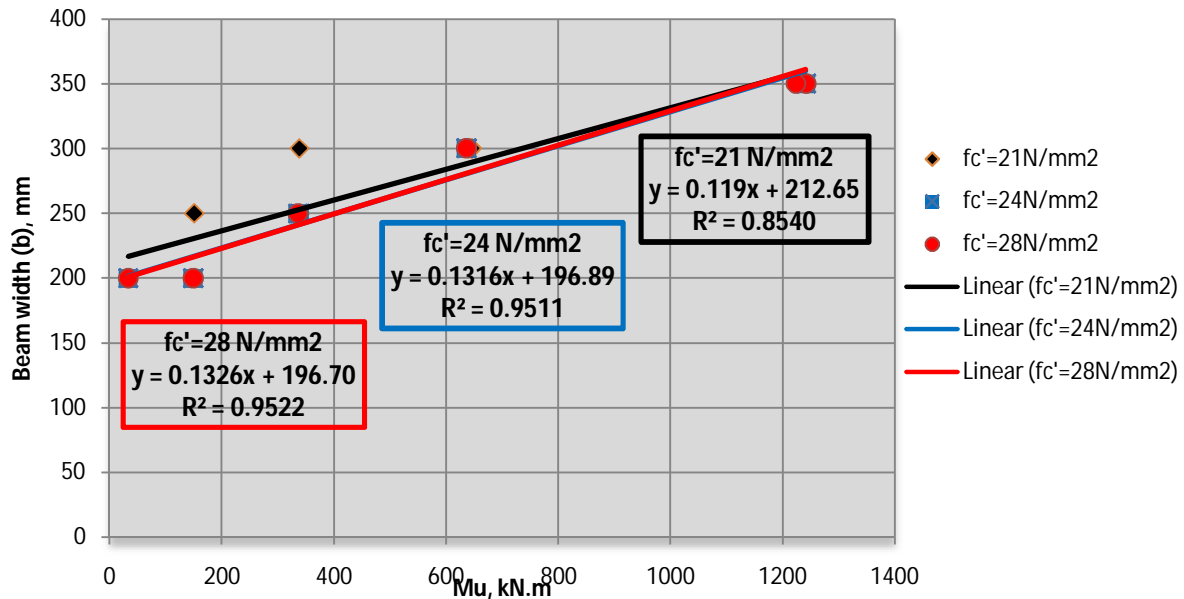


Fig. 3 - Relationship between ultimate bending moment (M_u) and beam width (b)

To avoid exaggeration and to get a logical and simple equations for the best fitted relationship, a linear relation with a strong correlation coefficient have been chosen between the ultimate moment (M_u) and the beam width (b) for Fig. (3), while Fig. (4) provides the relationship between the ultimate moment (M_u) and the complete section modulus (bh^2).

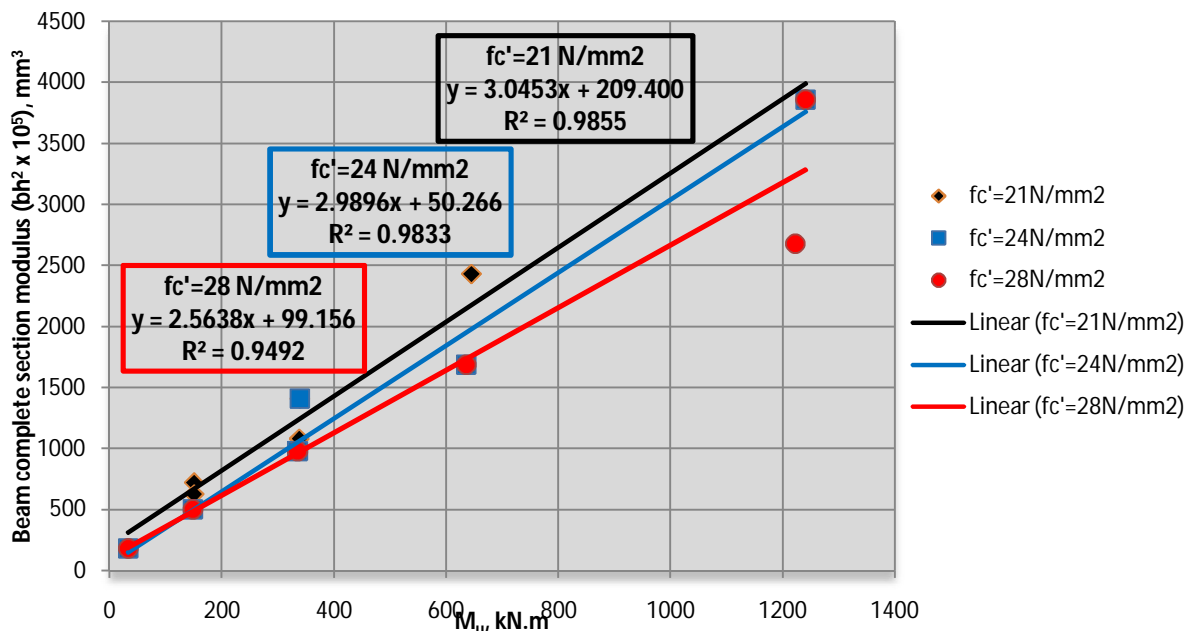


Fig. 4 - Relationship between ultimate bending moment (M_u) and complete section modulus (bh^2)

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The results of this study show that the standard widths of economical beam design are 200, 250, 300 and 350 mm as illustrated in Fig. (3). Both parametric design curves – i.e Fig. (3) and Fig. (4) are comprised numerical equations for concrete strengths 21, 24 and 28 MPa to calculate the beam width (b) and the complete section modulus (bh^2) respectively.

Economical beam design can be approached based on the following *iterative method* [12]:

1. Calculate the external factored moment (M_e) – i.e without the beam self-weight.
2. Determine approximate M_u including the beam self-weight by multiplying M_e by the average moment factor (F) which is equal 1.07.
3. Find the width of the beam (b) from the appropriate equation of Fig. (3) and rounding it to nearest 50 mm.
4. Find the complete section modulus (bh^2) from the appropriate equation of Fig. (4), then use the above b to calculate the height of the beam (h) and also rounding it to nearest 50 mm.
5. Calculate the amount of steel reinforcement required for bending and shear design by using *computer methods* like STAAD Pro software or *hand calculations* [15].
6. Calculate the beam total cost per unit length as per the EXCEL spreadsheet of Table (3).
7. Select another h by rounding up or down the dimension of step 4 to nearest 50 mm.
8. Complete the cycle of economical beam total cost per unit length.

Several iterations in total cost calculations by rounding up or down the width of the beam (b) of step 3 to nearest 50 mm, and consequently the height of the beam (h) lead to more economical beam design.

The preceding approach to the economical beam design is straightforward, without enormous iterations and tedious calculations which is time consuming, provide applicable solution in practice [19] and satisfy the design requirements of ACI 318M-14 code for bending and shear.

IV. CONCLUSIONS

The main cost results for the economical simply supported RC rectangular beam design by using STAAD Pro software as per ACI 318M-14 code can be indicated as following:

1. The average costs ratio of concrete, reinforcement and formwork to total cost are 32%, 32% and 36% respectively, whereas the stirrups cost constitutes 9% of the total cost.
2. The average reinforcement ratio (ρ) is approximately 1% for concrete strengths 21, 24 MPa and 1.25% for concrete strength 28 MPa.
3. The h/b ratio is in the range of 1.5 to 3 for beams up to and including 9 m in length. In general, using deep and narrow beams leads to satisfy both design requirements and economy.
4. The formwork unit cost (U_f) is more effect than concrete unit cost (U_c), and the average increases in the economical beams total costs costs per unit length are in the range between 21% and 111% for small moments, and in the range between 12% and 70% for large moments when the formwork unit cost (U_f) increases in the range between 5 $\$/m^2$ and 30 $\$/m^2$.
5. The average increases in the economical beams total costs costs per unit length are in the range between 5% and 16% for small moments, and in the range between 7% and 22% for large moments when the concrete unit cost (U_c) increases in the range of 80 $\$/m^2$ and 160 $\$/m^2$.
6. From a cost point of view, it seems that it is preferable to use low concrete strength in the economical beam design.
7. The moment factor (F) is in the range between 1.05 and 1.09 with an average of 1.07.
8. Economical beam design can be attained from several iterations in total cost calculations, and more attempts to find the beam section dimensions provide more economical beam design. Numerical equations for the economical beam design have been developed and can be used swiftly to estimate the beam width and height without prior understanding of optimization for concrete strengths 21, 24 and 28 MPa.

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