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Optimizing reinforced concrete beams under different load cases and material mechanical properties using genetic algorithms

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Abstract. Genetic Algorithm (GA) is a meta-heuristic algorithm which is capable of providing robust solutions for optimal design of structural components, particularly those one needs considering many design requirements. Hence, it has been successfully used by engineers in the typology optimization of structural members. As a novel approach, this study employs GA in order for conducting a case study with high constraints on the optimum mechanical properties of reinforced concrete (RC) beams under different load combinations. Accordingly, unified optimum sections through a computer program are adopted to solve the continuous beams problem. Genetic Algorithms proved in finding the optimum resolution smoothly and flawlessly particularly in case of handling many complicated constraints like a continuous beam subjected to different loads as moments shear - torsion regarding the curbs of design codes.

Keywords: reinforced concrete; optimum structures; genetic algorithms; optimization

1. Introduction

In current practice, a trial-and-error process is commonly used to design a structural component. According to the different applications of structural components, the compressive strength is the critical feature of the concrete. Therefore, the composite beams and floor systems that faced the axial and compressive forces should be investigated under several loading patterns. Besides, the compressive, tensile, and flexural strength of concrete can be evaluated while subjected to different experimental analyzes, and hence, different design parameters and loading scenarios can be estimated with respect to the highest risk. Also, the effectiveness of cementitious additives has been proved by precursor studies where the slag and fly ash represented the most significant role (Shah *et al.*, Suhatril *et al.*, Shariati 2008, Arabnejad Khanouki *et al.* 2010, Shariati *et al.* 2010, Arabnejad Khanouki *et al.* 2011, Daie *et al.* 2011, Hamidian *et al.* 2011, Shariati *et al.* 2011a, Shariati *et al.* 2011b, Shariati *et al.* 2011c, Shariati *et al.* 2011d, Shariati *et al.* 2020h, Hamidian *et al.* 2012, Jalali *et al.* 2012, Shariati *et al.* 2012a, Shariati *et al.* 2012b, Shariati *et al.* 2012c, Shariati *et al.* 2012d, Shariati *et al.* 2012e, Sinaei *et al.* 2012). Although this solution can meet structural requirements and design criteria, it might not be the optimum solution based on the total cost of the structure (Mohammadhassani *et al.* 2013, Armaghani *et al.* 2020, Shariati 2013, Shariati *et al.* 2013, Mohammadhassani *et al.* 2014a, Mohammadhassani *et al.* 2014b, Mohammadhassani *et al.* 2014c, Shariati 2014, Shariati *et al.* 2014a, Shariati *et al.* 2014b, Toghroli *et al.* 2014, Khorramian *et al.* 2015, Shah *et al.* 2015, Shariati *et al.* 2020b, Shariati *et al.* 2015a, Shariati *et al.* 2020c, Shariati *et al.* 2015d). On the other hand, considering all the influential parameters on the problem is not easy at all (Shao *et al.* 2015, Heydari *et al.* 2018, Hosseinpour *et al.* 2018, Ismail *et al.* 2018, Nasrollahi *et al.* 2018, Nosrati *et al.* 2018, Paknahad *et al.* 2018, Sadeghipour Chahnasir *et al.* 2018, Sedghi *et al.* 2018, Shao *et al.* 2018, Shariat *et al.* 2018, Wei *et al.* 2018, Zandi *et al.* 2018, Ziaei-Nia *et al.* 2018, Shao *et al.* 2019a, Shao *et al.* 2019b, Shi *et al.* 2019a, Shi *et al.* 2019b). Therefore, it seems reasonable that more advanced algorithms are used to consider all the possible combinations of system components and determine the best one (Arabnejad Khanouki *et al.* 2016, Khorramian *et al.* 2016, Safa *et al.* 2016, Shahabi *et al.* 2016a, Tahmasbi *et al.* 2016, Khorami *et al.* 2017a, Khorami *et al.* 2017b,

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Mansouri *et al.* 2017, Shariati *et al.* 2017, Toghroli *et al.* 2017, Shariati *et al.* 2019a, Shariati *et al.* 2019d, Shariati *et al.* 2019e, Trung *et al.* 2019a).

A research by (Camp *et al.* 2003) considered the number of reinforcement steel bars along with the width and thickness of sections as design variables and used genetic algorithm (GA) for forming an unconstrained problem. Numerous studies have shown the high influence of reinforcement steel bars on the strength of concrete structures (Shariati 2008, Shariati *et al.* 2011a, Shariati *et al.* 2011b, Sinaei *et al.* 2011a, Sinaei *et al.* 2011b, Sinaei *et al.* 2012, Aghakhani *et al.* 2015, Mohammadhassani *et al.* 2015, Toghroli 2015, Shariati *et al.* 2016, Abedini *et al.* 2017, Sari *et al.* 2018, Toghroli *et al.* 2018a, Zhao *et al.* 2018, Abedini *et al.* 2019, Xie *et al.* 2019). A steel frame was selected as a good example in the previous studies (Sharma *et al.* 2012, Shah *et al.* 2016a, Heydari and Shariati 2018, Shariati *et al.* 2018). Other materials such as fibers were used to reinforced concrete as well (Naghipour *et al.* 2020).

A study by (Aschheim *et al.* 2008) used non-linear conjugate gradient search technique to determine a general solution for the optimum reinforcement of rectangular concrete sections under a general *P*, *Mx* & *My* load combination. In this study, the reinforcement ratio of beams, columns, and wall sections was considered as variables of the optimization process and the dimension of sections were determined following ACI code. Also, the optimum solution was obtained in different conditions, including equal reinforcement on all faces, equal reinforcement on opposite faces and unique reinforcement on each face. Optimum design of conical and cylindrical reinforced concrete water tanks was proposed by Barakat and Altoubat (Barakat *et al.* 2009). Usage of soft computing methods for this purpose have been previously conducted by many researchers. The finite element method in conjunction with the optimization method is used in the analysis and design of the RC water tanks. Finite element methods have been extensively used to study the deformation of structures (Shariati *et al.* 2015d, Shahabi *et al.* 2016b, Tahmasbi *et al.* 2016, Khorramian *et al.* 2017, Nasrollahi *et al.* 2018, Nosrati *et al.* 2018, Paknahad *et al.* 2018, Mehrmashhadi *et al.* 2019a, Safa *et al.* 2019, Shariati *et al.* 2019c). They evaluated the impact of designing method, the reinforcement bar size, the inclination of the water tank, and the unit cost of materials for the optimum design of water tanks. The former studies showed that for cylindrical water tanks, the total cost is more than that of conical water tanks with the same capacities by up to 20% to 30% when using the working stress design (WSD) method, and 18% to 40% when employing stress design (SD) method. Also, the obtained results from the experimental tests and the sensitivity analysis indicated that the robust search capabilities of Shuffled Complex Evolution (SCE) algorithm are well suited for solving the structural design problem of optimizing conical and cylindrical water tanks (Toghroli *et al.* 2018b). GA was also employed by (Sahab 2008) to determine the optimum cost of flat slab buildings. In this study the cost of materials, labor, and reinforcement as well as the formwork of floors, columns, and foundations were taken into account. Also, the influence of the unit cost of the materials and their properties was evaluated on the optimum design. The design variables were represented by the slab thickness and dimensions, the reinforcing steel and its distribution, columns dimensions (which was assumed to be equal) with its reinforcing steel. The effect of the unit cost was studied through a numerical example which was chosen from a report on the comparative costs of concrete and steel framed office building that has been recommended to be a benchmark for future studies.

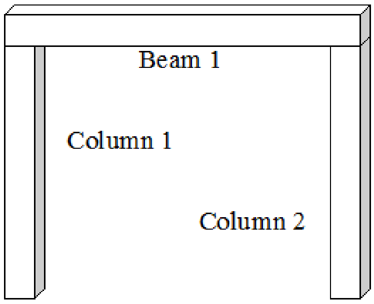
A rigorous search might be performed to measure the unique resolution(s) so that an appropriate model could be nominated as an AI (Artificial Intelligence) model as Gas (Safa *et al.* 2016, Chen *et al.* 2019, Davoodnabi *et al.* 2019, Katebi *et al.* 2019, Luo *et al.* 2019, Milovancevic *et al.* 2019, Sajedi *et al.* 2019a, Shariati *et al.* 2019b, Shariati *et al.* 2020g, Shariati *et al.* 2019f, Trung *et al.* 2019b, Xie *et al.* 2019, Xu *et al.* 2019, Shariati *et al.* 2020e, Shariati *et al.* 2020d, Shariati *et al.* 2020f). GAs is used to find optimum (semi-optimum) resolutions to discrete variable optimization drawbacks like concrete structures design provided in this study in order to show the acceleration and effectiveness of solving the reinforced concrete problem(s) while ingoing many discrete design constraints and values.

2. GA methodology

Genetic algorithm (GA) has been inspired by the evolution of human beings based on the Darwin theory (Toghroli *et al.* 2016). The main element of GA is the strings of chromosome representing individuals that contain different gens (variables) in the space of the problem. The most common coding model of GA is to show each variable with a binary string of digits in a specific length. For instance, consider Fig. 1 that shows a part of the concrete frame. In columns 1 and 2, chromosome includes six genes to show the column height, width and four reinforcement ratios, so that each gene stands for the reinforcement ratio of a single face of column section. Adoption of this process ensures that the optimum design occurs even if the reinforcement ratio is not equal to all the faces of the section. The same process can be also applied to the beam with this difference, that it is represented by only three genes due to three design variables, including the effective depth, width, and the reinforcement ratio of the beam.

In GA, 0 and 1 numbers are randomly assigned to a string of chromosome showing the characteristics of each individual. The sequence of GA starts with the creation of an initial population, in which the population size is defined by the user. Binary string data of each solution should be transformed into the problem variables and the cost of each string of a chromosome is calculated. Next, the crossover processing starts by means of which the genius of two "parents" ate combined to make a couple of offspring (Fig. 2). Different methods can be found to select parents involved in each crossover.

Scattered crossover is one of these methods. A group of the most fitted along with a newly created parent is



Frame design variables		
Column 1	Column 2	Beam 1
width b1	width b2	width b3
height h1 reinforcement ratio ρ 1	height h2 reinforcement ratio ρ 5	effective depth d reinforcement ratio ρ 9
reinforcement ratio ρ 2	reinforcement ratio ρ 6	
reinforcement ratio ρ 3 reinforcement ratio ρ 4	reinforcement ratio ρ 7 reinforcement ratio ρ 8	

Fig. 1 Frame to be optimized by genetic algorithm

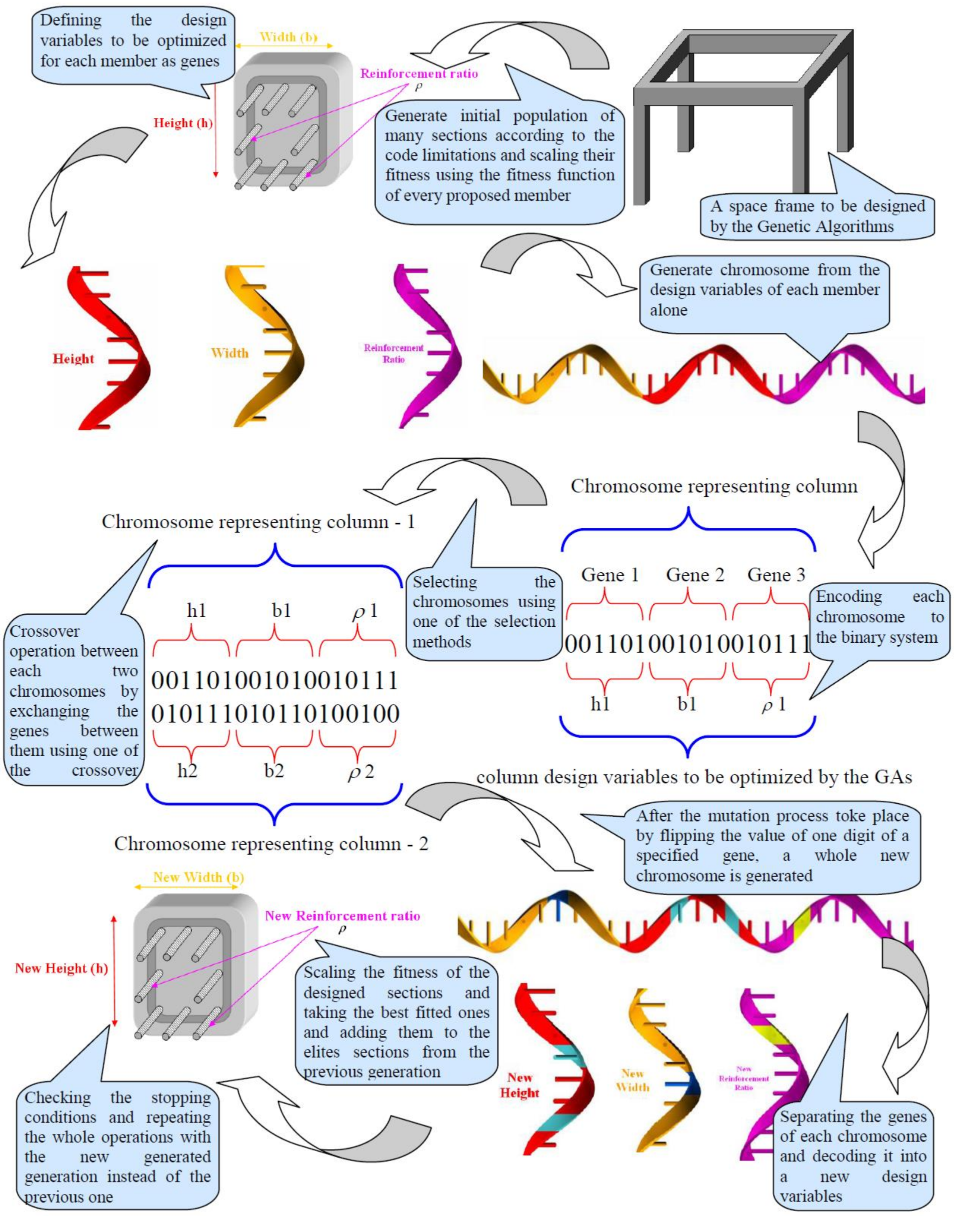


Fig. 2 Genetic Algorithms in structural optimization

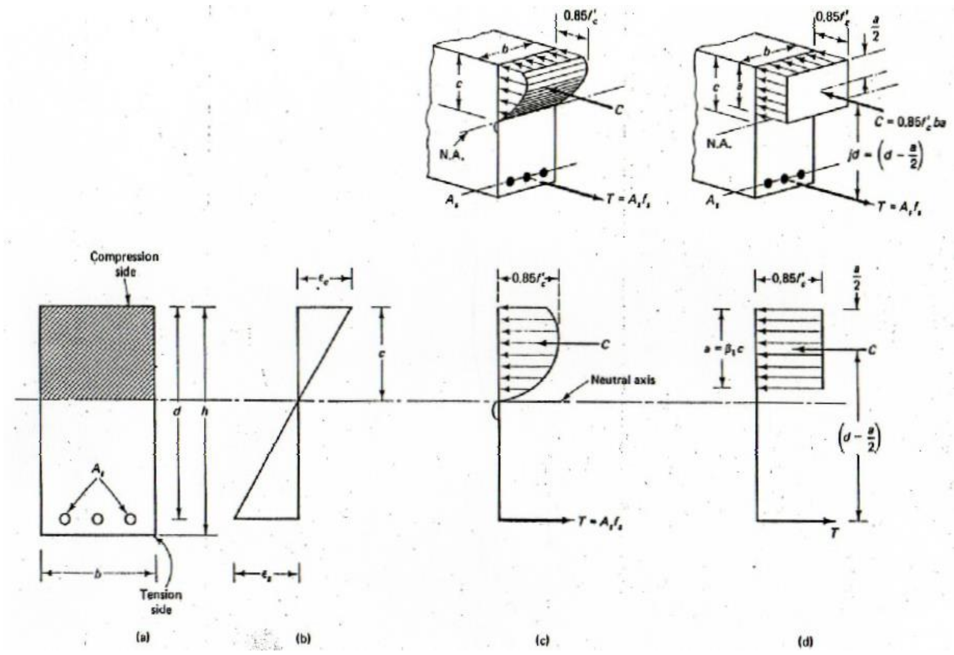


Fig. 3 Stress and strain distribution across the beam depth: (a) beam cross section, (b) strains, (c) actual stress block and (d) assumed equivalent stress block (Nawy 2000)

permitted to pass into the new generation, thereafter, less fitted resolutions are removed.

Then, mutation operation is applied in which for a percentage of the population, a gene in the string of a chromosome is changed. Mutation operation improves the exploration phase of the GA algorithm.

However, it can also decrease the capability of GA adversely by changing the chromosome strings of the best solutions. To address this issue, elitism is proposed that keeps the highly-fitted individuals from mutation. As a result, the new generation represents an optimal solution of the design variables adjusted to design constraints. Finally, GA operations are conducted and the whole process is iterated for a user-defined generation. GA can be run until the desired stopping criteria is satisfied (Holmström *et al.* 2010).

3. Optimum design of RC beams

The real distribution of compressive stress in a section is in the form of a rising parabola (Fig. 3(c)). As is known, an equivalent rectangular stress block can be considered instead of the rising parabola to calculate the equivalent force. This equivalent stress block has a depth of *a* and an average compressive strength of *0.85* f_c'. (Fig. 3(d)). *a* can be calculated from the product of β_1 and c i.e., *A =,* in which the area of the equivalent rectangular block is almost equal to parabolic compressive block, leading to a compressive force *C* with the same value in both cases. The value of average stress of equivalent compressive block *(0.85* f_c'*)* is based on the core test of concrete at a minimum age of 28 days. According to the empirical test results, a maximum allowable strain of (0.003) is adjusted by ACI code as a safe limiting variable (Nawy 2000).

Using all the preceding assumptions, the stress distribution diagram shown in (Fig. 3(c)) could be re-drawn as (Fig. 3(d)), showing that the compression force *C* is equal to *(0.85* f_c' *a b).* In a proper design, the tensile steel bars are firstly yielded $\in_s > \in_y$. Thus, tensile force *T* is equal to ($A_s f_y$), and the equilibrium equation (*C = T*) can be written as

$$0.85\times f_c'\times a\times b = A_s f_y \tag{1}$$

$$\text{or:}\quad a=\frac{A_s f_y}{0.85\times f_c'\times b} \tag{2}$$

The moment resistance of the section can be also expressed as

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

At each section of a flexural member, the tensile required reinforcement should not be less than

$$A_{s,\min}=\rho_{\min}\times b\times d=\left(\frac{0.25\times\sqrt{f_c'}}{f_y}\times b\times d\right),$$
$$\text{but not less than }\left(\frac{1.4}{f_y}\times b\times d\right) \tag{4}$$

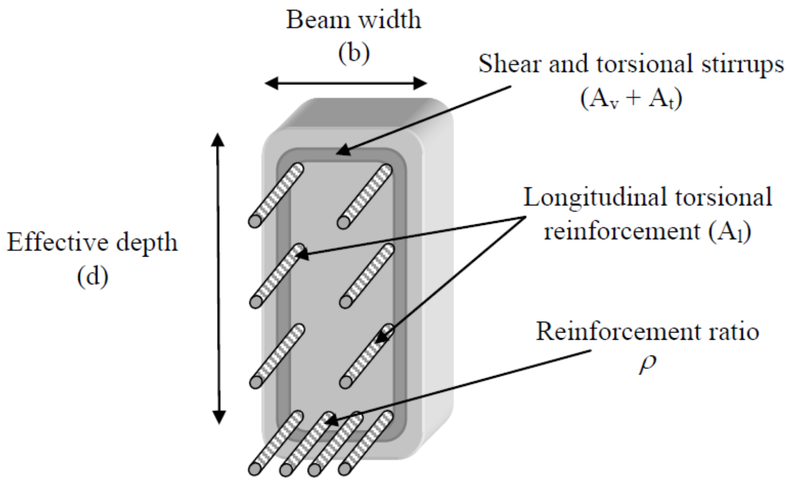


Fig. 4 Reinforced concrete beams design variables

And not greater than

$$A_{s,\max} = \rho_{\max} \times b \times d = 0.85 \times \beta 1 \times \frac{f_c'}{f_y} \times \frac{0.003}{0.003 + 0.005} \times b \times d (mm^2) \quad (5)$$

3.1 Objective function

The cost of a reinforced concrete beam can be divided into two parts of concrete cost and steel cost. Therefore, the objective function (cost function) can be defined as below

$$C_t = Vol_c\, C_c + Vol_s\, C_s \quad (6)$$

This cost function is similar to the one-way slab except defining the width of the beam as a design variable instead of considering it unit. Therefore, the final cost function of the beam is

$$C_t = C_c \times b \times [(d + t) + r \times \rho \times d\,] \quad (7)$$

Considering this fact that the cost value of shear and torsion steel reinforcement can be different from the cost value of flexure steel reinforcement, the beam is optimized into two levels of flexure and shear-torsion separately.

3.2 Design variables

Design variables (Fig. 4) include the with of the concrete section (b), depth of the concrete section (d), and the reinforced area of steel with the number of bars or topology of flexural reinforcement (A_s). The effect of shear-torsion will be considered on the optimum dimensions of the section through the code constraints. Since the dimensions of the concrete beam and the flexural reinforcement are optimally determined based on flexure, and shear-torsion, the rest of the design variables such as the longitudinal torsional reinforcement (A_l) and the stirrups for shear (A_v) and torsion (A_t) are obtained based on those optimal values.

3.3 Design constraints

The structural capacity of reinforced concrete beams should be more than the factored loading so that it meets all the requirements of the ACI Code (Zhao *et al.* 2019). This provision has constraints and limitations about the cross-sectional geometry of the beam and the quantity and position of steel reinforcement for different types of loading. Several researchers have only used the dimensions of sections as design variables and based on them, the reinforcement ratio has been calculated (Govindaraj and Ramasamy (Govindaraj *et al.* 2005). However, this study has not only used the reinforcement ratio as a design variable the dimensions (minimum cost), but has included the influence of shear - torsion on these optimal dimensions beside other constraints. These constraints have been applied to spot the major values, thereby resisting toward the applied loads (in many ways) and staying within the applied code's curbs toward the optimal resolution as more realistic and applicable. The first constraint Eq. (8) is applied to make the three values p , b and d (reinforcement ratio, beam width and beam effective depth) of the section, carrying the smallest variables that resisting on the section's applied moment. Eqs. (9) and (10) have shown the applied limitations to avoid the reinforcement ratio from exceeding the maximum value or below the minimum value based on ACI Code.

$$\frac{k \times w \times L^2}{0.9(\rho \times b \times d \times f_y \times (d - \frac{(\rho \times b \times d \times f_y / 0.85 \times f_c' \times b)}{2}))} - 1 \le 0 \quad (8)$$

$$1 - \frac{\rho}{\rho_{\min}} \le 0 \quad (9)$$

$$\frac{\rho}{\rho_{\max}} - 1 \le 0 \quad (10)$$

Regarding the influence of cracking and reinforcement on member stiffness (Adeli *et al.* 2006), Eq. (11) is applied to guarantee that the optimal section wouldn't have a depth less than the one in controlling elastic deflection, ACI code (9.5.2.2).

To provide more realistic dimensions, equations (12 and 13) are used to keep the ratio of optimal depth to the optimal width as 1.5 to 2.5 (specified by the designer).

Dimensions of optimum width (200 - 500 mm) and depth (300 - 1250 mm) have been applied in Eqs. (14) and (15) (specified by the designer)

$$1-\frac{h}{h_{\min}}\le 0 \tag{11}$$

$$1.5-\frac{h}{b}\le 0 \tag{12}$$

$$\frac{h}{b}-2.5\le 0 \tag{13}$$

$$(1-\frac{b}{200mm}\le 0)\ \ and\ \ (\frac{b}{500mm}-1\le 0) \tag{14}$$

$$(\frac{h}{1250mm}-1\le 0)\ \ and\ \ (1-\frac{h}{300mm}\le 0) \tag{15}$$

To decline unsightly (Bobaru *et al.* 2018, Li *et al.* 2019, Mehrmashhadi *et al.* 2019b, Bobaru *et al.* 2020) cracking and to prevent surface concrete crushing because of the inclined compressive stresses caused by shear - torsion, Eq. (16) is applied to confine the optimal dimensions in this condition. There wouldn't be other specifications to confine the reinforcing steel for shear - torsion because of its depending on the section dimensions before optimally finding. Thus, if the steel area is applied as constraints, the resolution direction has reinforced the section width (out) minimal reinforcement. This is not a general optimal resolution, but an optimal design for a special case taken before beginning the resolution. Considering the shear - torsion, the right decision for maximum optimization of the section should confine the cross sectional dimensions through the code specifications and leave the steel-reinforced area found and optimized through the process of bar selection (by designer).

Ultimately, Eqs. (17) and (18) are utilized for reinforcement topology through the section, regarding the minimal spacing between the selected bars (Adeli and Sarma 2006).

$$\frac{\sqrt{\left(\frac{V_u}{bd}\right)^2+\left(\frac{T_uP_h}{1.7A_{oh}^2}\right)^2}}{\phi\left(\frac{V_c}{bd}+0.66\sqrt{f_c'}\right)}-1\le 0 \tag{16}$$

$$(1-\frac{Bars\_Spacing}{Bars\_Diameter}\le 0)\ \ or\ \ (1-\frac{Bars\_Spacing}{25mm}\le 0) \tag{17}$$

$$(1-\frac{Layers\_Spacing}{25mm}\le 0) \tag{18}$$

3.4 Shear - torsion calculations

While GAs has optimized the beam section under flexure, shear - torsion and the optimum dimensions with flexural reinforcement are found (Shah *et al.* 2016b, Shah *et al.* 2016c). Then the shear capacity of optimal section is also found (Eq. (21), and the reinforced shear area (A_v) is computed through the code provisions to determine whether the section is not reinforced or carried the lowest or more reinforcement. The sections located in lower than distance *d* from the face of the support should be allocated to be designed for V_u calculated at a distance *d*, therefore, the design of cross section subjected to shear should be on the Eq. (19).

$$\varphi V_n\ge V_u \tag{19}$$

V_u = factored shear force at the considered section
V_n = nominal shear strength computed by

$$V_n = V_c + V_s \tag{20}$$

V_c = shear strength provided by concrete (Eq. (21))

$$V_c = 0.17\lambda\sqrt{f_c'}bd \tag{21}$$

λ = factor reflects the lower tensile strength of lightweight concrete
λ = 1 for normal weight concrete
V_s = nominal shear strength provided by shear reinforcement based on ACI code

Considering the lowest shear reinforcement area, $A_{v,min}$ should be provided in all the reinforced concrete flexural members

$$V_u > 0.5\varphi V_c \tag{22}$$

equal to

$$A_{v,\min} = 0.062\sqrt{f_c'}\frac{bs}{f_{yt}} \tag{23}$$

but shouldn't be less than

$$A_{v,\min} = \frac{0.35bs}{f_{yt}} \tag{24}$$

If V_u exceeds φV_c, the shear reinforcement should be provided based on Eq. (25)

$$A_v = \frac{V_s\times S}{f_{yt}\times d} \tag{25}$$

but shouldn't be greater than

$$V_s = 0.66\sqrt{f_c'}bd \tag{26}$$

The spacing of shear reinforcement shouldn't be exceeded (d / 2) or (600 mm), if

$$V_s > 0.33\sqrt{f_c'}bd \tag{27}$$

Later, the highest spacing curbs should be declined by one half. Considering the torsional design, the torsion effect should be neglected if subjected to

$$T_u < \varphi 0.083\lambda\sqrt{f_c'}\left(\frac{A_{cp}^2}{P_{cp}}\right) \tag{28}$$

A_{cp} = Area enclosed by the outside perimeter of the concrete cross section (mm^2)
P_{cp} = Outside perimeter of concrete cross section (mm)
Torsional design of cross section should be on

$$\varphi T_n \geq T_u \tag{29}$$

$$T_n = \frac{2A_o A_t f_{yt}}{s}\cot\vartheta \tag{30}$$

$$A_o = 0.85A_{oh} \tag{31}$$

A_o = Gross area enclosed by the shear flow path (mm^2)
A_{oh} = Area enclosed by the centerline of the outermost closed transverse torsional reinforcement (mm^2)
ϑ = taken as 45° for non – pre-stressed members
After finding (A_t / s), it should be added to (A_v / s), according to Eq. (32), and should be compared with the minimum value allowed by the code.

$$\frac{(A_v + 2A_t)}{s} = 0.062\sqrt{f_c'}\frac{b}{f_{yt}} \tag{32}$$

But shouldn't be less than

$$\frac{(A_v + 2A_t)}{s} = (0.35b)/f_{yt} \tag{33}$$

The longitudinal torsional reinforcement is computed based on

$$A_l = \frac{A_t}{s}P_h\left(\frac{f_{yt}}{f_y}\right)\cot^2\vartheta \tag{34}$$

Adding that, if the reinforcement is needed, it shouldn't be less than

$$A_{l,\min} = \frac{0.42\sqrt{f_c'}A_{cp}}{f_y} - \left(\frac{A_t}{s}\right)P_h\frac{f_{yt}}{f_y} \tag{35}$$

(A_t / s) shouldn't be less than 0.175 b / f_{yt}

Spacing of transverse torsion reinforcement should not be exceeded from the smaller of (P_h /8) or (300 mm). After finding total area of steel for shear - torsion, an optimization process is adopted to select what bar diameter could provide the lowest cost (economical) to be used as stirrups in the section. The bar selection is based on database, including φ 8, φ 10, φ 12 and φ 16 arranged through the longitudinal direction according to the code curbs of minimal and maximal spacing.

Also, the minimum allowed spacing for stirrups less than shear stirrups spacing limitations or torsional stirrups spacing limitations would be compared under control. The same process is used for the maximal spacing, thus, the longitudinal reinforcement needed for torsion should be distributed around the perimeter of the closed stirrups with a maximum spacing (300 mm) divided into layers that are distributed through the section height based on the final optimal dimension with a distance not more than (300 mm) between each two layers. Thus, the lower layer has been added to the optimal flexural reinforcement before selecting the proper bar number. For the rest layers of longitudinal reinforcement, the same process for selecting from the database is adopted to find the bar diameter with the least cost.

4. Unifying the sections

GAs in the presence of Matlab is used to find the optimal solution by measuring the fitness of problem (the cost of sections) with the influence of same GAs design constraints and using the same design variables with little differences. GAs is majorly used in finding the optimal resolution for dimensions and the reinforcement ratio of a specified section along the span separately, however, the resulting beam (Fig. 5) could be inapplicable without fulfilling its purpose as a structural member. To deal with this problem, some modifications should be performed for the optimum design process in two levels: 1) all the chosen sections have been optimized by using GAs as a single case, 2) unifying the dimensions only for all the optimized sections (Fig. 6) by checking each available section in database and measuring its fitness, then finding the closest section that gives the nearest cost to all the optimized section without violating any design constraints used in optimizing each section separately through GAs resolution

First, the applied loads and moments with shear - torsion have been calculated according to ACI code (8.3.3), later, an analysis, processing are carried out to specify the moments, shear - torsion results needed to design the continuous beam optimally. Regarding the moment section positions used in this study, beam has been designed through GAs model by presenting each span with three different chromosomes. Among which, two chromosomes represent the sections with the critical adverse moments near the supports, and the third one represents the middle span section with the positive moment. All these chromosomes carry a number in a predefined database consisting all the possible sections for beams with their dimensions. These sections satisfy any moment requirements (within a certain limitation) and steel

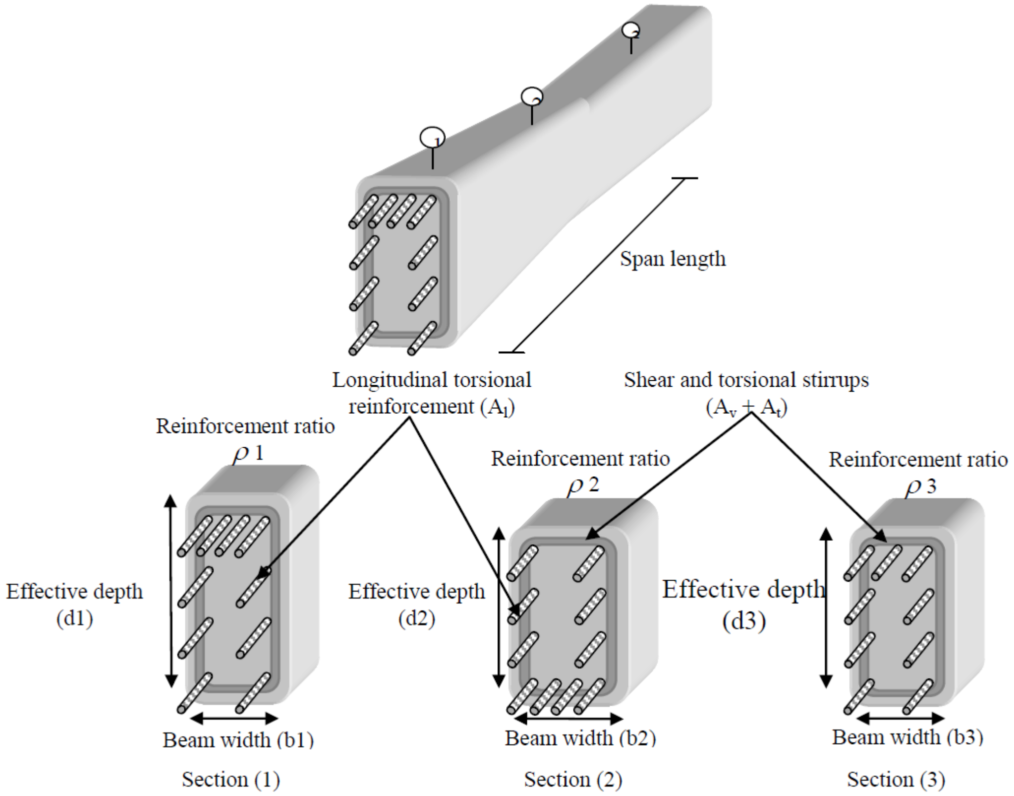


Fig. 5 Optimum design for continuous beam using GAs

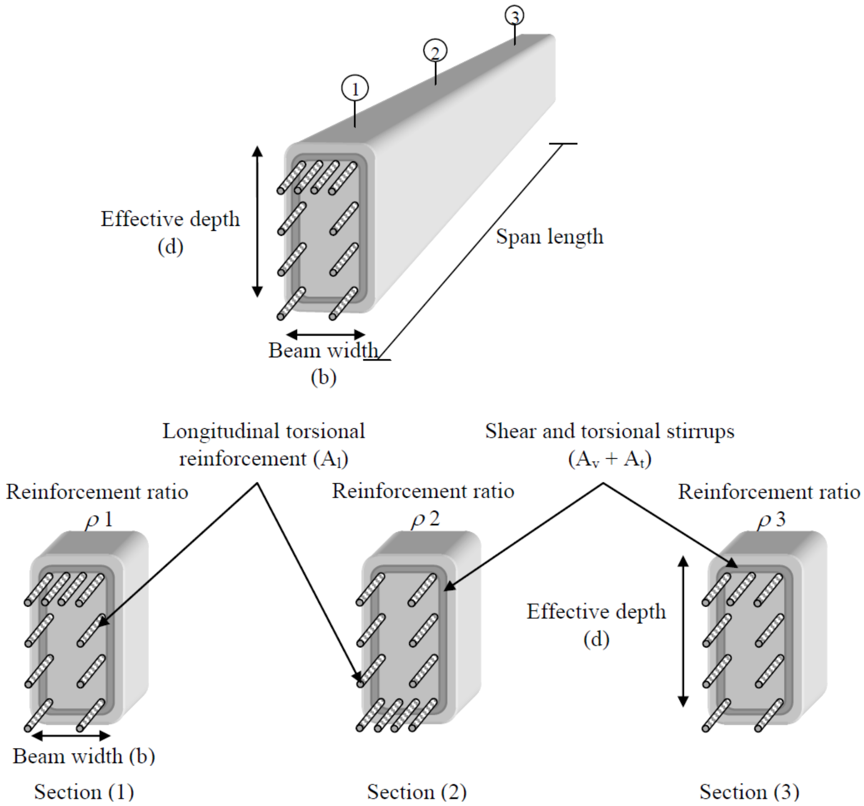


Fig. 6 Optimum design for continuous beam with unified section

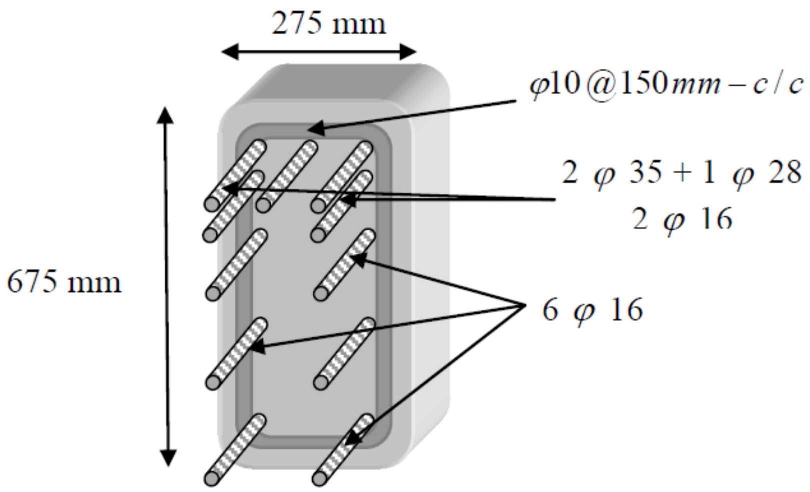


Fig. 7 Reinforced concrete beams design variables

reinforcement with bar positioning. Since the optimum depth of the section has not been found yet, the minimum allowable depth for deflection could be controlled. Section position used for negative moments is also used for shear - torsion. The design variables for the second level are the dimensions of the unified section for the whole span under the effect of flexure, shear - torsion, also the flexural reinforcement ratio of each optimized section (depending on the accuracy of the resolution) and the longitudinal torsional reinforcement with the transverse reinforcement for shear - torsion (Fig. 6).

5. Stirrups distribution

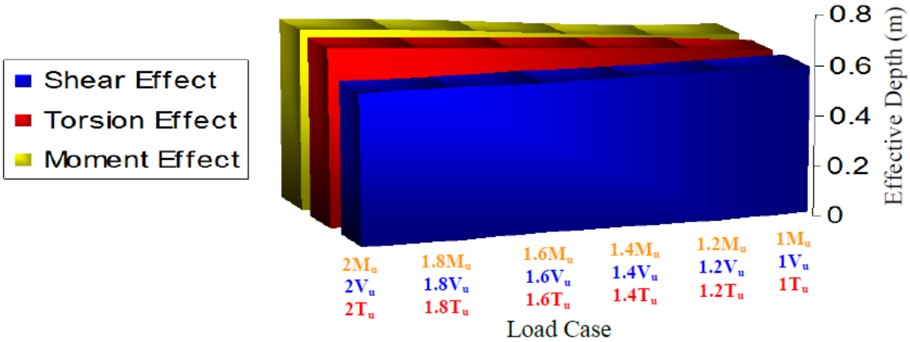
After finding the transverse reinforcement (A_v and A_t), representing any kind of stirrups' distribution with an extreme difference between any adjacent sections could be difficult, in case of selecting either the proper bar size or the correct spacing which is considered as an optimum resolution for the whole span (because the spacing of stirrups at a specified section is intersected with the spacing of stirrups at the next closest section which is different from the previous spacing). A specific and correct optimum answer for bar numbering and spacing is gained in a specific section of span. Therefore, the precise results to the optimum resolution for this case have found the spacing for each bar number of whole span at each point without defining spacing for a certain section. This help designer to decide which bar number could be used at any section with the stirrups spacing at that span. As an ultimate resolution, each continuous beam's section (Fig. 6) could be designed by GAs in terms of all the limitations and finding the optimal reinforcements and dimension for each section while defining the bar size of stirrups and spacing at that certain section that is leading to a multi-dimensioned beam at each span (not practical). As a result, a developed program is required to unify the cross sectional dimension that leave the stirrup distribution(s) undefined instead of an optimum stirrup spacing for overall unified span at each point that is found for many bar numbers to help designer in decisions.

6. Parametric study

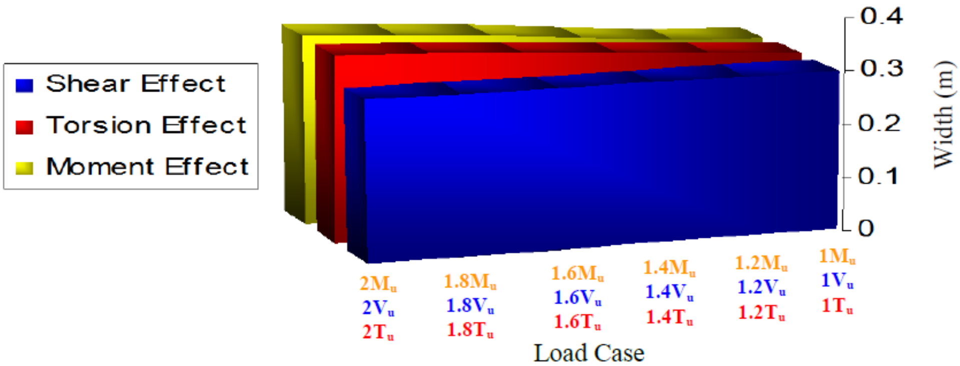
A few examples observed the effect of applied loads, shear - torsion and the properties of materials with the material cost on the optimal cost and optimal design variables of designed members.

6.1 Effect of moment, shear and torsion

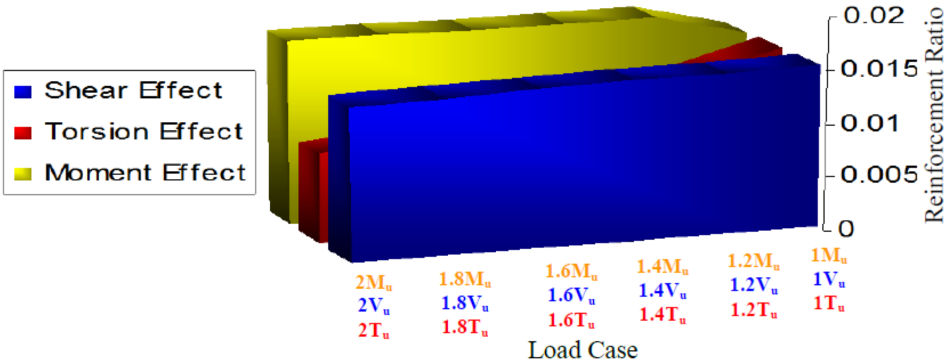
A cantilever beam with a span of 5.0 m is optimally designed. The beam is loaded with: M_u = 500 kN . m, V_u = 150 kN , T_u = 50 kN . m, and the needed design information are: r = 75, f_c' = 30 MPa, f_y = 400 MPa. The optimum design dimensions are b=296 mm, d = 588.6 mm, and the reinforcement ratio is 0.0154. The cost of this optimally designed section is 0.394 C_c, therefore, the suboptimum resolution for this section is shown in Fig (7). The same beam has been repeatedly re-designed with the same applied load except the moment increased by 20% at each time in which the section is designed till reaches to 200% of its original value. The same process has been iterated, however, now the moment and torsion have been remained at their values and the applied shear is increased by the same percent till reaches to 200% of its original value. Also, the torsion is over loaded by the same percent while keeping the moment and shear at their original values till reach to 200%. Regarding the effect of moment, shear - torsion on the optimum cost is shown in Figs. (8) and (9). Thus, this effect is mostly noticed on the cross sectional area under the effect of moment and torsion, while the shear has slightly affected the cross sectional area of beam (Table 1).



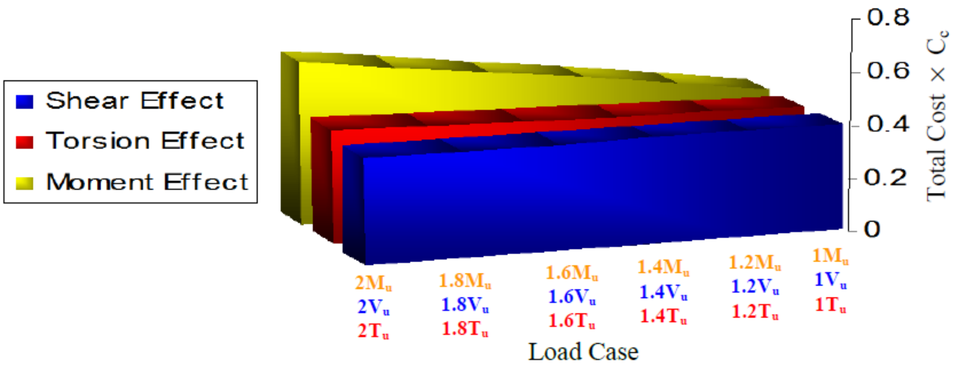
(a) Moment, shear and torsion effect on optimum effective depth



(b) Moment, Shear and torsion effect on optimum width



(c) Moment, Shear and torsion effect on optimum reinforcement ratio

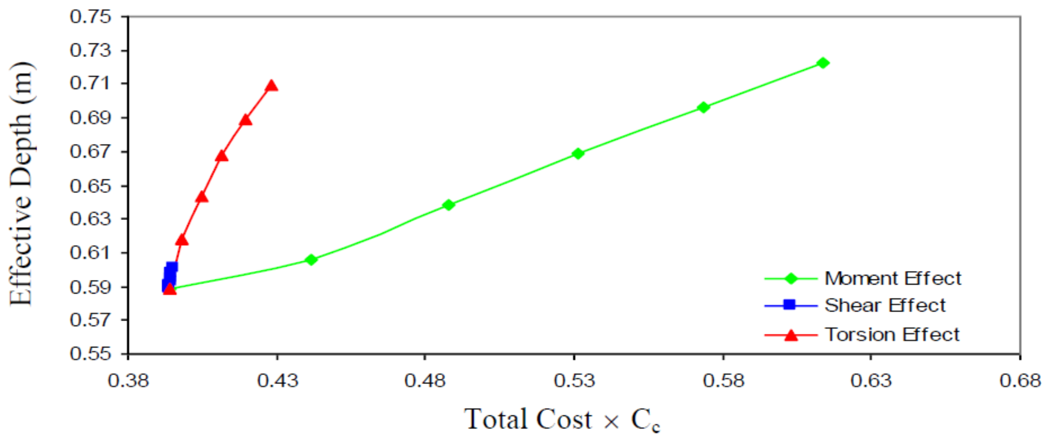


(d) Moment, Shear and torsion effect on optimum cost

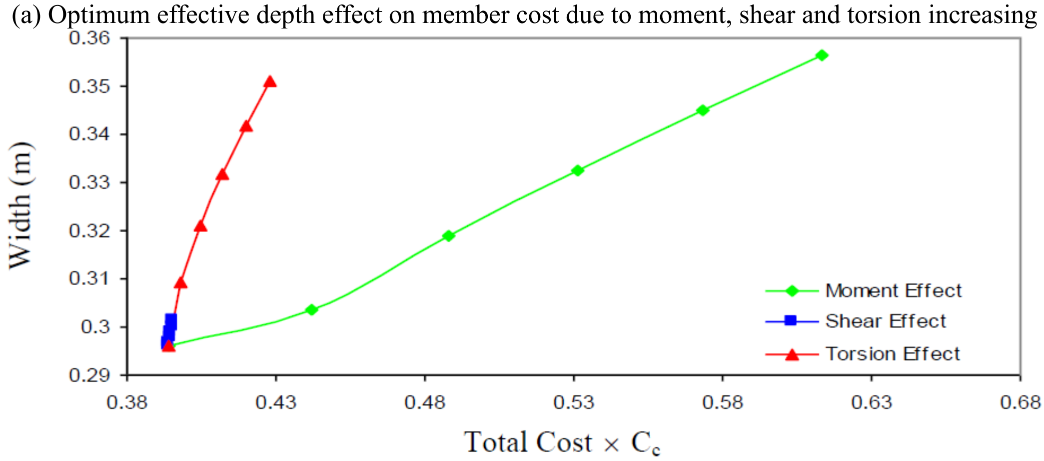
Fig. 8 Effect of moment, shear and torsion on the optimum design variables

Table 1 Optimum design results for a cantilever beam loaded with bending moment, shear - torsion

Load Case	Optimum Results				Suboptimum Results		
V_u=150 kN T_u=50 kN.m	Width (mm)	Effective Depth(mm)	ρ	Cost/C_c	Width (mm)	Height (mm)	Rein. Bars
$1M_u,1V_u,1T_u$	296	588.6	0.0154	0.394	275	675	'2 φ 35+1 φ 28''2 φ 16'
$1.2M_u,1V_u,1T_u$	303.7	605.7	0.0173	0.4417	300	675	'3 φ 35''5 φ 12'
$1.4M_u,1V_u,1T_u$	318.8	638.8	0.0173	0.4877	300	725	'3 φ 35''4 φ 16'
$1.6M_u,1V_u,1T_u$	332.4	668.8	0.0173	0.5314	325	750	'3 φ 35''3 φ 22'
$1.8M_u,1V_u,1T_u$	345	696.5	0.0173	0.5733	325	775	'3 φ 35''3 φ 25'
$2M_u,1V_u,1T_u$	356.6	722.1	0.0173	0.6136	350	800	'3 φ 35''2 φ 20+1 φ 12'
$1M_u,1.2V_u,1T_u$	296.8	590.4	0.0152	0.3942	275	675	'2 φ 35+1 φ 28''2 φ 16'
$1M_u,1.4V_u,1T_u$	297.7	592.5	0.0151	0.3944	275	675	'2 φ 35+1 φ 28''2 φ 16'
$1M_u,1.6V_u,1T_u$	298.8	595	0.0149	0.3947	275	675	'2 φ 35+1 φ 28''2 φ 16'
$1M_u,1.8V_u,1T_u$	300.1	597.7	0.0146	0.395	300	675	3 φ 35
$1M_u,2V_u,1T_u$	301.5	600.8	0.0144	0.3954	300	675	3 φ 35
$1M_u,1V_u,1.2T_u$	309.2	617.7	0.0131	0.3983	300	700	3 φ 35
$1M_u,1V_u,1.4T_u$	321	643.7	0.0115	0.4045	300	725	2 φ 35+1 φ 32
$1M_u,1V_u,1.6T_u$	331.8	667.4	0.0102	0.4118	325	725	2 φ 35+1 φ 32
$1M_u,1V_u,1.8T_u$	341.7	689.3	0.0092	0.4198	325	750	2 φ 35+1 φ 32
$1M_u,1V_u,2T_u$	351	709.6	0.0084	0.4281	350	750	2 φ 28+3 φ 25

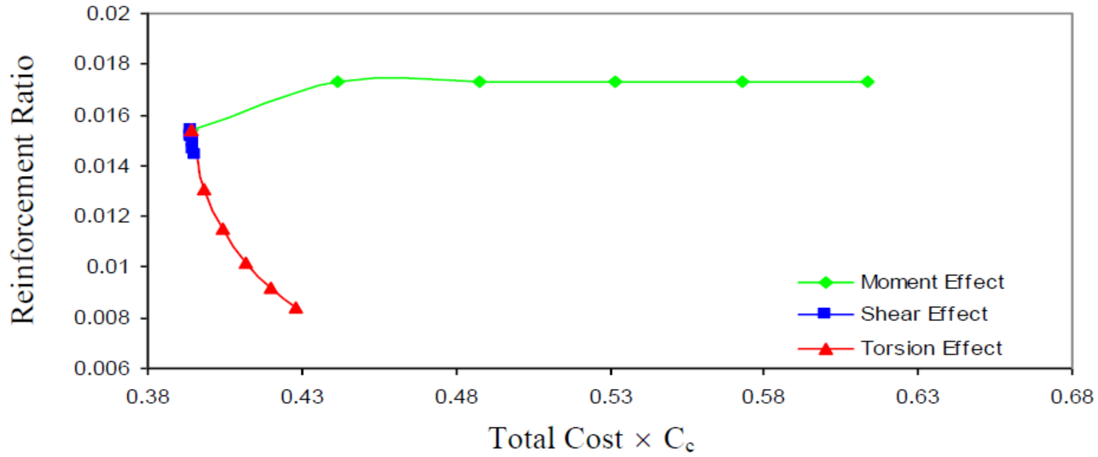


(a) Optimum effective depth effect on member cost due to moment, shear and torsion increasing



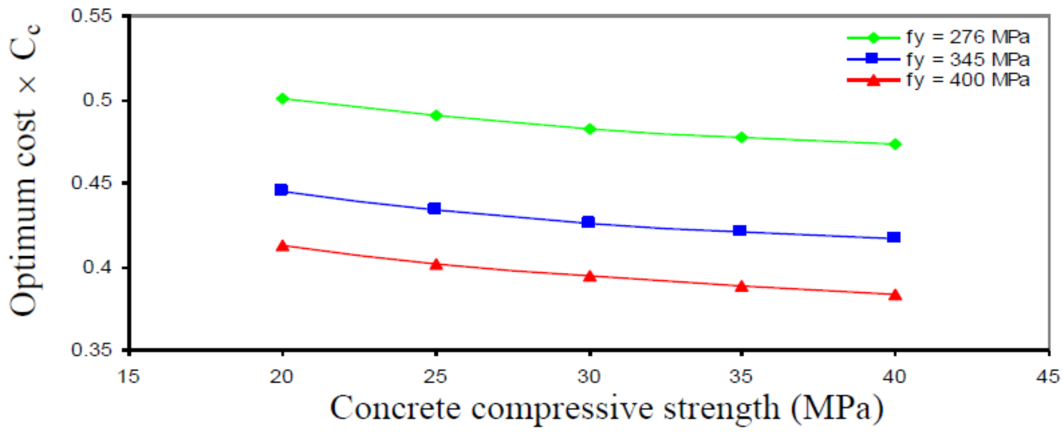
(b) Optimum width effect on member cost due to moment, shear and torsion increasing

Continued-

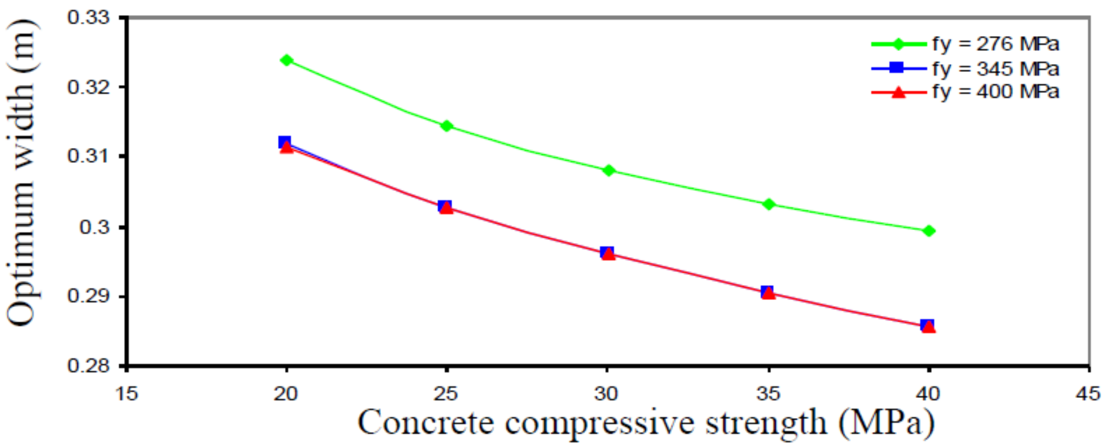


(c) Optimum reinforcement ratio effect on member cost due to moment, shear and torsion increasing

Fig. 9 Optimum design variables effect on member cost due to moment, shear and torsion increasing



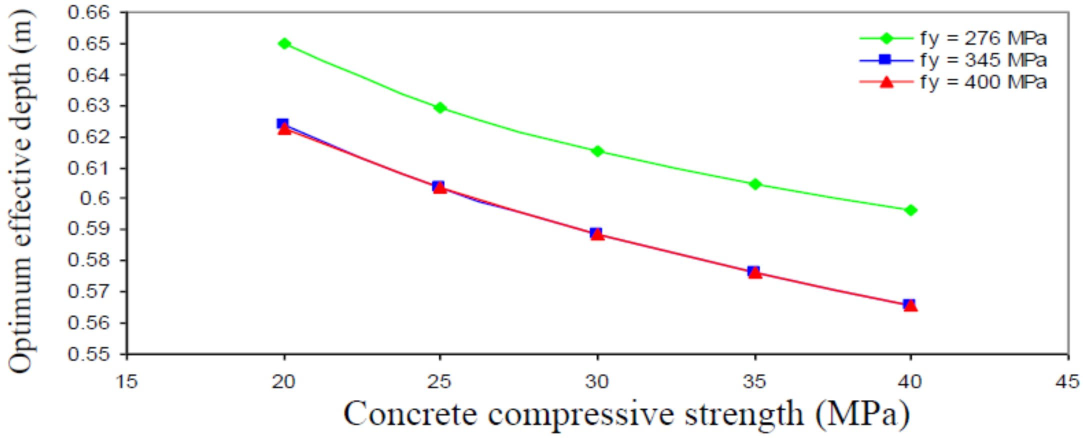
(a) Concrete compressive strength effect on the optimum cost of the section



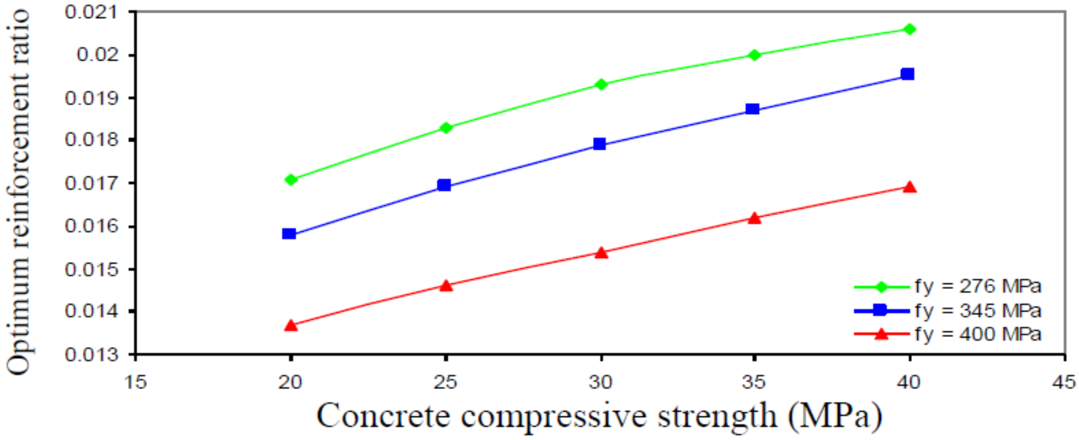
(b) Concrete compressive strength effect on the optimum width of the section

Continued-

Also, according to Fig. 7 the reason behind the members' cost increment under the effect of moment, shear - torsion is not the reinforcement ratio that is decreased or stabled by cost raising. Approximately, this is noticed under the torsion effect, while remained almost constant under the moment effect with slightly reduction under the shear effect.

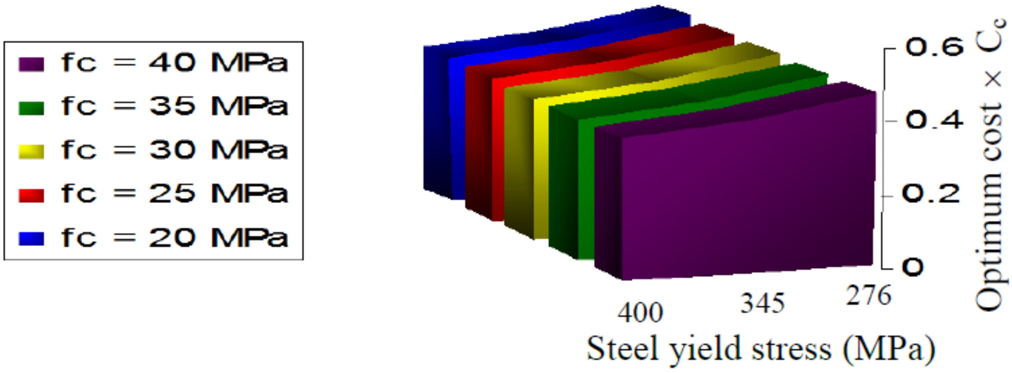


(c) Concrete compressive strength effect on the optimum effective depth of the section



(d) Concrete compressive strength effect on the optimum reinforcement ratio of the section

Fig. 10 Concrete compressive strength effect on the optimum design variables



(a) Steel yield stress effect on the optimum cost of the section

Continued-

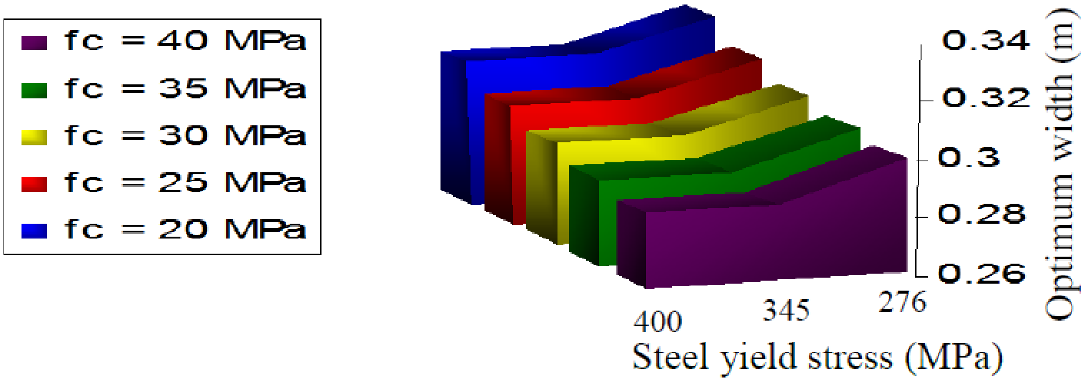
The main reason for raising the cost by raising the concrete volume is that GAs use the cheapest material in finding the optimal member cost.

Fig. (9) shows that the whole effect of applied torsion doubling on total section cost not exceed 20% of the moment increment effect, and the whole shear effect on the cost not exceed 20% of one torsional increment effect on the cost.

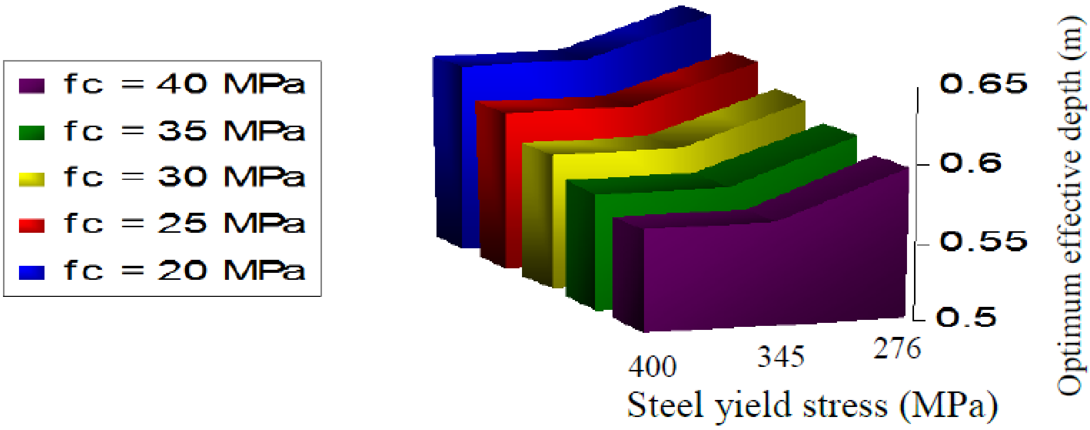
6.2 Effect of f_c' and f_y on optimum cost

The same example was solved again, but this time to find out how far the compressive strength of concrete and the steel yield stress affects the optimum design variables and optimum cost.

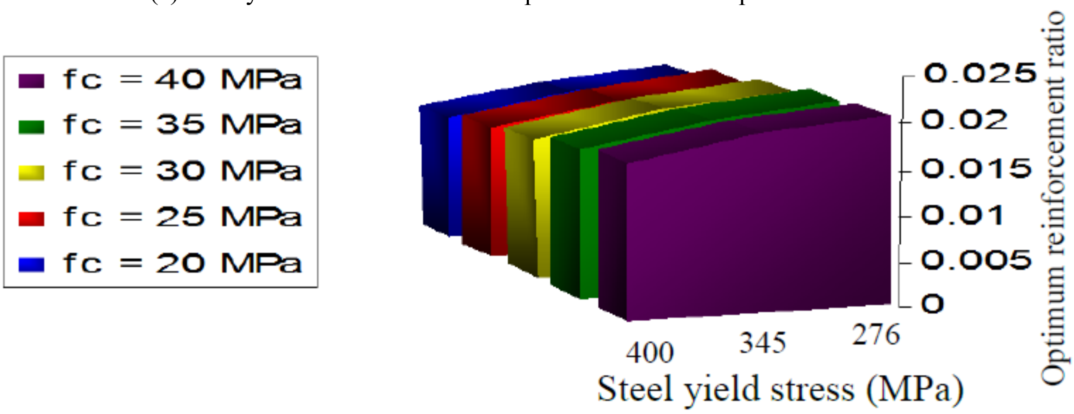
As shown in Fig. (10), the fitness of the optimum sections decreases with the increase in the compressive



(b) Steel yield stress effect on the optimum width of the section



(c) Steel yield stress effect on the optimum effective depth of the section



(d) Steel yield stress effect on the optimum reinforcement ratio of the section

Fig. 11 Steel yield stress effect on the optimum design variables

strength of concrete due to the decrement of the optimum dimensions (both width and effective depth), also noticing that the section will witness cost increases when using steel reinforcement with lower yield stress, and this is because of the need for more reinforcement ratio, as shown in this figure.

Increasing the concrete compressive strength decreases the optimum width and effective depth by almost 7.8%, and this will also decrease the optimum cost by 5.4%, as shown in Fig. (10) for a yield stress of steel equal to 276 MPa.

Fig. (11) shows that increasing the yield stress will decrease the optimum design variables and the optimum cost of the sections by changing the yield stress of the used reinforcing steel for the same compressive strength of concrete. This effect is mostly noticed at the lower yield stress on the optimum sectional dimensions. Also shown in this figure is that the optimum dimensions and cost increases by decreasing the concrete compressive strength except for the optimum reinforcement ratio.

Increasing the steel yield stress in this figure with 20 MPa concrete compressive strength, decreases the optimum dimensions by about 4% causing a saving in the optimum cost of 17.5%.

Obviously, seeking the cheapest beam section for this case is done by controlling the used steel in the design, because its effect on the cost is more than the concrete

7. Conclusions

Indeed, the cost optimization is the optimization type that should be used for a two-material structure or more. Because some of the design properties and their major effect on the structure could be handled mostly by only one material against the other. By increasing the applied torsion on a beam to double its original value, the total cost increases by only 20% from the cost of doubling the applied moment on the same beam. Also doubling the applied shear on the beam, increases the total cost by about 20% from the cost of doubling the applied torsion. Also by increasing the applied torsion on beams, the optimum reinforcement ratio no longer decreases with the increased steel price at some level, and as for the optimum dimensions, it will no longer increases with the steel price increment. This is because when a design variable reaches its limits, the other design variables handle the applied torsion at that level even when it is more expensive to use the first design variable to resist the applied torsion. Increasing the yield stress of the used steel in the designed beams sections, decreases the total cost because of the use of less reinforcement ratio and also less dimensions for the cross section which be used when using a higher concrete compressive strength.

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