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A fast and robust procedure for optimal detail design of continuous RC beams

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Abstract. The purpose of the present study is to present a new approach to designing and selecting the details of multi-dimensional continuous RC beam by applying all strength, serviceability, ductility and other constraints based on ACI318-14 using Teaching Learning Based Optimization (TLBO) algorithm. The optimum reinforcement detailing of longitudinal bars is done in two steps. in the first stage, only the dimensions of the beam in each span are considered as the variables of the optimization algorithm. in the second stage, the optimal design of the longitudinal bars of the beam is made according to the first step inputs. In the optimum shear reinforcement, using gradient-based methods, the most optimal possible mode is selected based on the existing assumptions. The objective function in this study is a cost function that includes the cost of concrete, formwork and reinforcing steel bars. The steel used in the objective function is the sum of longitudinal and shear bars. The use of a catalog list consisting of all existing patterns of longitudinal bars based on the minimum rules of the regulation in the second stage, leads to a sharp reduction in the volume of calculations and the achievement of the best solution. Three example with varying degrees of complexity, have been selected in order to investigate the optimal design of the longitudinal and shear reinforcement of continuous beam.

Keywords: continuous beam; optimization; reinforced concrete; teaching learning based optimization algorithm; reinforcement detailing; cost function

1. Introduction

The design of concrete structures involves a wide range of parameters and constraints, and a correct answer must be able to satisfy all of these constraints. In conventional design methods, using some of the parameters as problem inputs, the other parameters are calculated. if the answer satisfies all the constraints, it can be chosen as the correct answer, Otherwise, the input values will be improved and this process continues until the user can achieve an answer satisfying all constraints. Although the answer to the set of solutions is acceptable, the answer may not be optimal. Achieving optimal solution with trial and error requires a long time and high user experience (Sarma and Adeli 1998). To overcome this problem and to achieve real optimal solution in the least time, many methods and studies have been done.

In recent decades, many optimization techniques have been used to optimize structures. Most of these methods are divided into two sections of gradient-based methods and random methods (Dizangian and Ghasemi 2015). These optimization techniques are used for optimal design purposes for structures such as RC frames (Megros 2018, Guerra and Kiousis 2006, Tapao and Cheerarot 2017, Kaveh and Sabzi 2011), RC beams and columns (Amir and Shakour 2018, Sánchez-Olivares and Tomás 2017), RC retaining walls (Ghandomi *et al*. 2017), truss structures (Kanno 2019), and estimating the failure probability of structures (Nobahari *et al.* 2017, Arab and Ghasemi 2015) Some of these studies in the field of optimization of continuous reinforced concrete beams, are continuously described below:

Friel (1974) studied the singly reinforced flexural members with ultimate strength method. He obtained an equation to determine the optimal steel-to-concrete ratio. In this method, for the purpose of designing a flexural member, the optimal ratio of steel to concrete is used as a starting point to find the residual dimensions of the member. Chou (1977) uses the Lagrange multiplier method to determine the depth and the cross section of flexural steel in a singly reinforced T- beam based on ACI code. Kirsch (1983) uses a three-step iterative method to optimize the rectangular continuous RC-beam. So that in the first level optimizes the value of reinforcements based on cross-sectional dimensions and design moment. on the second level, it was designed to optimize the sectional dimensions based on design moment, and at the third level to optimize the design moment based on elastic analysis results. This iterative process begins with the assumption of the initial dimensions of the section and the determination of the moment under the ultimate loads by the elastic analysis method and is reversed from the third to the first level. Parakesh *et al*. (1988) uses Lagrangian and simplex methods to optimize singly and doubly RC beams, slabs, T-shaped RC beams, and columns with different strengths of steel and concrete according to requirements of Indian code. Karihaloo (1991) has used sequential linear programming and sequential convex programming techniques for optimizing single and multi-span RC beams and RC columns. Chakabarty (1992) has used geometric

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programming and Newton-Rapson methods to optimize the RC rectangular beams.

Coello *et al*. (1997) has used a simplified genetic algorithm to optimize the singly reinforced rectangular beam. The results obtained from this method were compared with the results of geometric programming method. Koumousis and Arsenis (1998) have been developed a genetic algorithm to optimize members of multi-storey RC buildings. Leps (2003) uses a combination of genetic algorithm and simulated annealing to optimize the RC beam according to the EC2. Govindaraj and Ramasamy (2007) used a genetic algorithm for optimizing the cross-sectional dimensions and reinforcement detailing in the T-shaped RC beam with regard to the serviceability, strength and ductility constraints, according to Indian regulations. The area of steel is defined as a set of longitudinal bars with a given number and diameter in a database. Barros *et al.* (2005) has optimized the rectangular RC sections according to EC2 and compared its results to the ultimate strength design based on the ACI. Fedghouche and Tiliouine (2012) used a gradient reduction method to optimize the T-shaped RC beams under ultimate design loads according to EC2. due to the impact of the beam weight on the long spans on the ultimate bending moment capacity, in the objective function and related constraints, it is considered variable as well (Fedghouche 2012). Jahjouh *et al.* (2013) uses an improved artificial bee colony algorithm to optimize the RC rectangular beam based on ACI. The dimensions of the beam are assumed to be the same at all spans. Sharafi *et al.* (2012) has optimized the multi-span RC beams under the dynamic response using the Ant colony algorithm. Ozturk *et al.* (2012) has optimized the cost of an RC beam with Simple supports using the bee colony algorithm.

The present study, using a new method, attempts to achieve the best solution by satisfying all resistance, exploitation, and other constraints related to the RC continuous beam according to ACI318-14 (2014). On the longitudinal reinforcement detailing design of the RC beam, the area of steel is completely dependent on the dimensions of the cross section of the beam in each span. Regarding this, in this study, a two-stage process has been used to optimize the details of longitudinal bars of continuous RC beams. The dimensions of the cross section of the RC beam in each span are the input parameters of stage one. In the second step by using a catalog list, a precise answer is given to the longitudinal reinforcement details in each span.

The optimization of shear bars is one of the complicated problems of concrete structural members (Prera and Vique 2009). In recent studies (Govindaraj and Ramasamy 2005, Jahjouh *et al.* 2013), the design process of the shear reinforcement details along the RC beam has been continuously applied in each span in the usual manner based on codes. In this study, by minimizing gradient-based methods, the equation is related to the total number of shear bars during each of the spans optimized and the least weight of the shear reinforcement is obtained.

Among the methods of random optimization, we can refer to a variety of meta-heuristic methods (Munk *et al.* 2015). PSO (Hanoon *et al.* 2017), GA (Senouci and Al-Ansari 2009, Pérez *et al.* 2012), ABC (Tapao and Cheerarot 2017), HS (Akin and Saka 2015) and SA (Paya-Zaforteza *et al.* 2009) algorithms are well-known and widely used algorithms for the optimization of concrete structures. All these methods are based on a search in a random space. The TLBO-based algorithm is an emerging and population-based algorithm that was presented by Rao *et al.* (2011). This algorithm is inspired by the teacher's influence on student learning in the classroom and is based on two phases: Teacher and students (Rao *et al.* 2012). This algorithm has been considered in many engineering sciences, including mechanics (Rao and More 2015), structural engineering (Farshchin *et al.* 2016, Cheng and Prayego 2017) and has proved its ability to solve complex engineering problems. Further, the steps for each section are explained in detail and are fully discussed.

2. Optimal detail designing of reinforcement

The optimum detail design of longitudinal reinforcement is possible in a continuous RC beam, in a multi-stage process and in accordance with specific design criteria. For a RC beam with specified dimensions and loading in each span, the maximum bending moment and shear force at each point of the continuous beam is determined. In the first step, the required area of the longitudinal steel at each point of the length of the beam is determined. In the second step, using a catalog list containing all longitudinal reinforcement patterns, based on the results of the step one, the pattern with the least longitudinal steel weight is chosen as the optimal pattern of the longitudinal reinforcement of the span.

2.1 Catalog list production process

In order to ensure the operational structure of the required area of steel in the RC beam, it should be expressed as a set of bars with a specific number and diameter. In previous studies (Govindaraj and Ramasamy 2005), a separate database was created for each width of the beam but, in the present study, before the start of the optimization process, all the possible patterns for longitudinal reinforcement can be determined by changing the number and diameter of the bars, and stored as a general database. This database is called at each stage of optimal details design of longitudinal reinforcement. This process will accelerate the optimization process and select the best available mode according to the rules mentioned in the code. Each section of the beam is considered as a singly reinforced layer and longitudinal compressive bars are not included in the calculations. The area of required longitudinal steel consists of four groups of bars with a different number and diameter. This leads to the optimal possible range, based on the area of required longitudinal steel in each section of the beam. In this study, for the production of the catalog list, the minimum and maximum number of longitudinal bars in the RC beam is considered to be 2 and 8 respectively.

According to Fig. 1, n_i and Φ_i are the number and diameter of the longitudinal bars of each group, respectively. The minimum values of S and C are based

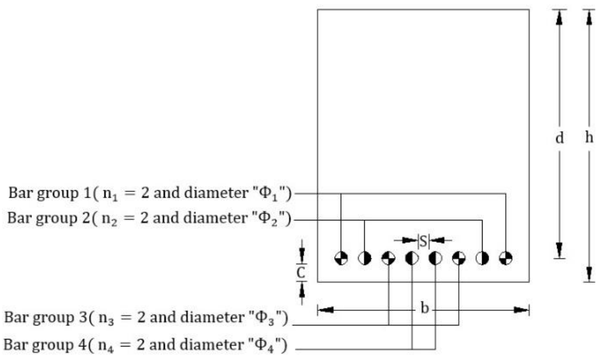

Fig. 1 cross-sectional longitudinal reinforcement detail pattern

on the ACI318-14, with the largest values of 25 mm d_b, $1.33d_{agg}$, and 40 mm respectively. d_b is the largest diameters of longitudinal bars and d_{agg} is the largest diameter of aggregate in concrete. in order to consider all modes, 12, 14, 16, 18, 19, 20, 22, 24, 25, 26, 28 and 30 standard diameters are used for longitudinal bars. Each pattern is created by changing the diameter and the number of bars. If longitudinal bars with different diameters are used in a longitudinal reinforcing bar placement pattern, the effective depth of section is calculated considering the largest diameter of the longitudinal bar used in the given pattern. However, the method used in this study has no limitations in the number and diameter of longitudinal bars. Taking into consideration the above conditions, all possible states of the diameters and the numbers of longitudinal bars are produced. What the strength point of this approach is that, unlike recent studies (Govindaraj and Ramasamy 2005) in which, patterns with the same longitudinal steel are removed from the set, in this approach, compounds with the same longitudinal steel due to the effect the diameter of the bar in determining the development length are retained. In the production of the catalog list, the b_{min} parameter is

Table 1 Part of the catalog list produced in this study

Patt no	Φ12	Φ14	Φ16	Φ18	Φ19	Φ20	Φ22	Φ24	Φ25	Φ26	Φ28	Φ30	$A_s(\mathrm{mm}^2)$	b_{min}(mm)
number of patterns with 2 bar=12														
1	2	0	0	0	0	0	0	0	0	0	0	0	226.19	149
2	0	2	0	0	0	0	0	0	0	0	0	0	307.87	153
3	0	0	2	0	0	0	0	0	0	0	0	0	402.12	157
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
12	0	0	0	0	0	0	0	0	0	0	0	2	1413.70	190
number of patterns with 3 bar=144														
13	3	0	0	0	0	0	0	0	0	0	0	0	339.29	186
14	2	1	0	0	0	0	0	0	0		0	0	380.13	188
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
156	0	0	0	0	0	0	0	0	0	0	0	3	21206	250
number of patterns with 4 bar=78														
157	4	0	0	0	0	0	0	0	0	0	0	0	452.38	223
158	2	2	0	0	0	0	0	0	0	0	0	0	534.07	227
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
234	0	0	0	0	0	0	0	0	0	0	0	4	2827.4	310
number of patterns with 5 bar=936														
235	5	0	0	0	0	0	0	0	0	0	0	0	565.48	260
236	4	1	0	0	0	0	0	0	0	0	0	0	606.32	262
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
1170	0	0	0	0	0	0	0	0	0	0	0	5	3534.3	370
number of patterns with 6 bar=364														
1171	6	0	0	0	0	0	0	0	0	0	0	0	678.58	297
1172	4	2	0	0	0	0	0	0	0	0	0	0	760.26	301
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
1534	0	0	0	0	0	0	0	0	0	0	0	6	4241.2	430
number of patterns with 7 bar=4368														
1535	7	0	0	0	0	0	0	0	0	0	0	0	791.68	334
1536	6	1	0	0	0	0	0	0	0	0	0	0	832.52	336
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
5902	0	0	0	0	0	0	0	0	0	0	0	7	4948.00	490
number of patterns with 8 bar=1365														
5903	8	0	0	0	0	0	0	0	0	0	0	0	904.77	371
5904	6	2	0	0	0	0	0	0	0	0	0	0	986.46	375
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
7267	0	0	0	0	0	0	0	0	0	0	0	8	5654.90	550

calculated and stored. This parameter represents the minimum possible value for the width of the RC beam. Table 1 shows part of the catalog list produced in this study.

2.2 How to choose the optimal longitudinal reinforcement pattern

Due to the optimal design and weight reduction of the consumption steel in a continuous RC beam, the pattern of cutting longitudinal bars by the critical areas of bending moments along the beam is used (Akin and Saka 2015, Jahjouh *et al.* 2013). Therefore, the longitudinal bars in the beam can be divided into the longitudinal continuous bars and longitudinal additional bars (Extra bars). Choosing the best longitudinal reinforcement pattern is divided into two sections of the selection of continuous bars and the selection of additional bars. With regard to the different nature of the selection of continuous longitudinal bars and additional longitudinal bars in different areas of the RC beam, each section is explained and addressed separately.

2.2.1 Selection of continuous longitudinal bar

For continuous RC beams, the process of selecting continuous longitudinal bars for the positive and negative bending moment is the same. the process by applying limiting conditions to the catalog list produced in the previous sections begins. based on the ACI (22-3-1-1) the required area of the longitudinal steel in each section of the beam is determined by using the Eq. (1).

$$A_s = 0.85db\frac{f_c'}{f_y} + \sqrt{(0.85db\frac{f_c'}{f_y})^2 - \frac{1.7f_c'bM_u}{\emptyset f_y^2}} \qquad (1)$$

In Eq. (1), $\emptyset$ is the resistance reduction coefficient that is equal to 0.9, M_u is the maximum bending moment produced by the analysis, A_s is the required area of tensile longitudinal steel, f_y is the yielding resistance of the steel, d is the effective depth of the cross section, b is the width of the beam and f_c' is the compressive strength of the concrete. The minimum and maximum required area of the longitudinal steel in the beam are calculated based on the ACI (9-6-1-2) and ACI (9-3-3-1), respectively.

After determining the above values, using the set of effective conditions, the unauthorized patterns are eliminated from the list and only the patterns that can be applied in all of the advanced conditions are maintained in the set. The limiting conditions of the catalog list at this stage are as follows:

• Patterns with longitudinal steel area larger than the permitted amount of rules are deleted.

$$(A_{s,patt} > A_{s,max,all})$$

$A_{s,patt}$ is the longitudinal steel area of each of the patterns in the catalog list.

$$A_{s,patt} - max(A_{s,max,span_i}) > \varepsilon \ , i = 1, \ldots, N_{span}$$

• Patterns with a longitudinal steel area larger than the maximum longitudinal steel area in all the spans will be emitted. The closest longitudinal steel area to the maximum required area of longitudinal steel in all of the spans is maintained in the catalog list.

$A_{s,max,span}$ is the maximum required area of longitudinal steel in each span, N_{span} is the total number of spans, and ε is defined as the difference between the maximum required area of longitudinal steel in all spans with the closest longitudinal steel area larger than that.

$$A_{s,patt} < max(A_{s,min,span_i}) \ , i = 1, \ldots, N_{span}$$

• After limiting the area of the longitudinal steel in each span, based on the minimum permissible values in the code, patterns with longitudinal steel area smaller than the largest minimum area of longitudinal steel in all the spans are totally emitted.

$A_{s,min,span}$ is the minimum required area of longitudinal steel in each span.

$$b_{span} > b_{min}$$

• Patterns with larger b_{min} than the width of the beams are deleted.

b_{span} is the width of the beam in each span.

After applying all the above conditions, the numbers of patterns allowed for continuous longitudinal bars are significantly reduced. At this stage, the remaining patterns are tested for additional longitudinal bars.

2.2.2 Selection of additional longitudinal bars

Selection of additional longitudinal bars is a process that is completely dependent on longitudinal bars. Therefore, at each stage of the testing process of the continuous longitudinal bars is repeated. For this purpose, the RC beam is continuously divided into different regions. The number of these zones for the longitudinal bars of the positive and negative bending moment is N_{span} and $N_{span} - 1$ respectively. Additional longitudinal bars are positioned at the bottom for the positive bending moment of the beam, in the middle of the span and for the negative bending moment above the beam, in the supports. Every zone of the continuous beam is Separately examined and the best longitudinal reinforcement pattern for it, is determined as well. The limiting conditions of the catalog list for the selection of additional longitudinal bars are as follows:

• Patterns that do not include continuous longitudinal bars of the preceding stage will be deleted.

• Patterns with a greater longitudinal steel area than the maximum permitted in the code, are eliminated.

$$(A_{s,patt} > A_{s,max,all})$$

• Patterns with a smaller longitudinal steel area than the maximum longitudinal steel area in each area are eliminated.

$$A_{s,patt} < A_{s,max,span_i} \ , i = 1, \ldots, N_{span}$$

• Patterns with larger b_{min} than the width of the beams are deleted.

$$b_{span} > b_{min}$$

• Based on the ACI (9-5-1-1), patterns with a design bending strength less than the maximum flexural strength of the analysis in each area are eliminated.

$$\emptyset M_{n,patt} < M_{u,max,span_i} \ , i = 1, \ldots, N_{span}$$

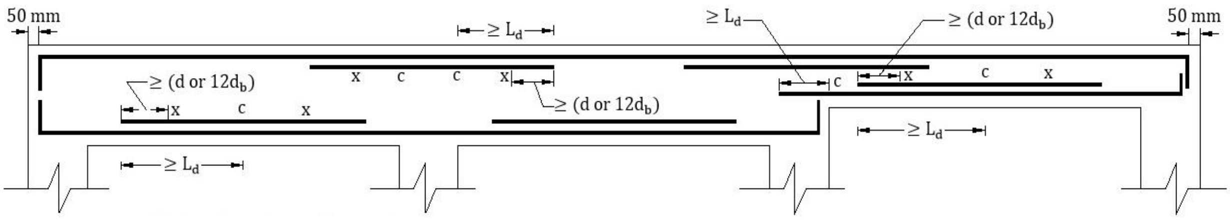

Fig. 2 Determination of the length of additional longitudinal bars in the spans

$M_{u,max,span_i}$ is the maximum bending moment produced by the analysis in each span and $\emptyset M_{n,patt}$ is the design bending strength based on the dimensions of cross-section at each span for each pattern.

• Based on ACI (9-7-3-8-2), patterns in which have longitudinal attachments larger than 4 times the number of continuous longitudinal bars in the previous step are eliminated.

$$L_d = \left(\frac{f_y}{1.1\lambda\sqrt{f_c'}} \frac{\Psi_t \Psi_e \Psi_s}{\left(\frac{c_b + K_{tr}}{d_b}\right)} \right) d_b \geq 300\ mm\ , \quad \frac{c_b + K_{tr}}{d_b} \leq 2.5 \tag{2}$$

After applying the above conditions, the number of patterns allowed for additional longitudinal bars in each area decreases significantly. Based on the ACI clause (9-7-3-2), according to the flexural moment diagram, the theoretical cutoff points in each region are determined to control the length of the extra longitudinal bars. The development length for each of the rebar patterns is determined based on the largest diameter in the pattern, according to ACI (25-4-2-3) and Eq. (2).

In Eq. (2), Ψ_t, Ψ_e, Ψ_s are development length coefficients and are calculated using the ACI (25-4-2-4) .d_b is the largest existing diameter in the rebar reinforcement pattern, c_b is the smallest distance from the center of the rebar to the concrete surface and half the distance from the center to the center of the bars, λ is the modification factor of concrete, that is used for concrete with a normal weight of 1, and K_{tr} is the transverse reinforcement index, which is calculated by Eq. (3).

$$K_{tr} = \frac{40A_v}{S_v n} \tag{3}$$

In the Eq. (3), A_v is the area of the cross-section of the shear bars, S_v is the distance between the shear bars, which based on ACI(9-7-6-2-2) due to considering the most stringent condition is equal to $d/2$ and n, is the number of extra longitudinal bars that are developed. Fig. 3 shows how to determine the length of the extra longitudinal bars based on the distance from the critical points c and the theoretical points of the x in the spans with an identical and non-identical height.

In the following, for all allowed patterns at the same time, the development length values are calculated and, according to the ACI clause (9-7-3-2), the length of the additional longitudinal bars is determined. Then, the additional longitudinal reinforcement pattern with the lowest weight for each zone is selected as the optimal solution of that zone. This process is repeated individually for all positive and negative flexural moment zones and the best longitudinal cross bars for each continuous longitudinal reinforcement pattern are selected. The least weight pattern is stored as the optimal solution. The best solution of the longitudinal bar in the continuous beam is the sum of the best response to the longitudinal bars of the positive moment and the longitudinal bar of negative bending moment.

It is worth noting that other criteria of the code, including the length of the lap splices, the length of the bend and the straight extension of rebar, are based on the ACI (9-5-7-7), (25-3-1) and (25-5-2-1) in order to determine the optimal solution.

2.3 Optimal shear reinforcement selection

The optimal shear reinforcement process can be done simultaneously with the process of determining the optimal longitudinal rebar. The shear reinforcement in this study is done as a vertical stirrup along the openings of the RC beam. For this purpose, the maximum shear force input on the beam is calculated based on the shear force diagram of the various loading components and is limited to the distance d from the support, according to the clause (9-4-2-3) of the ACI. The nominal shear strength of an RC beam section is defined in accordance with the ACI (22-5-1-1) as defined in Eq. (4) in which

$$\emptyset V_n = \emptyset(V_c + V_s) \tag{4}$$

In Eq. (4), V_c is the nominal shear strength of concrete, V_s is the nominal shear strength of the shear steel, and $\emptyset$ is the strength reduction coefficient which is 0.75 based on The ACI (21-2-1). The nominal shear resistance of concrete is determined according to the ACI clause (22-5-5-1). The nominal shear strength of steel is calculated based on ACI (22-5-10-5-3) using Eq. (5).

$$V_s = \frac{A_v f_y d}{S_v} \tag{5}$$

In continuous beams, shear force near the support is greater than the shear force in the middle of the crater. Based on the ACI (22-5-1-10), for selecting the optimum shear reinforcement rebar, each span can be divided into several zones based on the shear value. In this study, each span of the continuous RC beam is divided into three zones. These three zones include the internal zone, the middle zone and the terminal zone. The spacing of shear rebar in the internal and the terminal zones are calculated and controlled

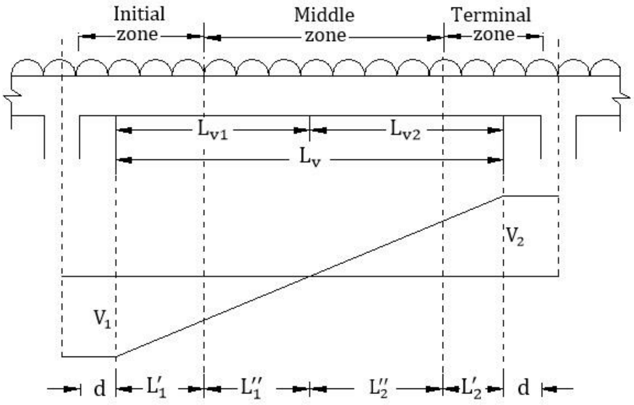

Fig. 3 Segmentation of the span to different zones for shearing reinforcement

based on shear force at distance d from the support using the Eq. (4)-(5), ACI(9-6-3-3) and ACI(9-7-6-2-2) with the permitted values of the code. The length of the internal and the terminal zones and the distance between the shear bars in the middle zone are the design variables at this stage. Fig. 3 Shows how to divide each span according to the method described.

The optimization equation is calculated as the total number of shear bars in three zones. Since the objective function is to reduce the weight of the shear bars, the problem of optimization is minimized and is defined as Eq. (6).

$$Min\ Z_i = n_{v1,i} + n_{v2,i} + n_{v3,i} \quad , \qquad i = 1, \dots, N_{span}$$

$$subject\ to: S_{v,i,j} \geq S_{v,all} \quad , \qquad j = 1,2,3 \qquad (6)$$
$$S_{v,i,j}, L'_{i,j} \geq 0$$

In the Eq. (6), $S_{v,i,j}$ is the shear rebar spacing in every one of the zones and $L'_{1,i} + d$, $L'_{2,i} + d$ and $L'_{3,i} = L''_{1,i} + L''_{2,i}$ are the length of the internal, terminal and middle zones respectively. $n_{v1,i}$, $n_{v2,i}$ and $n_{v3,i}$,are the number of shear bars in the internal, terminal and middle zones in every single span respectively, which are determined as follows:

$$n_{v1,i} = \left[\frac{L'_{i,1} + d - S_1}{S_{v,i,1}}\right] + 1 \ , n_{v2,i} = \left[\frac{L'_{i,2} + d - S_1}{S_{v,i,2}}\right] + 1 \ , n_{v3,i} = \left[\frac{L'_{i,3}}{S_{v,i,3}}\right] - 1$$

S_1, the distance between the first rebar of the edge of the support is 50 mm. Also, the values $L''_{1,i}$ and $L''_{2,i}$ are assumed to be the same. After solving Eq. (6) based on the derivatives, the lengths of the internal, middle, and terminal zones are determined, and subsequently the number of shear bars in each zone is obtained as well. Then the Eq. (7) is used to calculate the weights of the shear bars in the reinforced concrete beam.

$$W_v = \left(\sum_{i=1}^{N_{span}} \sum_{j=1}^{3} \frac{\pi}{4} d_k^2 \times n_{v,i,j} \times L_{v,i} \right) \times \gamma_s \qquad (7)$$

In Eq. (7), W_v is the weights of shear bars in the continuous beam, d_k the diameter of the shearing rebar, $n_{v,i,j}$ is the Number of shear bars in every existing zones for each span, $L_{v,i}$ is the length of the shearing rebar in each span and γ_s is the specific weight of the steel. In this study, shear reinforcement with the same area and 10, 12 and 14 diameters are used in the whole RC beam. The number, spacing and diameter of the shear reinforcements relative to the lowest weight of the shear bars are stored as the optimal solution and their weight is added to the total weight of the steel consumed in the beam.

It is worth noting that prior to the beginning of the process of reinforcement optimizing, according to the ACI (22-5-1-2), if the maximum shear force in the continuous beam exceeds the permitted value of the ACI code, the dimensions are not accountable and the cross section is rejected. The related flowchart for selecting the optimal longitudinal and shear reinforcement for the specified dimensions of the beam is shown in Fig. 4.

3. Formulation of the optimal design problem in a RC beam

An optimal design problem involving objective function, design variables, boundaries related to design variables and constraints is discussed below. The optimal solution in the optimization process is the solution that, in addition to minimizing or maximizing the objective function, satisfies the corresponding constraints. The various sections of the optimal design problem for RC beam are defined as follows:

3.1 The objective function

Optimization of concrete structures is done in order to reduce the cost of concrete, steel, and casting. Therefore, the objective function is used to minimize the total cost of the above items. objective function can be expressed as Eq. (8).

$$F = V_{con}C_{con} + W_{st}C_{st} + A_f C_f \qquad (8)$$

V_{con} is consumed concrete volume in beam, W_{st} is consumed concrete weight in beam, A_f is the molding area, C_{con} is concrete unit cost, C_{st} is steel unit cost, and C_f is molding unit cost. The value of W_{st} is calculated in the previous step and the values of V_{con} and A_f are calculated using Eqs. (9)- (10).

$$V_{con} = \sum_{i=1}^{N_{span}} b\ h_i L_{ci} + \sum_{i=2}^{N_{span}} \frac{w}{2}\ b\ |h_{i-1} - h_i| + \frac{w}{2} b(h_1 + h_{N_{span}}) \qquad (9)$$

$$A_f = \sum_{i=1}^{N_{span}} b\ L_i + \sum_{i=1}^{N_{span}} 2\ h_i L_{ci} + \sum_{i=2}^{N_{span}} w\ |h_{i-1} - h_i| + w(h_1 + h_{N_{span}}) \qquad (10)$$

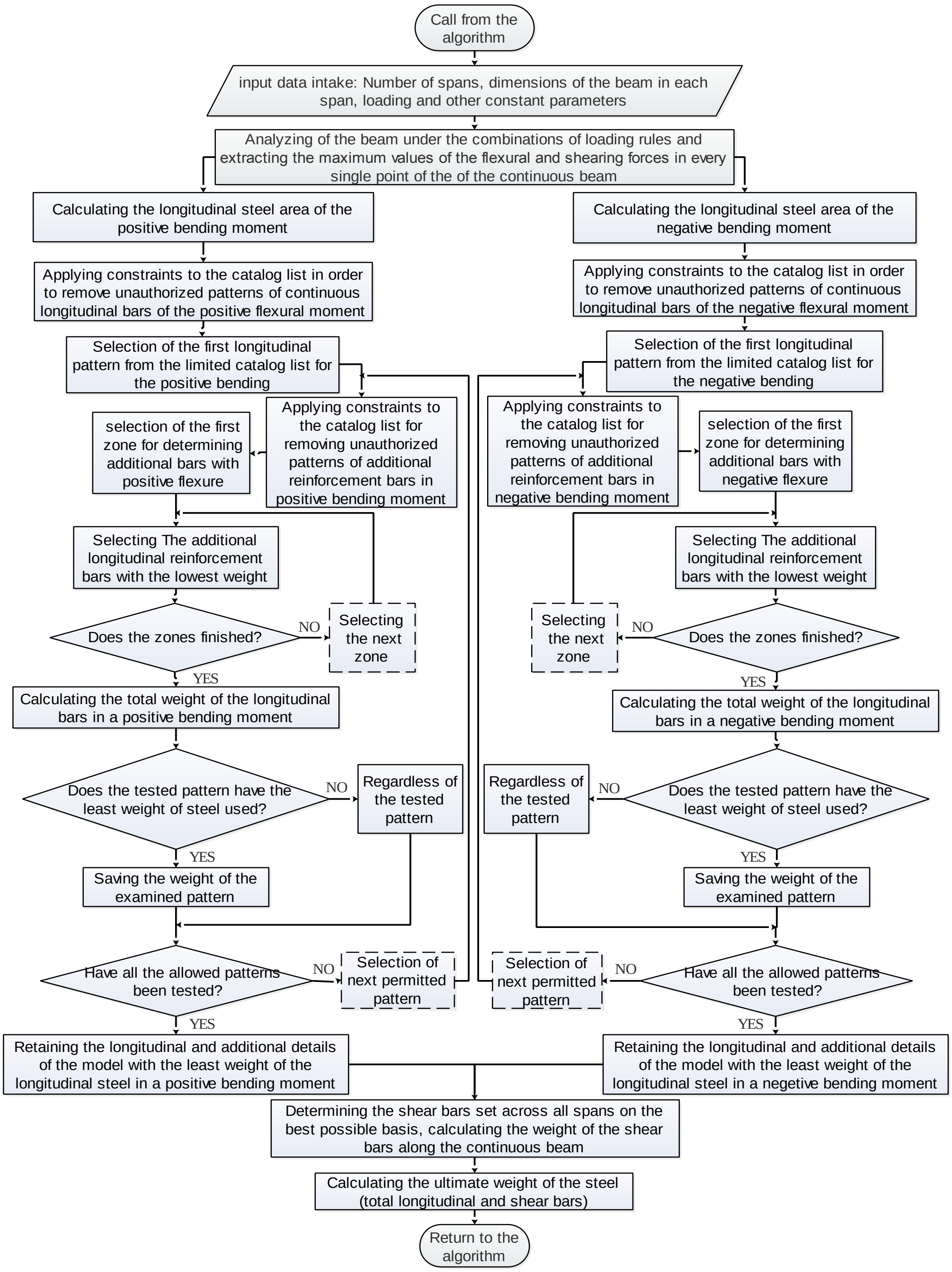

Fig. 4 Optimization method flowchart for longitudinal and shear bars used in this study

b is concrete beam width, h_i is the height of the beam per opening, L_i net length of each span, L_{ci} the the center to center length of the support in each span, and w is the width of the support.

3.2 Design variables

In this study, optimization of the continuous RC beam is divided into two separate sections. For this purpose, the design variables required to start the algorithm are limited to the dimensions of the RC beam at each span. This will simplify the process of optimization and reduce the computational volume. Since generally, the width of the beam is considered to be the same in all spans (Govindaraj and Ramasamy 2005, Jahjouh *el al.* 2013), so in this study, the beam width is assumed to be the same and only the beam height is considered different in each span. The number of variables in terms of the number of spans is expressed as $N_{span} + 1$.

3.3 Constraints

Due to the nature of the concrete structures construction, a series of restrictions are always applied to the design process, the optimization of concrete structures, including continuous RC beams. whole these restrictions are applied to optimization problems as constraints.

• At each span, the effective depth ratio to the width of the beam should be within the range defined by the user. This study limits this value between 1 and 2, thus:

$$1 \leq \frac{d_i}{b} \leq 2 \;\; , i = 1, \dots, N_{span} \tag{11}$$

• Based on the ACI (9-5-1-1), at every node of the beam, the value of the design flexural and shear strength should be greater than the flexural and shear strength obtained from the analysis at that node, respectively.

$$M_r = \emptyset M_n \geq M_u \, , \, V_r = \emptyset V_n \geq V_u \tag{12}$$

• The longitudinal steel area at each cross section of the continuous beam should be smaller than the maximum required longitudinal steel area calculated value based on clause (9-3-3-1) of ACI.

$$A_s \leq A_{s,max,all} \tag{13}$$

• according to the ACI (9-6-1-2), longitudinal steel area at each section of the beam should be greater than the minimum required area longitudinal steel according to the code.

$$A_s \geq A_{s,min,all} \tag{14}$$

• according to ACI (25-2-1), the minimum net distance between the longitudinal reinforcements at each section of the beam should be greater than the maximum value of 25 mm , $d_{b,max}$ and $1.33 d_{agg}$. d_b is the largest diameters of longitudinal bars and d_{agg} is the largest diameter of aggregate in concrete.

• Based on ACI (9-7-3-8-2), at least one quarter of the longitudinal bars in the beam should extend over the beam to the support.

• Based on the ACI (9-6-3-3), the ratio of the shearing bar area to the distance between stirrups should be greater than the minimum value specified by the code.

$$(\frac{A_v}{S_v})_{req} \geq (\frac{A_v}{S_v})_{min,all} \tag{15}$$

• Based on clause (9-7-6-2-2) of the ACI, the distance between the shear bars S_v, in every section of the beam, must be less than the maximum value of code.

• The height of the beam in each span must be lower than the allowable maximum permitted by the code. The minimum allowed height per spans for continuous one way spans, to *L*/18.5 and for continuous two way spans to *L*/21 are limited. *L* is the net length of the span.

4.Optimization algorithm

The TLBO-based algorithm is inspired by the impact of a teacher on students in the classroom, as well as the impact of interaction between students on their learning. In this algorithm, every solution is considered as a single student and design variables are defined as student's marks. Student's grades distributions in a class follows the normal distribution function. one strength point of the TLBO algorithm is that this algorithm, unlike other meta-heuristic methods, such as PSO, GA and etc., only consists of control parameters of population and maximum iteration (Rao and Vakharia 2012). This algorithm consists of two main phases, which are as follows:

4.1 Teacher phase

In this phase, the teacher, as the person with the highest level of knowledge in the classroom, is using his abilities to bring the class level to a level equal to itself. The class level is measured based on the average grades of students in that class. The education process can be defined mathematically as follows

$$Diffrence\_Mean_i = r_i(X_T - T_F M_i) \;\; , i = 1, \dots, N_{iter} \tag{16}$$

X_T is Teacher's position as the best answer in each iteration, M_i is average scores of all students per iteration, N_{iter} is the Number of algorithm repetitions, and T_F is the teaching factor that varies between 1 and 2 , and finally r_i is a random number between zero and 1. After this step, the new position for each solution is determined based on Eq. (17).

$$X_{new,i} = X_{old,i} + Diffrence\_Mean_i \tag{17}$$

If the new solution has a better fit than the previous one, it will replace the previous answer.

4.2 Student phase

In a class, students, in addition to learning from the teacher, improve and exceed their knowledge and information by interacting each other. In this phase, one student is randomly selected based on one single student (these two answers must not necessarily be the same) and then the interaction between two students takes place based on Eq. (18)

$$\begin{aligned} X_{new,i} &= X_{old,i} + r_i(X_i - X_j) \quad if \quad f(X_i) < f(X_j) \\ X_{new,i} &= X_{old,i} + r_i(X_j - X_i) \quad if \quad f(X_j) < f(X_i) \end{aligned} \tag{18}$$

This process is repeated for each student, and if the new solution has a better fit than the previous solution, it replaces the previous answer. In Fig. 5 The steps of the TLBO algorithm are displayed.

The TLBO algorithm, as well as the optimal design process for longitudinal and shear bars, has been developed using the Microsoft Windows 10, 64 Bit, and 8 GB RAM and Intel Corei7 2.2 GHz CPUs in the MATLAB R2014a software environment.

5. Constraints handling method

On a problem of minimization, the optimal answer is the answer that, in addition to minimizing the objective function, considers all of the constraints. If an answer has a violation of the limits specified in the problem in the search space, it should be addressed. The method of penalty function is one of the traditional and the usual methods for dealing with constraints (Mezura-Montes *et al.* 2011). In this study, unlike recent studies, the Deb constrains handling method (Deb 2000) has been used, which is one of the suitable methods for dealing with constraints for the algorithms such as GA and TLBO. The basis of this method

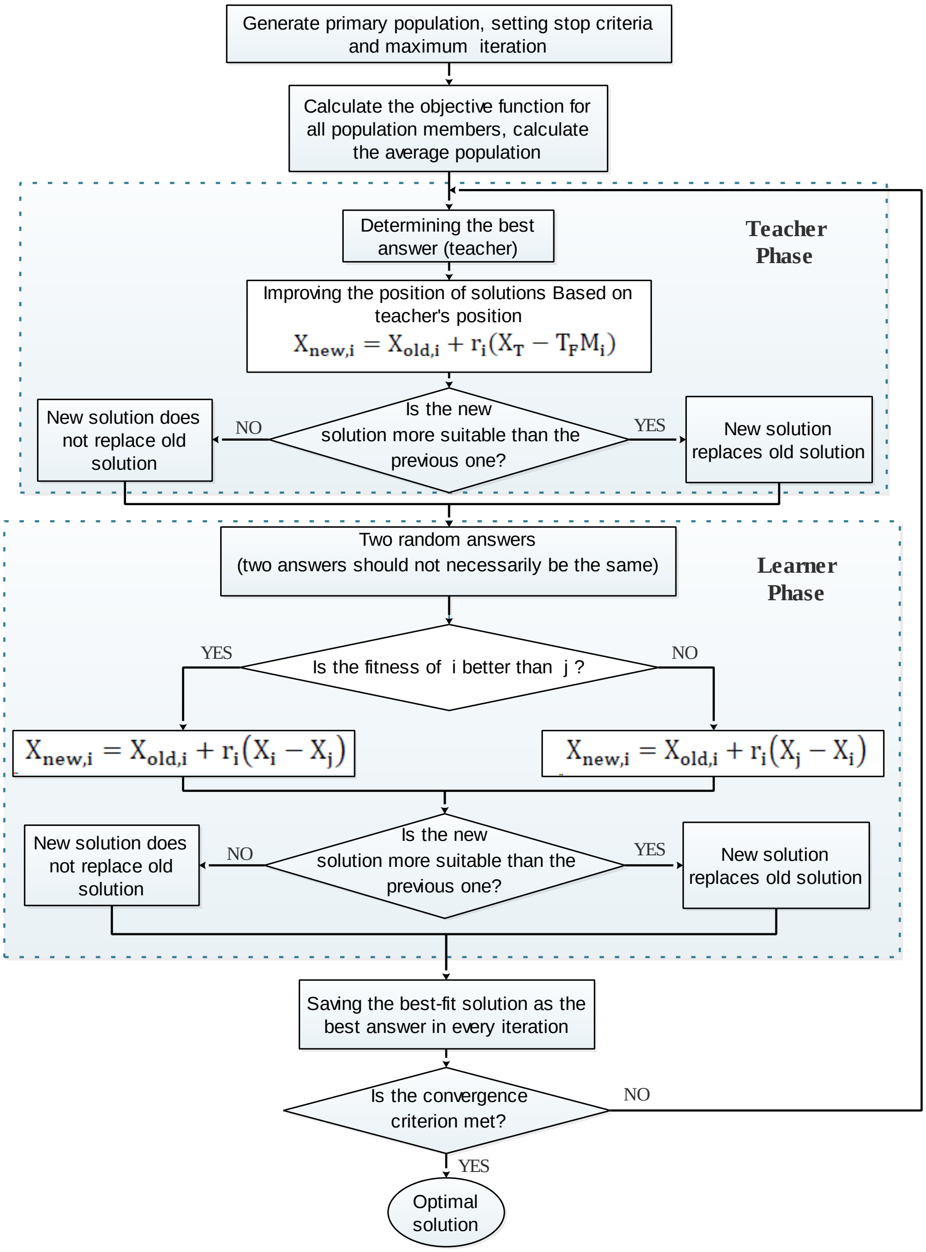

Fig. 5 TLBO algorithm Flowchart

is the use of a tournament selection operator between the two available solution. The value of the violation of solutions are determined according to the type of inequality as follows

$$\begin{aligned} &\text{if } C_i(x) \le C_{i,all}(x)\,; && \text{then: } g_i(x) = C_{i,all}(x) - C_i(x) \ge 0\,, i = 1, \dots, N_{cons} \\ &\text{elseif } C_i(x) \ge C_{i,all}(x)\,; && \text{then: } g_i(x) = C_i(x) - C_{i,all}(x) \ge 0\,, i = 1, \dots, N_{cons} \end{aligned} \tag{19}$$

$C(x)$ is the value of design variables in the problem, $C_{all}(x)$ is the allowable value assigned to the design variable by the user, $g(x)$ is an inequality constraint in the problem that should always be greater than zero, and N_{cons} is the number of problem constraints. The suitability value of every single response is calculated based on the amount of the violation according to Eq. (20).

$$F(x) = \begin{cases} f(x) & \text{if } g_i(x) \ge 0\,, i = 1, \dots, N_{cons} \\ f_{max} + \sum_{i=1}^{N_{cons}} |g_i(x)| & \text{otherwise} \end{cases} \tag{20}$$

In Eq. (20), $F(x)$ is the fitness of answers, $f(x)$ is the objective function in the problem, f_{max} is the worst fitness of the solutions in the possible region of Problem (solutions that do not exceed the constraints), $g(x)$ is unequal constraints and N_{cons} are the total number of constraints in the problem. If all solutions have violations of constraints at each iteration of the optimization algorithm, f_{max} will be zero. Accordingly, the set of commands for the selection of the competitor is defined as follows:

• If two answers do not violate, then, the more suitable answer is chosen.

• If one answer has no constraint violation and the other

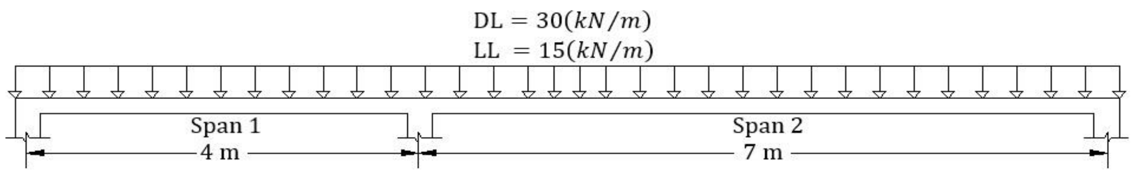

Fig. 6 Details of loading and length of spans in first problem

Table 2 Optimal design details of the longitudinal bar for the first example

Span	Method	Width (mm)	Height (mm)	Bottom reinforcement			Top reinforcement			
				Cont.	Add bar	Volume (m^3)	Cont.	Add bar (left)	Add bar (right)	Volume (m^3)
1	Jahjouh *et al.* (2013)	300	600	5Φ12	----	13.21×10^{-3}	3Φ12	----	4Φ22	9.189×10^{-3}
2				3Φ20	3Φ20			4Φ22	----	
1	Present Study	300	600	2Φ19	----	11.79×10^{-3}	2Φ12	----	4Φ22	8.64×10^{-3}
2					2Φ16 +1Φ28			3Φ24	----	

has, then the answer to which the violation is not constrained is selected.

• If both answers contain violations of the constraint, then the answer which has the least violations of the constraint, is chosen.

This operator is used at the end of the two phases of the TLBO algorithm. Using this method, in addition to having a proper look up with solutions, does not require any control parameters and results in non-violent solutions.

6. Design examples

In order to evaluate the efficiency of the method described in this study to optimize continuous RC beam, three examples of RC continuous beams are provided. In all cases, based on ACI (5-3-1), in order to achieve the most critical live load condition, maximum positive bending moment in the middle of the span and the maximum negative bending moment in the support of the various combiners of loading of the load are considered as follows:

1. The live load on all spans is alternative.
2. live loads on the adjacent spans are applied fully and on other spans are used alternatively.

Then, the design was based on the maximum positive bending moment, the maximum negative bending moment, and the maximum shear force obtained from the analysis. Loading components are defined as follows according to ACI (ACI318 2014).

$$U = 1.4\,DL$$
$$U = 1.2DL + 1.6LL \tag{21}$$

DL is a uniform dead load applied on each span and LL is uniform live loading on each span. The beam weight is variable based on the dimensions and is calculated in every single analysis and then is added to the dead load on each span. based on ACI318-14, in order to consider the effect of cracking, the moment inertia of the beam cross section is calculated as $I_{Beam} = 0.35I_g$ .where I_g is the gross moment of inertia of the beam cross section.

The continuous beam with determined length and cross-sectional dimension is modeled, analyzed and verified in the ETABS software, then results are obtained with the first-order analysis using coding in the same mathematical environment.

6.1 First example, two-span continuous beam

In this case, a two-span beam has a simple support. the lengths of spans, details about the loading and other constraints are considered as Jahjouh *et al.*'s (2013) numerical example. Details are shown in Fig. 6. The lengths of spans from the left are 4 m and 7 m . the width of all supports are 200 mm. Concrete compressive strength, f_c' equals to 20 MPa and f_y, steel yielding tension, equals to 420 MPa. Concrete specific weight and its unit costs are $25\ \mathrm{kN/m^3}$ and $100\ \mathrm{USD/m^3}$ respectively. the specific weight of steel and the cost per unit of steel consumption are respectively $78.5\ \mathrm{kN/m^3}$ and 87 USD/kN also the molding unit cost equals to $5\ \mathrm{USD/m^2}$. The width and height of the beam in both spans are fixed and the maximum and minimum values of the depth and width of the beam in each opening are 500 to 1000 mm and 300 to 700 mm, with a step of 50 mm.

All the development length coefficients are considered as Jahjouh *et al.*'s (2013) article. Jahjouh *et al.* (2013) considered $6N_{span} + 3$ design variables for the optimization algorithm, While, at the presented approach in this study, only depth and width of cross section are variables of the optimization algorithm. The maximum iteration in the TLBO algorithm is equal to 50 and the population size 10 is used to examine the presented approach and the optimization method. The criterion of termination is determined by maximum iteration of the algorithm or non-changing of the objective function in 3 successive sequences. The details of the longitudinal rebar reinforcement of the beam are shown in Table 2. For an optimal solution of 300 mm width and 600 mm height, total number of possible patterns for continuous longitudinal bars of the negative and the positive flexural moment after the constraints apply and remove unauthorized are 448 and 407 of total 7267 respectively. For additional longitudinal bars,

Table 3 The values of concrete, steel, and the formwork for the first example

Method	Quantity			Cost of components		
	Concrete (m^3)	Formwork (m^2)	Steel (kN)	Concrete (USD)	Formwork (USD)	Steel (USD)
Jahjouh *et al.* (2013)	N. A	N. A	N. A	N. A	N. A	N. A
Present Study	1.989	16.38	2.055	198.9498	81.9	178.78

	Optimum Cost (USD)	Iteration no	Number of Analyze
Jahjouh *et al.* (2013)	461.758	723	58640
Present Study	459.69	4	90

2641 longitudinal reinforcement patterns for a negative bending moment region and totally 10279 patterns for both areas of the positive bending moment have been investigated simultaneously. the intervals, the location of the cuttings and the length of the longitudinal bars are simplified to multiples of 5 in order to perform the structure properly. With regarding to the different values of the number and diameter of bars used for the continuous longitudinal bottom reinforcement in the presented method by Jahjouh *et al.* (2013), the presented approach by this study achieved to smaller than the amount of consumption steel.

The cost of concrete, steel, and the molding of the optimal design, are totally mentioned in Table 3. it should be noted that the columns named "Iteration no" gives the iteration number at which the optimum has been achieved. Number of beam analyzed at the optimization process are shown in Table 3, Too. It should be mentioned that the TLBO algorithm archives the optimal solution in less than two minutes with an iteration number of 4 with 90 analyzes.

The details of the shear reinforcement in the spans are displayed in Table 4 and Fig. 7. In Table 4 The distance between the shear bars and the number of stirrups is shown in the internal, middle and terminal zones. Straight extension and total length of stirrups in each span are shown in Table 4, too.

The total number of shear bars is calculated from the sum of N values in the three corresponding zones. In order to calculate the length of the shear bars, related angle and the length of the bending are considered based on ACI318-14 with 135-degree hook.

6.2 Second example, continuous three-span beam

In this case, a three-span beam with a simple support is examined. The side and lateral spans have the same length and dimensions of the whole cross section is assumed to be the same at all spans. details of loading and length of openings are shown in Fig. 8. in this problem alike the previous one, a symmetric continuous beam is evaluated for optimal design consideration. the length of both lateral spans is 6 m, the middle span is 4 m and the width of all the supports is equal to 300 mm. In this case concrete compressive strength, f_c' equals to $30\ \mathrm{MPa}$ and f_y, steel yielding tension, equals to $400\ \mathrm{MPa}$.

Concrete specific weight and its unit costs are $25\ \mathrm{kN/m^3}$ and $100\ \mathrm{USD/m^3}$ respectively. the specific weight of steel and the cost per unit of steel consumption are respectively $78.5\ \mathrm{kN/m^3}$ and $87\ \mathrm{USD/kN}$ also the molding unit cost equals to $5\ \mathrm{USD/m^2}$. The width and height of the beam in both spans are fixed and the maximum and minimum values of the depth and width of the beam in each opening are 225 to 900 mm and 225 to 700 mm, with a step of 25 mm. all the parameters of the optimization algorithm are same as the previous example.

The problem is considered to be two-variable due to the uniformity of the width and height of the section in all spans. The TLBO algorithm achieves the optimal solution in less than two minutes with an iteration number of 4 and 110 analyzes. The total number of examined patterns for optimal solution is equal to total 3078. during the optimization process, every specific set of patterns of additional bars at each analyze are simultaneously examined.

Table 4 Optimal shear design details for the first example

Span	Initial Zone			Middle Zone			Terminal Zone			Stirrups Length (mm)	L_{ext} (mm)
	Length (m)	S_v (mm)	N	Length (m)	S_v (mm)	N	Length (m)	S_v (mm)	N		
1	0.315	265	2	1.315	265	4	2.17	265	9	1625.62	75
2	2.33	190	13	3.36	265	12	1.11	265	5	1625.62	75

optimum diameter of stirrups=10 mm

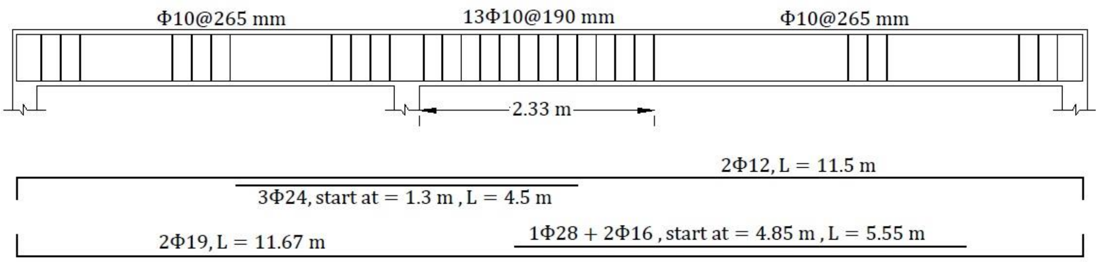

Fig. 7 Results of the optimal design in continuous double-span beam in the first example

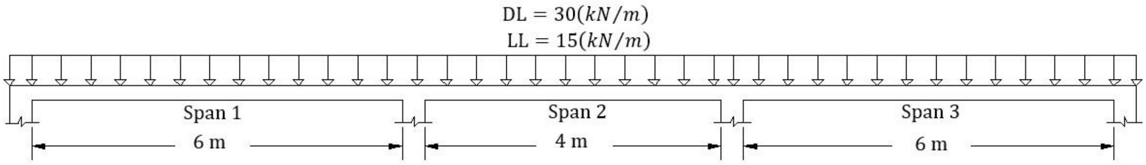

Fig. 8 Details of the loading and length of spans in the second example

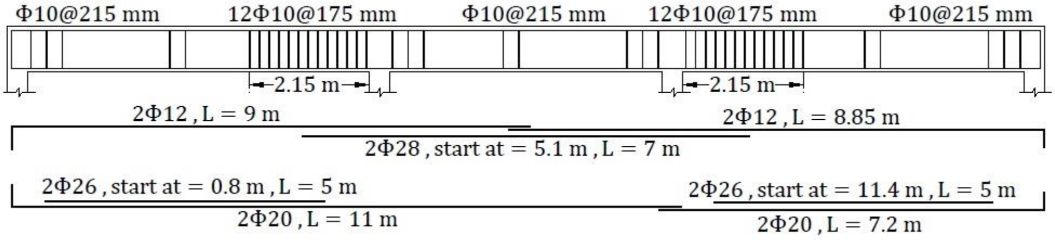

Fig. 9 Optimal design results for double-span beam in the second problem

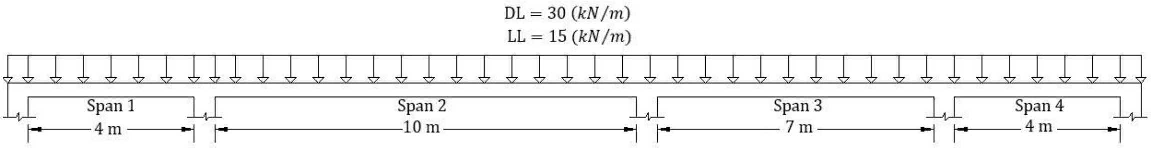

Fig. 10 Details of loading and dimensions of the four-span beam in the third example

Table 5 Optimal design details of longitudinal bar for the second example

Span	Width (mm)	Height (mm)	Bottom reinforcement		Top reinforcement		
			Cont.	Add bar	Cont.	Add bar (left)	Add bar (right)
1	275			2Φ26		----	2Φ28
2		500	2Φ20	----	2Φ12	2Φ28	2Φ28
3				2Φ26		2Φ28	----

Table 6 Optimal shear design details for the second example

Span	Initial Zone			Middle Zone			Terminal Zone			Stirrups	L_{ext}
	Length (m)	S_v (mm)	N	Length (m)	S_v (mm)	N	Length (m)	S_v (mm)	N	Length (mm)	(mm)
1	1.125	215	6	2.275	215	12	2.15	175	13	1375.6	75
2	1.125	215	6	0.675	215	3	2.2	215	11	1375.6	75
3	2.15	175	13	2.275	215	12	1.125	215	6	1375.6	75

optimum diameter of stirrups=10 mm

For continuous longitudinal rebar reinforcement of the negative flexural moment and positive flexural moment after applying the constraints and eliminating patterns, 181 and 218 patterns from 7267 templates remain respectively. Details of the optimal design of longitudinal rebar and the optimal design details of the shear rebar reinforcement are shown in Tables 5-6. Straight extension and total length of stirrups with 135-degree hook in each span are shown in Table 6, too. Results from Tables 5-6 are drawn in Fig. 9.

Because of the symmetry existing in the beam and the uniformity of the cross section dimensions in all spans, the number and length of the longitudinal and shear bars relative to the middle span center are symmetrical. The cost of concrete, steel, and the molding of the optimal design are

Table 7 The values of concrete, steel, and the formwork for the second example

Quantity			Cost of components			Optimum Cost (USD)
Concrete (m^3)	Formwork (m^2)	Steel (kN)	Concrete (USD)	Formwork (USD)	Steel (USD)	
2.3216	20.7275	3.5157	232.16	103.6375	305.865	641.524

shown in Table 7.

As the optimization algorithm in the first and second problem has only two variables of designing height and width of the reinforced concrete continuous beam at two and three spans, the minimum, mean, and maximum values of the objective function are thus equal and the standard deviation is zero.

8.3 third example, four-span continuous beam

In this case, the optimization of a continuous four-span beam is considered. Contrary to the previous two examples, in order to better evaluate the method studied in this study, the height of the beam in each span is assumed variable and the width of the cross section of the beam is assumed to be constant at all spans. Therefore, using the TLBO algorithm, the 5-variable problem is optimized. Details of loading and length of spans has been shown in Fig. 10.

In this case, the support width, the compressive strength of the concrete, f_c' , steel yielding stress, f_y, specific weight of concrete, unit cost of concrete, specific weight of steel and the cost of steel consumption plus cost of formwork unit and the maximum and minimum values for the depth and width of the beam Are considered as the second problem.

Considering the cross-sectional dimensions for all variables in the problem optimization algorithm, the search

Table 8 Results for four span beam in third example

Number of Population	Maximum optimum Cost (USD)	Average optimum Cost (USD)	Minimum optimum Cost (USD)	Standard Deviation	Iteration Number at optimum Cost
50	1309.8901	1309.8901	1309.8901	0.00	17
40	1309.8901	1309.8901	1309.8901	0.00	21
30	1309.8901	1309.8901	1309.8901	0.00	22
20	1334.1006	1322.2166	1317.3351	5.13	27
10	1358.4187	1333.5701	1325.0541	8.94	39

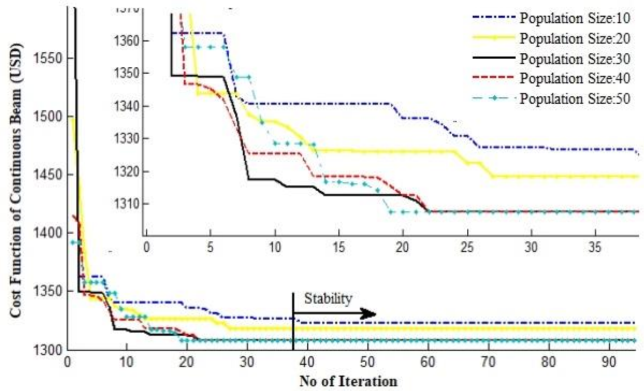

Fig. 11 Convergence diagram of the third example

space is equal to 10^7. In order to investigate the efficiency of the TLBO algorithm in solving RC continuous beam problems in finding optimal solution, the control parameters of the TLBO algorithm have been studied. Since this algorithm has only two control parameters: maximum iteration and population size, so using the number of Different populations size in a number of different iterations this algorithm has been evaluated. Minimum, average, maximum, and standard deviation values of the objective function for 10 run that have been made separately for each number of population with maximum iteration equal to 100 are presented in Table 8.

Fig. 11 shows the convergence chart for each of the population of 10,20,30,40 and 50. It is observed that for all convergence charts after the 40th repetition, no change occurs in the value of the objective function. However, this stability has not occurred in the optimal objective function for the convergence diagram of the population of 10 and 20, indicating that the algorithm is enclosed in the local optimum.

In this situation, due to the low population of members and the nature of the algorithm, that moves in the teacher's phase towards the best solution as a teacher, it is enclosed in an optimal localization and it is not possible to achieve the optimal overall solution.

This is despite the fact that the population of 30,40 and 50, can achieve optimal solution in less than 25 iterations, based on Fig. 11. What can be distinguished in the members of the population in order to achieve the optimal solution, is the number of facial analyzes Taken to get the optimal solution. Given that the increase in the number of analyzes leads to the application of computational cost and an

Table 9 Optimal design details of longitudinal bar for the third problem

Span	Width (mm)	Height (mm)	Bottom reinforcement		Top einforcement		
			Cont.	Add bar	Cont.	Add bar (left)	Add bar (right)
1		675		----		----	1Φ19 + 2Φ26
2	325	700	2Φ16	2Φ25 + 1Φ26	2Φ24	1Φ19 + 2Φ26	3Φ25
3		700		1Φ12 + 2Φ14		3Φ25	1Φ19
4		450		1Φ12 + 2Φ14		1Φ19	----

Table 10 Optimal shear design details for the third example

Span	Initial Zone			Middle Zone			Terminal Zone			Stirrups	L_{ext} (mm)
	Length (m)	S_v (mm)	N	Length (m)	S_v (mm)	N	Length (m)	S_v (mm)	N	Length (mm)	
1	0.66	305	3	0.85	305	2	2.49	305	9	1825.6	75
2	3.85	200	20	2.11	315	6	4.04	190	22	1875.6	75
3	3.47	285	13	1.275	315	4	2.25	345	8	1875.6	75
4	1.95	190	11	1.05	190	5	1	190	6	1375.6	75

optimum diameter of stirrups=10 mm

increase in the duration of the optimal solution, therefore, the number of members in the population 30 can be used to optimize the continuous RC beam problems, as well as the maximum number of iteration in population 40 is to ensure optimal solution. Table 9 shows the optimal design results for the present problem.

In order to have the optimal solution to this problem, due to consideration of the minimum conditions and the maximum cross-sectional length of the longitudinal steel in all spans, and the determination of the best possible condition, the number of patterns examined from the catalog list for continuous longitudinal bars of the positive and negative bending moment, is 909 And 750 from 7267, respectively. Also for extra longitudinal bars, all of the openings for the negative and positive bending moments are 1606 and 27478, respectively. On the positive bending moment, because the first span from the left does not require any additional reinforcements in the end, in this way all possible patters of the catalog list are compared simultaneously at every stage. Due to the simultaneous comparison of all the states, this does not significantly increase the volume of the problem calculation.

The results of the shearing reinforcement in every one of internal, middle, and terminal zones in each span are shown in Table 10. Straight extension and total length of stirrups in each span are shown in Table 10, too. In order to calculate the length of the shear bars, related angle and the length of the bending are considered based on ACI318-14 with 135-degree hook. as well as all the results of Table 10 are shown in Fig. 12 executable.

It is worth noting that interrupting the longitudinal continuous bars in the supports position are based on Fig. 2. The bending length and cover patch for the positive flexural moment are 500 mm and 350 mm on the support, and for the negative bending moment, are 650 mm and 850 mm

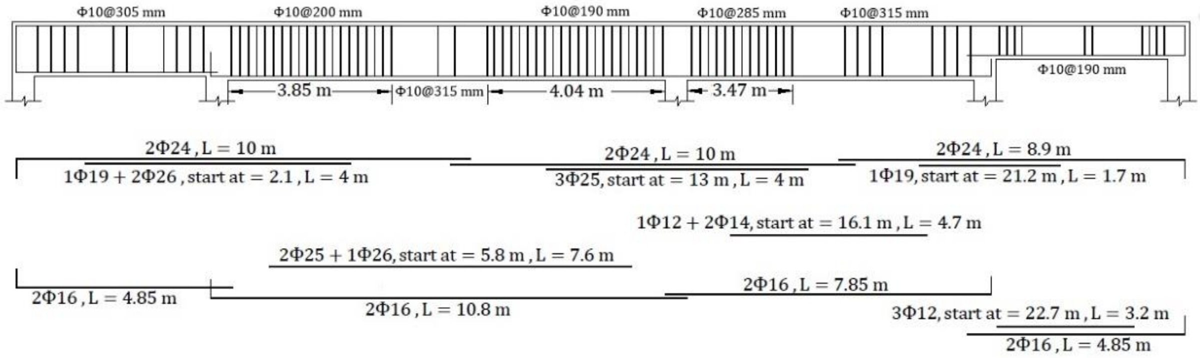

Fig. 12 The results of the optimal design of the four-span continuous beam in the third example

Table 11 The values of concrete, steel, and the formwork for the third example

Quantity			Cost of components			Optimum Cost (USD)
Concrete (m^3)	Formwork (m^2)	Steel (kN)	Concrete (USD)	Formwork (USD)	Steel (USD)	
5.5659	42.86	6.1959	556.59	214.3	539.043	1309.8901

respectively. The cost of concrete, steel, and the cost of the third problem molding, are given in Table 11.

9. Conclusions

This study presents a new method for optimal details design for continuous RC beam design. In the optimization process, the TLBO optimization algorithm was used and design constraints were applied based on the ACI318-14 code. The method uses a two-step process in which reduces the design variables of the optimization algorithm and also reduces the volume of assumption steel and the number of analyzes needed to achieve optimal solution to other similar articles studied in this study. During the optimization process, a catalog list, including all possible states for longitudinal beam framing has been used, which has a significant role in reducing the computational volume in the method used. In the production of the catalog list, four types of bars were used with different diameters. However, this method has no limitations on the number and dimensions, and the reduction of the number of the mentioned cases leads to the reduction of possible patterns and, consequently, the faster convergence of the algorithm to the optimal solution based on patterns produced. In the case of two-spans and three spans continuous beams, the ability of the proposed method was presented, and in the third problem, we examined the optimal control parameters of the TLBO algorithm. The results of the investigated problems show that the method has succeeded in finding the optimal solution based on the constraints and reducing the computational volume of continuous RC structures, and it can also be considered and used as a practical approach for designing and optimizing multi-span continuous beams. The authors propose the use of the above mentioned method to optimize RC concrete frames and reinforced concrete bridges.

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