Challenge Journal of Concrete Research Letters

Research Article

Optimization of reinforced concrete frame structures and matrix displacement method

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ABSTRACT

In this study, reinforced concrete frame system is generated, and all structural elements which are beam and columns are optimized according to the applied distributed loads and different concrete classes by using Matlab program. Jaya algorithm which is a Metaheuristic Algorithm that enables to optimization process and finds the best cross sections, reinforcement area as well as cost of the system, is proposed. It is observed that cross-section, reinforced area as well as cost of the system are changed when concrete classes are used differently. After finding the optimum design values for frame system, the matrix displacement method is utilized to specify the system displacements and all nodes forces. Furthermore, columns and beam displacement results are not similar, and also internal forces are different for nodes. TS500 (2000) (Reinforced concrete structures design and construction rules) and TBDY (2018) (Turkey Building Earthquake Regulation) are used together to specify variables, constraints and also necessity values. The proposed method is feasible for frame structures consisting of different members.

ARTICLE INFO

Article history:
Received 28 November 2022
Revised 17 December 2022
Accepted 21 December 2022

Keywords:
Metaheuristic algorithms
Jaya algorithm
Frame system
Matrix displacement method
Optimization

1. Introduction

The pace of development in any area has been increasing significantly (Oliva et al. 2017) in recent decades (Mei and Wang 2021) in the world. Therefore, a lot of unprecedented tools, programs and systems have been invented recently such as artificial intelligence (Perea et al. 2008; Jones 2003; Sriram 2006). As recent examples, Cakiroglu et al. (2022a) exploited machine learning to estimate concrete-filled steel tubular columns' axial compression capacity. Bekdaş et al. (2022a) used harmony search to optimize the design of cylindrical walls, and they utilized ensemble learning models to forecast the best values with high accuracy. Ensemble Learning Models were also applied to civil engineering problems such as finding the rheological properties of self-compacting concrete (Cakiroglu et al. 2022b), optimization of reinforced concrete circular columns (Bekdaş et al. 2022c) and retaining walls (Bekdaş et al. 2022c). Interpretable machine learning algorithms were used to find the axial force capacity of fiber-reinforced polymer including reinforced concrete columns by Cakiroglu et al. (2022c). These developments influence our lives in terms of the quality of the system which we utilize every time. They are not limited to only one area; however, they can be in all areas, and civil engineering is at the forefront of these areas. Along with the developments, important changes are made in the features and design stages of the building systems, and it is tried to enable the use of more convenient and sustainable systems. In general, some of the main requirements requested from the building are; It should be resistant to loads that may affect it, to be aesthetic, to be applicable in terms of cost (Nigdeli and Bekdaş 2017), and the majority of the materials used should be designed without harming the environment (sustainable systems). Design engineers have to consider these while performing the design, and they use different computer programs for these circumstances. In this way, designs are made according to the loads that may affect the structure (earthquake, wind) and the purpose of use of the building, taking into account the regional soil classes. The realization of designs in this way

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ISSN: 2548-0928 / DOI: https://doi.org/10.20528/cjcrl.2023.01.002

prevents deviations from the regulations, and by doing it in accordance with its purpose, in case of any possible impact (earthquake load), it prevents the systems or the structure from being significantly damaged. Nonetheless, regulations allow structures with certain safety coefficients to be damaged in a controlled manner, instead of the structure being damaged unexpectedly. Demanding this type of damage like this is to prevent loss of life.

Frame systems are used extensively in certain regions of some countries. In the case of seismicity in some regions and higher than certain story heights, it is not preferred much. Even if it is preferred, it should be supported with different building carrier elements. The most important reason for the overuse of these systems is their low cost. Since the energy dissipation that will occur in earthquake effects is less than other building systems, they are the systems that suffered the most damage or collapse under the effects of earthquakes (Doğangün 2019). As a consequence, to increase the earthquake performance, the rigidity of the structure is increased by adding shear walls to the framed systems. In this way, most of these dynamic loads are covered by shear walls in case of earthquake or wind effects. Ulusoy et al. (2020) studied to find the optimal design of reinforced concrete beams by examining the strength of concrete, and they used Metaheuristic Algorithm in this process. Leps and Sejnoha (2003) utilized simulated annealing, which is a metaheuristic algorithm, to optimize the continuous beam. In order to reach the optimum cost for reinforced concrete slabs, Shayegan (2022) used various metaheuristic algorithms and hybrid algorithms, and Ghandi et al. (2017) utilized cuckoo search algorithm.

In this study, the cross-section designs of the elements of the frame system are carried out using metaheuristic algorithms which have been utilizing engineering problems to reach optimum value, and optimum section designs are carried out in accordance with the regulations such as TS500 (2000) and TBDY (2018). Before the sections are determined by optimization, some material properties and constraint conditions and the maximum-minimum values of the variables which are taken by Balling and Rao (1997) are added to the algorithms. As a result of these, the forces (shear and axial forces) formed in all joint areas and the resulting displacement values are found and compared using the Matrix Displacement Method according to the optimum cross-section dimensions.

2. Methodology

2.1. Design of reinforced concrete frame structures

Reinforced concrete frame structure which consists of columns and beams has to be designed by using regulations. These regulations include some design values, constraints as well as limitation length of column and beam size. All features are used in the optimization process to reach optimum size by Mayencourt and Mueller (2020) and cost design.

Beam and column have various features to calculate the appropriate design. Some formulas show below for beam calculations. Eq. (1) demonstrates the decreasing amount of materials values to stay safe design. Beams have 2 sides which are the compression region as well as tensile region, and these effects should same to balance themselves Eq. (2). In addition, Eq. (3) shows stress block depth. Fig. 1 shows the beam section.

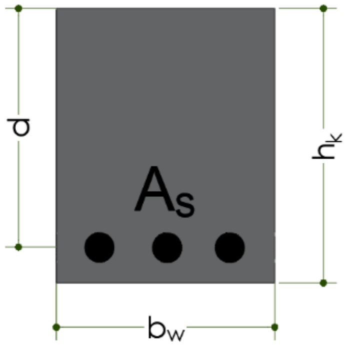

Fig. 1. Beam cross-section.

Regarding the given equations which are related to beam and column design, a is the stress block depth, M is the moment that has an impact on the structure, d is the distance from center of longitudinal tensile reinforcement from over tightening, f_{yd} is the design yield strength for steel, f_{cd} is the compressive strength of concrete design, f_{ck} is the concrete's characteristic compressive strength, f_{ctk} is the characteristic axial tensile strength of concrete, ρ_b is the balanced reinforcement ratio, and $k1$ changes according to the concrete class.

$$f_{cd} = \frac{f_{ck}}{1.5} \text{ and } f_{yd} = \frac{f_{yk}}{1.15} \quad (1)$$

$$F_c = F_s = 0.85 \times f_{cd} \times b_w \times a \quad (2)$$

$$a = d - \sqrt{d^2 - \frac{2 \times M}{0.85 \times f_{cd} \times b_w}} \quad (3)$$

For Eq. (4), after finding the reinforcement area, it is compared whether it is between the maximum and minimum reinforcement ratio.

$$0.8 \times \frac{f_{ctd}}{f_{yd}} \leq \rho = \frac{A_s}{b_w \times d} = \frac{\frac{M}{f_{yd} \times \left(d - \frac{a}{2}\right)}}{b_w \times d} \leq \begin{cases} 0.85 \times \rho_b \\ 0.02 \\ 0.235 \times \frac{f_{cd}}{f_{yd}} \end{cases} \quad (4)$$

Some formulas show below for column calculations. A reinforced concrete column has to provide adequate capacity to withstand axial force and bending moment (Camp and Hug 2013). Fig. 2 shows the column section. In order to find column cross-sections, it is necessary to use some of the equations. With Eq. (5), neutral axis distance is determined for balanced conditions, while Eqs. (6) and (7) are used for finding stress block depth and for finding axial pressure force respectively. d' is known as concrete cover.

$$c_b = \frac{600}{600 + f_{yd}} d \tag{5}$$

$$a_b = k_1 \times c_b \tag{6}$$

$$N_b = 0.85 \times f_{cd} \times a_b \times b \tag{7}$$

After finding the axial pressure force, it is compared with Eqs. (8) and (9), and therefore, it is checked whether rebar is needed or not. While stress block depth can be found by Eq. (10), reinforcement area for the column can easily be found by Eq. (11).

$$\psi_c = 0.85 \times \frac{d'}{h} \times \frac{600}{600 - f_{yd}} \tag{8}$$

$$\text{Control} = \frac{N_d}{b \times h \times f_{cd}} \tag{9}$$

$$a = \frac{N_d}{0.85 \times b \times f_{cd}} \tag{10}$$

$$A_{st} = 2 \times \frac{M - N_d \times (\frac{h}{2} - \frac{a}{2})}{f_{yd} \times (d - d')} \tag{11}$$

2.2. Matrix displacement method

There are many displacement methods and one of them is the matrix displacement method, which is the method that generates the unknowns of the displacement components of the system. The matrix displacement method is the determination of the displacement value of the structure under the static and dynamic loads that may be effective on the structure, the internal force values and the deformation effects that may occur. Impact such as loads, displacements and reaction force in the system are defined in the global coordinate system. Despite this, the section effects are formed by changing relative to the global coordinate system according to the location of the building element and it is called the local coordinate system. Transitions from the global coordinate system to the local coordinate system (Fig. 3) or completely reversible can be done easily with angles.

Some of the names of the angles in formulations are abbreviated. It can be easily comprehended to how they can use it.

For abbreviation: $S = \sin(\theta)$, $C = \cos(\theta)$

$$X_L = Y_G \times \sin(\theta) + X_G \times \cos(\theta) \longrightarrow X_L = Y_G \times S + X_G \times C \tag{12}$$

$$Y_L = Y_G \times \cos(\theta) - X_G \times \sin(\theta) \longrightarrow Y_L = Y_G \times C - X_G \times S \tag{13}$$

Although the global coordinate's axis names are X_G and Y_G, the Local coordinate's axis names are X_L and Y_L. Thus, these can easily be seen in Equations. Eqs. (12) and (13) are used to reach Local coordinate locations and these abbreviations can be seen respectively. A matrix which is given as Eq. (14) enables finding Local Coordinate property. The stiffness matrices in local and global coordinates have the relation given in Eq. (15). Node displacement (Kaveh and Zaerreza 2022) can be found in Eq. (16), while internal loads can be found in Eq. (17).

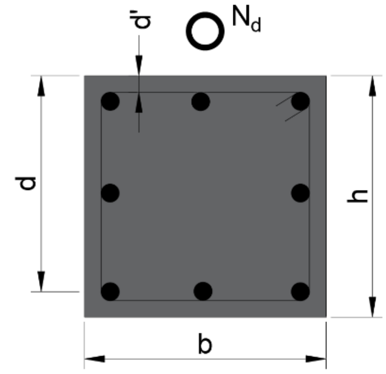

Fig. 2. Column cross-section.

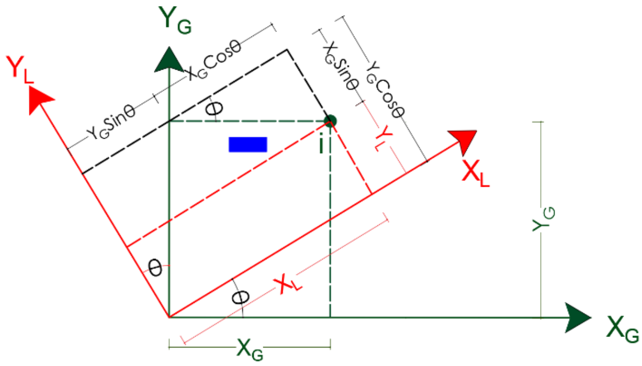

Fig. 3. Global-local coordinate system.

$$\begin{bmatrix} X_{Li} \\ Y_{Li} \\ \theta_{Li} \\ X_{Li} \\ Y_{Li} \\ \theta_{Li} \end{bmatrix} = \begin{bmatrix} C & S & 0 & 0 & 0 & 0 \\ -S & C & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & C & S & 0 \\ 0 & 0 & 0 & -S & C & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} X_{Gi} \\ Y_{Gi} \\ \theta_{Gi} \\ X_{Gi} \\ Y_{Gi} \\ \theta_{Gi} \end{bmatrix} \tag{14}$$

$$[K_G] = [R]^T * [K_L] * [R] \tag{15}$$

$$[\Delta_L]_F = [R]_F * [\Delta_G]_F \tag{16}$$

$$[P_L]_F = [K_L]_F * [\Delta_L]_F \tag{17}$$

P refers to internal force, *K* refers to stiffness matrix and Δ refers to displacement. Moreover, some features of materials and cross-section values are necessary to know in order to find stiffness matrix results. As seen in Eq. (18), these features are seen as *E*, *A*, *I* as well as *L* on the matrix. *E* is the modulus of elasticity, *A* is the area of cross-section, *I* is the moment of inertia as well as *L* is the length of structure elements.

$$[K_L]_F = \begin{bmatrix} \frac{EA}{L} & 0 & 0 & -\frac{EA}{L} & 0 & 0 \\ 0 & \frac{12EI}{L^3} & \frac{6EI}{L^2} & 0 & -\frac{12EI}{L^3} & \frac{6EI}{L^2} \\ 0 & \frac{6EI}{L^2} & \frac{4EI}{L} & 0 & -\frac{6EI}{L^2} & \frac{2EI}{L} \\ -\frac{EA}{L} & 0 & 0 & \frac{EA}{L} & 0 & 0 \\ 0 & -\frac{12EI}{L^3} & -\frac{6EI}{L^2} & 0 & \frac{12EI}{L^3} & -\frac{6EI}{L^2} \\ 0 & \frac{6EI}{L^2} & \frac{2EI}{L} & 0 & -\frac{6EI}{L^2} & \frac{4EI}{L} \end{bmatrix} \tag{18}$$

2.3. Jaya algorithm

Metaheuristic algorithms include Particle Swarm Optimization (PSO) developed by Kennedy and Eberhart (2001), Jaya Algorithm developed by Rao (2016), the Teaching Learning Based Optimization (TLBO) developed by Rao (2012). Design time, cost and sufficient design (Giran et al. 2017) can be also designed by algorithms. Jaya algorithm is working more efficiently in various problems to reach objective functions in a short time. To exemplify for one of the column problems, Cakiroglu and Bekdaş (2022) carried out the maximum axial load for a concrete filled steel tubular column by using Jaya algorithm which is 10759 kN. Jaya algorithm process is generally similar just some formulations can be changed according to problems. After generating the initial matrix, solutions are compared according to the Jaya algorithm's generated new solutions and initial matrix solutions to choose the best one in order to reach the minimum objective function. Eq. (19) is the Jaya algorithm equation that is used in the optimization process.

$$X'_{i,\text{new}} = X_{i,j} + r()\left(X_{i,g_{\text{best}}} - |X_{i,j}|\right) - r()\left(X_{i,g_{\text{worst}}} - |X_{i,j}|\right) \quad (19)$$

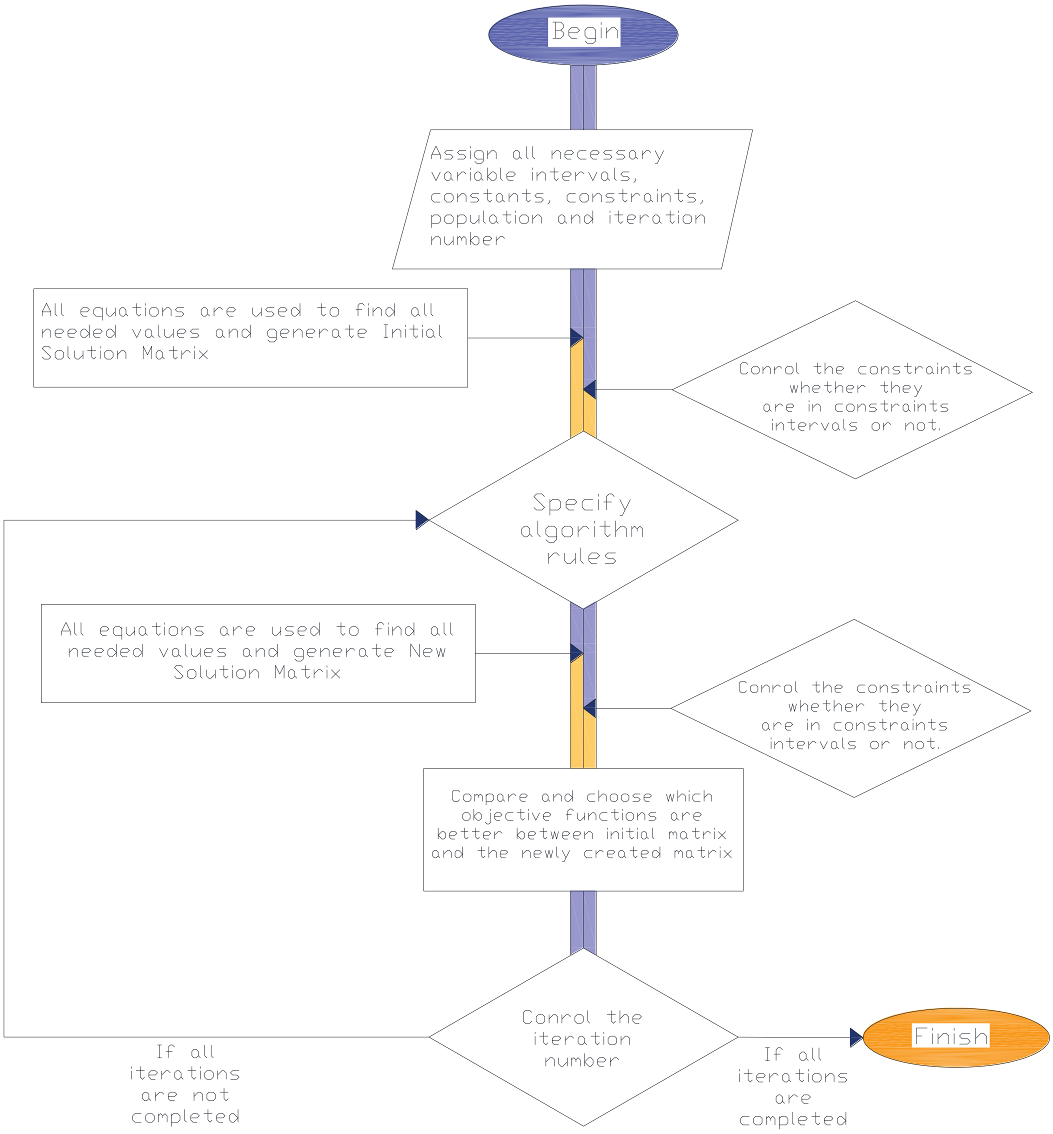

Fig. 4. Optimization process using Jaya algorithm.

Fig. 4 delineates the flowchart which is related Jaya algorithm. There are several steps to reach objective function, and they consist of preparing optimization, solving equations as well as comparing matrices to find the best values for problems. Iteration steps continue until the iteration number completes exactly its maximum values.

3. Numerical Example

Fig. 5 demonstrates the frame system which is optimally designed via the Jaya algorithm.

Table 1 consists of variables, constants and cost values. The clear cover is chosen as 30 mm.

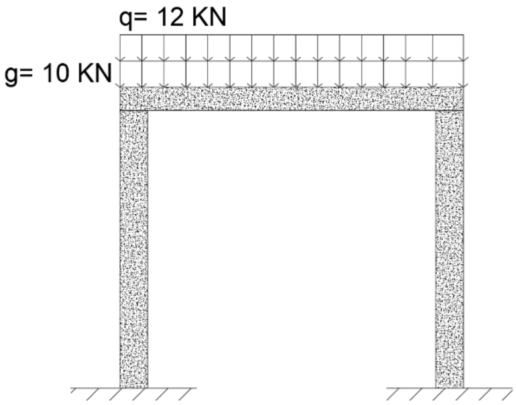

Fig. 5. Frame structure.

The given frame structure is solved by Jaya Algorithm in order to reach the most design cost. To complete this process, the algorithm and necessary equations are added to Matlab program. The objective function is specified as Eq. (20).

$$\text{FrameSystemCost} = \text{TotalConcreteVolume} \times C_c + \text{TotalSteelArea} \times C_s + \text{TotalArea} \times (C_{k,m} + C_{k,i}) \quad (20)$$

Table 2 has different constraints for the design of the frame system which consist of a beam and two columns. These constraints are about comparing maximum and minimum reinforced area, checking stress block depth and also comparing axial force.

Table 1. Design values.

Explanation	Symbol	Unit	Value
Beam min-max section width	$b_{w,\text{min-max}}$	mm	250-400
Beam min-max section height	$h_{k,\text{min-max}}$	mm	400-600
Column min-max section width	$b_{\text{min-max}}$	mm	300-600
Column min-max section height	$h_{\text{min-max}}$	mm	300-600
Live load - Dead load	q-g	kN/m	12-10
Beam length - Column height	L-H	m	6-3
Yield strength of concrete	f_{yk}	MPa	420
Specific gravity of steel	γ_s	t/m³	7.86
Cost of concrete per unit volume	C_c	TL/m³	C25/30 - 790 C30/37 - 820 C35/45- 875
Cost of steel per unit weight	C_s	TL/ton	14900
Cost of formwork material - Labour	$C_{k,m}$ -$C_{k,i}$	TL/m	104-60
Axial load	N_d	kN	300
Stirrup	Ø		8

Table 2. Constraint for the design of the frame system.

TS500	Constraints
Column	$g_1 = \psi < \frac{N_d}{b \times h \times f_{cd}}$
	$g_2 = 0.04$
	$g_3 \leq \begin{cases} b/3 \\ 100\ mm \end{cases}$
Beam	$g_4 = 0 < d - \sqrt{a} < h_k$
	$g_5 = \text{beam reinforcement area} < \begin{cases} 0.85 \times \rho \\ 0.02 \\ 0.235 \times \frac{f_{cd}}{f_{yd}} \end{cases}$
	$g_6 = \text{beam reinforcement area} \geq 0.8 \times \frac{f_{ctd}}{f_{yd}}$

In this problem, the Jaya algorithm is used as Metaheuristic Algorithm to find cost and cross sections. The result of this system is shown in Table 3 and the maximum cost occurs by using C25/30. Although concrete cost is the lowest compared to others, the necessity reinforced area (A_s) is the biggest one. That's why the cost of using C25/30 is more expensive.

Fig. 6 shows the positive direction notation and numbering of the frame structure. Positive direction property is used, when these notations show. With the Matrix displacement method, these notations are used in the algorithm to reach internal forces as well as displacement.

Table 3. Results of optimization.

Explanation	Beam			Column			Cost
	b (mm)	*h* (mm)	A_s (mm^2)	*b* (mm)	*h* (mm)	A_s (mm^2)	*F*(x)(TL)
C25/30	250	400.0	834.0	327.17	342.75	1214.5	3290.0
C30/37	250	400.0	814.0	300.00	350.70	1052.0	3232.0
C35/45	250	404.6	789.3	300.00	348.20	1044.5	3284.6

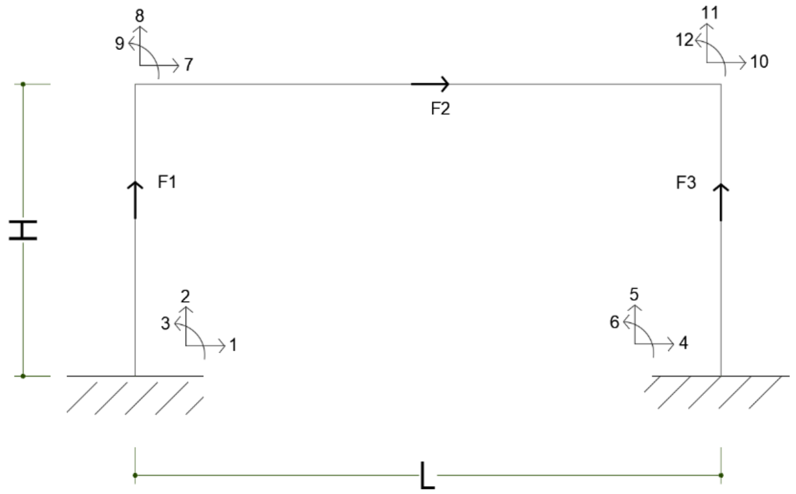

Fig. 6. Frame structure with numbering and direction rotation.

The process of the Matrix displacement method has different steps. It should be followed as below orders.

- The global axis stiffness matrix is translated to the local axis for each element.
- Transformation matrix is created for each element.
- Global axis stiffness matrix is found for each element
- The stiffness matrix of the system is found by superposing the global axis stiffness matrices for all elements.
- Displacement calculations are completed for each point by using loads affecting the system.
- The internal forces of each point are found according to the displacement values found.

Table 4 includes F1's data as internal force and displacement while Table 5 includes F3's data as internal force and displacement and also Table 6 includes F2's data as internal force and displacement. There are 12 nodes that have different features because of their locations. Looking at the tables in more detail, there is no displacement in 1-2-3 nodes and 1-7 nodes are the same amount of force with different directions. Table 3 consists of beam responses. All nodes have displacement because of non-fixed features.

Table 4. Internal forces and displacement for F1.

Explanation	1 (kN)	2 (kN)	3 (kNm)	7 (kN)	8 (kN)	9 (kNm)
$[P_L]_{F1}$ (Internal Force)	-99.60	33.19	33.04	99.6	-33.19	66.53
$[\Delta_L]_{F1}$ (Displacement)	0	0	0	$1.66*10^{-4}$	$4.98*10^{-5}$	0.0037

Table 5. Internal forces and displacement for F2.

Explanation	4 (kN)	5 (kN)	6 (kNm)	10 (kN)	11 (kN)	12 (kNm)
$[P_L]_{F2}$ (Internal Force)	-99.60	-33.19	-33.04	99.6	33.19	-66.53
$[\Delta_L]_{F2}$ (Displacement)	0	0	0	$1.66*10^{-4}$	$-4.98*10^{-5}$	-0.0037

Table 6. Internal forces and displacement for F3.

Explanation	7 (kN)	8 (kN)	9 (kNm)	10 (kN)	11 (kN)	12 (kNm)
$[P_L]_{F3}$ (Internal Force)	-33.19	$2.6 * 10^{-15}$	33.07	33.19	-2.6*10^{-15}	-33.07
$[\Delta_L]_{F3}$ (Displacement)	$-4.98 * 10^{-5}$	$1.7 * 10^{-4}$	0.0037	4.98*10^{-5}	1.66*10^{-4}	-0.0037

It is shown in Tables 4-6 by finding displacements and internal force values for each bar. From these tables, the displacements for the fixed numberings (1 2 3 4 5 6) for the frame systems are found to be zero, while the displacements will occur at the non-fixed (7 8 9 10 11 12) nodes and these displacements will take the same values in two opposite points.

4. Conclusions

In the case of using different concrete classes, reinforced area calculations were made in such a way that the values of the cross-section dimensions of the frame system elements and the boundary conditions were provided, and cost optimization was made for each concrete class, and the objective function was achieved, which all optimization steps are generated on Matlab. It is seen that the beam cross-section values for each concrete class are 250 mm and nearly 400 mm, while the column cross-section values take values in the range of 300-350 mm. Concrete classes have different cost values while the price of reinforcement is taken as the same price on a per-ton basis. In other words, the cost of the reinforcement varies depending on the area of reinforcement that is required to be used in the system. From this, it has been calculated that the design with concrete class C25/30 is more expensive than other concrete class designs, but there is not much change in the section dimensions. There is a cost difference of approximately 1.75% between the C25/30 and C30/40 concrete class design costs. While between the C25/30 and C35/45 concrete class design costs difference is roughly 0.16%. Moreover, after all these processes such as finding the optimum cross-section area, the necessary features are utilized to reach the system of internal forces and all nodes displacements. By using the Matrix displacement method, the system is divided into 3 parts which are F1, F2, as well as F3 and these are calculated separately. Non-fixed points can displace according to loading. The internal load can easily be seen that all separated parts same values in the same direction.

Acknowledgements

None declared.

Funding

The authors received no financial support for the research, authorship, and/or publication of this manuscript.

Conflict of Interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this manuscript.

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