Journal of Civil Engineering and Environmental Technology
Print ISSN : 2349-8404; Online ISSN : 2349-879X; Volume 2, Number 11; April – June, 2015 pp 89 – 94
Krishi Sanskriti Publications
http://www.krishisanskriti.org/jceet.html

Optimal Design of Semi Rigid Jointed Frame Structure

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Abstract: *Optimization is act of obtaining the best result under given circumstances. The aim of this study is to determine the effects of semi rigid connection in optimal design of frame structures. The design variables are the member sections where column and beam members are distinguished. The connection spring stiffness is also a design variable and is changed during the process in a predetermined range. The present study also has an objective to achieve least weight design of frame structures with semi-rigid connections, considering only flexural behavior, under applied loads. It is a discrete optimization problem in terms of the member sections and in terms of the rotational stiffnesses of end connections.*

The issue addressed here is multifold, since the objective function and the constraints are implicit functions of design variables. Thus two separate layers of analysis are proposed here. The first layer contents finding parameters of constraint equation using a special code developed in FORTRAN. The second layer contents optimization of frame structures of FEM results using program developed in EXCEL where constraints must be satisfied. And then optimization of bending moments and volume is achieved. The various numerical examples are performed and results are interpreted and discussed.

1. INTRODUCTION

Optimization is referred to as the procedure used to make a system or design as effective or as functional as possible, involving various mathematical techniques. The objective functions, the design variables, the pre assigned parameters and the constraints describe an optimization problem. The quantities which describe an optimization problem can be divided into two groups: Pre assigned variables and design variables. In most practical cases, an infinite number of feasible designs exist. In order to find the best one, it is necessary to form a function of the variables to use it for comparison of design alternatives. The objective function is the function whose least, or greatest is sought in an optimization procedure.

All of us are optimizers. We all make decisions that maximize our welfare in some way or another. Often the welfare we are maximizing may come later in life. By optimizing, it reflects our evaluation of future benefits versus current costs or benefits forgone. In economics, the extent to which we value future benefits today is reflected by what is called a discount rate. While economic criteria are only a part of everything we consider when making decisions, they are often among those deemed very important. So there is need to optimize semi rigid jointed frame by studying effects of semi rigid joint on frame structures.

The different single objective optimization techniques make the designer able to determine the optimum sizes of structures, to get the best solution among several alternatives. The efficiencies of these techniques are different. A large number of algorithms have been proposed for the nonlinear programming solution. The choice of a particular algorithm for any situation depends on the problem formulation and the user.

Several papers prove that in actual framed structures, rigid connections have some degree of flexibility, while pinned connections have some stiffness [1]. Three types of connection i.e. pinned, rigid and semi rigid were described in steel frames [2], [4]. The European Code (EC 3) for design of steel structures [2], [3] has adopted semi-rigid steel framing construction.

Along with semi rigid beam to column connections, column to foundation connections in steel frames has been studied [5], [6]. M. Brognoli *et. al.*[7] studied optimal design of semi-rigid braced frames via knowledge-based approach. To achieve this structural optimization on a system analysis is used rather than on a component analysis. Ayse Daloglu *et.*

al.[8] and Alexandre A. Savio *et. al.*[9] studied optimal design of steel plane frames using genetic algorithm due to their ability of providing a solution to discrete optimum design problems. Aniko Csebfalvi *et. al.* inspected effects of semi rigid connections in optimal design of frame structures [10], [11]. K. N. Kadam studied about optimization of truss using genetic algorithm.

This study presents various design constraints, design variables, objective function and formulation needed to satisfy all the constraints for optimization. By considering various design variables and design constraints optimal weight design of portal frame has done.

2. SYSTEM DEVELOPMENT

2.1 Definition of Optimization

Optimization is the process of maximizing or minimizing a desired objective function while satisfying the prevailing constraints. It is act of obtaining the best result under given circumstances. In optimization of a design, the design objective could be simply to minimize the cost of production or to maximize the efficiency of production.

2.2 Optimal Problem Formulation

An optimal design is achieved by comparing a few alternative solutions created by using problem knowledge. In this method feasibility of each design solution is first investigated. Thereafter an estimate of underlying objective (cost, profit, etc.,) of each solution is compared and best solution is adopted.

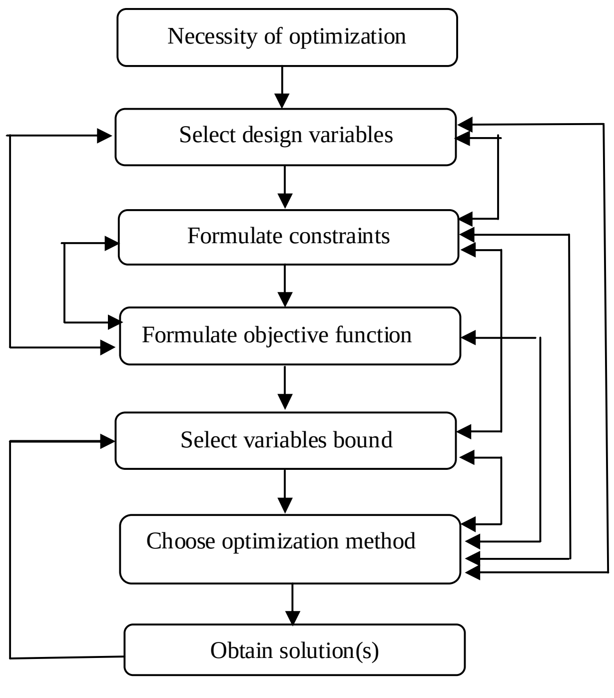


Figure 1. Flowchart of the generalized optimal design procedure

It is impossible to apply single formulation procedure for all engineering design problems, since the objective in a design problem and associated therefore, design parameters vary product to product different techniques are used in different problems. Purpose of formulation is to create a mathematical model of the optimal design problem, which then can be solved using an optimization algorithm. Figure 1 shows an outline of the steps usually involved in an optimal design formulation.

2.3 Optimization Problem

In this study the objective function is the least weight of the structure because the total cost is strongly depends on the actual price of raw materials and the actual cost of manufacturing. The maximum bending moment of semi-rigid beams under an applied member load has considered for the variation of the rotational stiffnesses of end connections will be adopted in this study. The minimum value of the maximum moments which can be achieved by adjusting connection stiffness has been presented.

2.3.1 Definition of the design problem

The cost of structure easily depends on cross-sectional areas of column elements as well as beam elements of structural member decides the material use and thus affect the cost. So cross section area are design variable. Here, the present study has an objective to the least weight design problem of frame structures with semi-rigid connections, considering only flexural behavior, under applied loads can be defined as a discrete optimization problem in terms of the member sections, Ai and in terms of the rotational stiffnesses of end connections, k. The design variables Ai are selected from a discrete set of the predetermined Ai $\in$ B = $\{B^1, B^2, \ldots B^N\}$ cross-sectional areas of column elements, $A_j \in C$ $\{C^1, C^2, \ldots, C^N\}$ cross-sectional areas of beam elements such that minimize the total weight, while rotational stiffnesses of end connections are changing in between a given equidistance range of kq $\in$ k = $\{k^1, k^2, \ldots, k^E\}$ values.

The objective function is

$$W(Ai, Aj) \rightarrow \min!, \quad i = 1, 2, \ldots, n \quad j = 1, 2, \ldots, m \tag{1}$$

where n is the number of column and m is the number of beam elements, q is the number of joints, N is the number of cross sectional catalogue values for columns, M the number of cross sectional catalogue values for beam elements, and E is the number of rotational stiffness value series.

The discrete minimal weight design is subjected to size, displacement, and stress constraints. In order to satisfy the design constraints listed above, we have to determine the displacements and internal force distribution of the framed structure in terms of member cross sections and connection stiffness of joint springs. In this study, for structural analysis of a 2D frame with semi rigid joints a program is developed. The structural model is formulated as a combination of 3D quadratic beam elements and linear torsional springs. The frame is defined in x, and y plane. Therefore, ux and uy displacements, θ_z rotation, Fx and Fy member forces, and Mz bending moment will be considered in the 3D coordinate system. The orientation of the beam and column sections is shown in Figure 3.

2.3.2 Displacement constraints

The displacement constraints are

$$u_k - \bar{u}_k < 0, \quad k = 1,2,\ldots,p \tag{2}$$

where u_k is the actual displacement value of the beam or column elements, $\bar{u}_k$ is its upper bound, and p is the number of restricted displacements.

2.3.3 Bending and Axial Tension Constraints of the Columns and Beams

Constraints for normal stresses are computed from the maximal value of bending moments and from the related normal forces or from the maximal value of axial forces and related bending moments.

$$\frac{N}{fyA} + \frac{Mz}{fyWz} \leq 1 \tag{3}$$

where N is the actual axial force of the beam (Fx) or column (Fy) elements, Mz is the bending moment, Wz is the section modulus, and the fy is the yield stress, modified by the partial safety factor.

2.3.4 Bending and axial compression constraints of the columns and beams

The frames are defined in the x, y, and z global coordinate system where z is the bending axis. The frame members are loaded by bending and axial forces. Therefore, the overall flexural and torsional buckling constraints are formulated according to Euro code 3. We have to satisfy the following buckling constraints about the z axis:

$$\frac{N}{\chi_z fyA} + kz\frac{Mz}{\chi_{LT} fyWz} \leq 1 \tag{4}$$

Where χ_z is the overall buckling factor for the axis z, χ_{LT} is the lateral-torsional buckling factor; kz is a modification factor in terms of the axial force effect.

The overall buckling factor χ_z for the axis z is

$$\chi_z = \frac{1}{\phi z + \sqrt{\phi z^2 - \bar{\lambda}_z^2}}, \tag{5}$$

where

$$\phi_z = 0.5\,[1 + \alpha_z\,(\bar{\lambda}_z - 0.2) \tag{6}$$

$$\alpha_z = \begin{cases} 0.21 & h_1/b_1 > 1.2 \\ & \text{If} \\ 0.34 & h_1/b_1 \leq 1.2 \end{cases} \tag{7}$$

The slenderness ratio of the column

$$\bar{\lambda}_z = \frac{2H}{r_z \lambda_E} \tag{8}$$

And the slenderness ratio of the beam is

$$\bar{\lambda}_z = \frac{1.3\,L}{r_z \lambda_E} \tag{9}$$

where

$$\lambda_E = \pi\sqrt{\frac{E}{f}} \quad \ldots\ldots\ldots \quad r_z = \sqrt{\frac{I_z}{A}} \tag{10}$$

The lateral-torsional buckling factor χ_T is

$$\chi_T = \frac{1}{\phi_T + \sqrt{\phi_T^2 - \bar{\lambda}_T^2}}, \tag{11}$$

where

$$\phi_T = 0.5\,[1 + \alpha_T\,(\bar{\lambda}_T - 0.2) + \bar{\lambda}_T^2] \tag{12}$$

and

$$\alpha_z = \begin{cases} 0.49 & h_1/b_1 > 2 \\ & \text{If} \\ 0.34 & h_1/b_1 \leq 2 \end{cases} \tag{13}$$

The relative lateral-torsional factor is computed from the following formula:

$$\bar{\lambda}_T = \sqrt{\frac{W_z fy}{M_{cr}}} \tag{14}$$

where Mcr in case of columns is replaced by

$$Mcr = 11.132\pi^2 E\frac{I_x}{H}\sqrt{\frac{I_w}{I_x} + \frac{H^2 GI_t}{\pi^2 EI_x}} \tag{15}$$

and in case of beams by

$$Mcr = 11.132\pi^2 E\frac{I_y}{L}\sqrt{\frac{I_w}{I_y} + \frac{L^2 GI_t}{\pi^2 EI_y}} \tag{16}$$

The k_z factor is computed from the following formula replaced by the above defined variables:

$$k_z = 0.9[1 + 0.6\bar{\lambda}_z \frac{N}{\chi z\, fyA}] \tag{17}$$

The buckling constraints about the x axis for the column and about the y axis for the beam elements are follows

$$\frac{N}{\chi_n fyA} \leq 1 \tag{18}$$

where N is the actual axial force of the beam (Fx) or column (Fy) elements, χ_n is the overall buckling factor related to the x axis for the column and about the y axis for the beam elements.

The overall buckling factor χ_n for the axis n = x of beam elements and n= y for the column elements is

$$\chi_n = \frac{1}{\phi_n + \sqrt{\phi_n^2 - \bar{\lambda}_n^2}}, \tag{19}$$

where

$$\phi_n = 0.5\,[1 + \alpha_n\,(\bar{\lambda}_n - 0.2) + \bar{\lambda}_n^2] \tag{20}$$

and

$$\alpha_n = \begin{cases} 0.21 & h_1/b_1 > 1.2 \\ & \text{If} \\ 0.49 & h_1/b_1 \leq 1.2 \end{cases} \tag{21}$$

The slenderness ratio of the column

$$\bar{\lambda}_y = \frac{2H}{r_y \lambda_E} \tag{22}$$

And the slenderness ratio of the beam is

$$\bar{\lambda}_x = \frac{1.3\,L}{r_x \lambda_E} \tag{23}$$

2.4 Optimization Procedure

The first design variables i.e. beam and column section are selected from available catalogue and the third design variable i.e. spring stiffness is chosen from a decided range with equal increments. A program for optimization is developed in EXCEL using the formulation proposed in article [12-13] and all the combination of design variables are checked for constraints and the bending moment is then minimized.

Based on the above system developed various 2D frames with semi rigid joint connections has solved. First the structural analysis is done using code developed in FORTRAN and then optimization of bending moments and volume is achieved using program developed in EXCEL.

3. FORMULATION

3.1 Optimization of semi rigid jointed plane frame

The effects of semi-rigid connections are observed to the optimal design of steel frames. An example of planar frames is studied here. In this study, a simple-bay frame (shown in Figure 2) was considered where the objective function is the minimal weight (volume) of the structure subjected to the sizing, displacement, and stress constraints including the member buckling as well. The design variables are discrete variables of the cross section of beam and column members. According to the structural symmetry requirements, symmetrical members are grouped into the same variables.

The applied material is prEN (Fe E 510) given according to the European Standard steel with a modulus of elasticity of 210 000MPa and a yield stress of 355 MPa. The Poisson factor is 0.3, and the material density is 7850 kg/m3. Length of the frame is 30 m. and height is 6 m. The cross sections are chosen from the European section profiles. In the presented example the beam and column profiles are distinguished, and the cross sections have been selected from the catalogue of Table 1, and Table 2. The applied load is p=5 kN/m, according to the Figure 2.

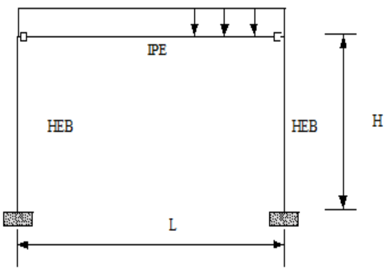
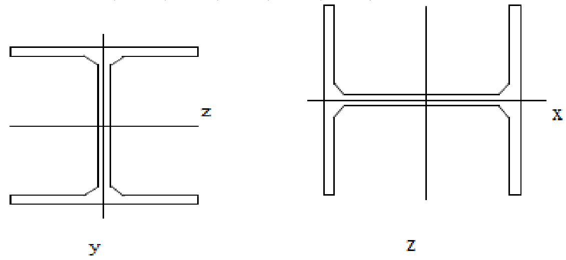


Figure 2. Semi-rigid single-bay frame

Beam-to-column connections are varying from ideally-pinned to fully-rigid behavior. The changes of the rotational stiffness of beam- to-column connections play a relevant role in the optimal design problem while the structural response is changing as well. In order to expose this effect to the optimal design, the rotational stiffness between beam element and column element is applied.

For pinned connections, the rotational stiffness of the connection tends to the zero. For rigid connections, the rotational stiffness of the connection tends to infinity, and in case of a more realistic design, the semi-rigid connection results a value in between infinity and zero. In this examples, the rotational stiffnesses of end connections are changing in between a given equidistance range of $k_q \in k = \{1E4; 5E4; 1E5; 5E5; 1E6; 5E6; 1E7; 5E7\}$ values.



(a) Beam section type (b) Column section type

Figure 3. Cross-section orientations in the global coordinate system

Table 1. Catalogue values of beam section types

Section type	h [cm]	b [cm]	A [cm2]	It [cm4]	Iz [cm4]	Iy [cm4]	Iω [cm6]
IPE 80	8	4.6	7.64	0.7	80.1	8.5	119
IPE 100	10	5.5	10.32	1.2	171	15.9	354
IPE 120	12	6.4	13.21	1.7	317.8	27.7	894
IPE 140	14	7.3	16.43	2.5	541.2	44.9	1989
IPE 160	16	8.2	20.09	3.6	869.3	68.3	3977
IPE 180	18	9.1	23.95	4.8	1317	100.9	7459
IPE 200	20	10	28.48	7	1943.2	142.4	13053
IPE 220	22	11	33.37	9.1	2771.8	204.9	22762
IPE 240	24	12	39.12	12.9	3891.6	283.6	37575
IPE 270	27	13.5	45.95	15.9	5789.8	419.9	70849
IPE 300	30	15	53.81	20.1	8356.1	603.8	126333
IPE 330	33	16	62.61	28.1	11770	788.1	199877
IPE 360	36	17	72.73	37.3	16270	1043.5	314645
IPE 400	40	18	84.46	51.1	23130	1317.8	492147
IPE 450	45	19	98.82	66.9	33740	1675.9	794245
IPE 500	50	20	115.52	89.3	48200	2141.7	1254253
IPE 550	55	21	134.42	123.2	67120	2667.6	1893154
IPE 600	60	22	155.98	165.4	92080	3387.3	2858585

Table 2. Catalogue values of column section types

Section type	h [cm]	b [cm]	A [cm2]	It [cm4]	Iz [cm4]	Ix [cm4]	Iω [cm6]
HE 120 B	12	12	34.01	13.8	864.4	317.5	9431
HE 140 B	14	14	42.96	20.1	1509.2	549.7	22514
HE 160 B	16	16	54.25	31.2	2492	889.2	48038
HE 180 B	18	18	65.25	42.2	3831.1	1362.8	93887
HE 200 B	20	20	78.08	59.3	5696.2	2003.4	171413
HE 220 B	22	22	91.04	76.6	8091	2843.3	295813
HE 240 B	24	24	105.99	102.7	11260	3922.7	487675
HE 260 B	26	26	118.44	123.8	14920	5134.5	754853
HE 280 B	28	28	131.36	143.7	19270	6594.5	1131686

For the selection there are 18 beam section profiles, 8 column section profiles and 8 rotational stiffnesses. So, there is need to analyze the frame 1296 times for several combinations of design variables, namely (beam section profiles, column section profiles and rotational stiffnesses). The optimization is carried out using the program done in EXCEL 2010 [12]. The design constraints are formulated in 3D coordinate system using equations (2)-(23). Using these equations design constraints are check for beam section profiles, column section profiles. If any combination satisfies all these constraints, then the program finds value of objective function and then the optimal solution for that frame is obtained.

Table 3. Optimal volume of single bay frame (k= 1 E 04)

Sr No.	Beam Section type	Column Section type	Axial force (kN)	Bending moment (kNm)	Volume (cm3)
1	IPE 550	HE 180 B	25.36	101.50	442410
2	IPE 550	HE 200 B	30.01	120.10	450108
3	IPE 550	HE 220 B	33.77	135.30	457884
4	IPE 600	HE 160 B	15.65	62.63	500490
5	IPE 600	HE 180 B	19.95	79.85	507090
6	IPE 600	HE 200 B	23.96	95.92	514788
7	IPE 600	HE 220 B	27.30	109.30	522564
8	IPE 600	HE 240 B	30.09	120.60	531534
9	IPE 600	HE 260 B	32.15	128.90	539004
10	IPE 600	HE 280 B	33.75	135.30	546756

In Table 3, only the combination of beam and column section are given, which satisfy all the constraint condition of the optimal solution for k= 1 E 04. From Table 3, it is seen that, though the volume of frame (combination of beam and column sections) is more than optimal volume, combination of more volume of frame does not satisfy all the constraints, so it is not optimal solution. Similarly, the volume of frame (combination of beam and column sections) is less than optimal volume, it not satisfy the all the constraints, and it is not optimal solution. Only those combinations are given in tables which satisfy all the constraints and these combinations are the optimal solution for the given frame.

Table 4. Optimal volume of single bay frame for different k

Sr No.	Beam Section type	Column Section type	k	Axial force (kN)	Bending moment (kNm)	Volume (cm3)
1	IPE 550	HE 180 B	1 E 04	25.36	101.50	442410
2	IPE 550	HE 200 B	1 E 04	30.01	120.10	450108
3	IPE 550	HE 220 B	1 E 04	33.77	135.30	457884
4	IPE 600	HE 160 B	1 E 04	15.65	62.63	500490
5	IPE 600	HE 180 B	1 E 04	19.95	79.85	507090
6	IPE 600	HE 200 B	1 E 04	23.96	95.92	514788
7	IPE 600	HE 220 B	1 E 04	27.30	109.30	522564
8	IPE 600	HE 240 B	1 E 04	30.09	120.60	531534
9	IPE 600	HE 260 B	1 E 04	32.15	128.90	539004
10	IPE 600	HE 280 B	1 E 04	33.75	135.30	546756
11	IPE 600	HE 180 B	5 E 04	25.57	102.30	507090
12	IPE 600	HE 200 B	5 E 04	32.55	130.30	514788
13	IPE 600	HE 220 B	5 E 04	39.03	156.30	522564
14	IPE 600	HE 240 B	5 E 04	45.02	180.40	531534
1	IPE	HE	1 E	26.5	106.0	50709

5	600	180 B	05	0	0	0
1 6	IPE 600	HE 200 B	1 E 05	34.0 8	136.4 0	51478 8
1 7	IPE 600	HE 220 B	1 E 05	41.2 4	165.2 0	52256 4
1 8	IPE 600	HE 180 B	5 E 05	106. 00	27.29	50709 0
1 9	IPE 600	HE 200 B	5 E 05	136. 40	35.40	51478 8
2 0	IPE 600	HE 220 B	5 E 05	165. 20	43.21	52256 4
2 1	IPE 600	HE 180 B	1 E 06	109. 20	27.40	50709 0
2 2	IPE 600	HE 200 B	1 E 06	141. 70	35.58	51478 8
2 3	IPE 600	HE 220 B	1 E 06	173. 00	43.46	52256 4
2 4	IPE 600	HE 180 B	5 E 06	27.4 8	110.0 0	50709 0
2 5	IPE 600	HE 200 B	5 E 06	35.7 2	143.0 0	51478 8
2 6	IPE 600	HE 220 B	5 E 06	43.6 7	174.9 0	52256 4
2 7	IPE 600	HE 180 B	1 E 07	27.4 9	110.0 0	50709 0
2 8	IPE 600	HE 200 B	1 E 07	35.7 3	143.0 0	51478 8
2 9	IPE 600	HE 220 B	1 E 07	43.7 0	175.0 0	52256 4
3 0	IPE 600	HE 180 B	5 E 07	27.5 0	110.1 0	50709 0
3 1	IPE 600	HE 200 B	5 E 07	35.7 5	143.1 0	51478 8
3 2	IPE 600	HE 220 B	5 E 07	43.7 1	175.1 0	52256 4

Out of 1296 combinations of design variables, only 32 combinations have satisfied constraints. Table 4 shows results of all these satisfactory 32 combination. Out of which some of volume are same due to same combinations but different rotational stiffness *i.e.* k. And from there, combination with less shear force and bending moment are considered as an optimal volume. It is found that for k= 1 E 04, the axial forces and bending moment are comparatively less than the other values of rotational stiffness.

4. CONCLUSIONS

Objective function for minimizing the weight is depends upon various parameters such as choice of design variables, constraints, organization of objective function and the factors related to it. Appropriate optimization has to be selected depending upon optimization problem and number of design variable.

Due to optimization optimal solution can be achieved, which is economical. The optimal solutions highly depend on the structural geometry and on the loading conditions. Due to optimization optimized bending moments can be achieved.

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