

OPTIMIZATION OF REINFORCED CONCRETE FRAMES BY USING SPREADSHEET SOFTWARE

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ABSTRACT: This study is focused on optimization of 2D Reinforced Concrete (RC) Frames. Three frames with different number of bays and stories were used in this study. The frames were analyzed using stiffness method. Lateral displacement in each frame under earthquake load was taken as the main constraint. The objective function was based on the weight of the structure. Frames were optimized in terms of concrete dimensions by keeping the lateral displacement constraints within the specified limits. Generalized Reduced Gradient (GRG) method was used for optimization after the analysis of frames. It was found that optimization along with member (beam or column) grouping plays a vital role in the optimization of structures. The GRG method works very efficiently during optimization process especially when the objective function lies within the feasible region.

Key words: objective function, local optimum, design variables, constraint.

INTRODUCTION

Computers have made computations easier and faster than ever before. Sooner or later conventional design process will be replaced by optimum design process. In last thirty years a lot of work has been done on structural optimization (Levy et al. 1987, Cyras, 1983, Karkauskas, 1997). It has always been human's desire to select the best one or opt for the best one. Optimization techniques are the answer to this question. In the conventional design process, a designer finalizes a design after a few trials using his intuition, past experience and skill. This process, in general will not produce the best design. The shortcoming of the indirect design can be overcome by using a direct design procedure. Optimum design process begins with the identification of design variables, objective or merit function and the constraints that must be satisfied. This phase of optimum design process is called problem formulation, which is the most important part of the design process. The correct formulation is essential and roughly it takes 50% of the total efforts need to solve it (Arora, 1989). The criterion that distinguishes alternate design is called the objective function or merit function. It enables us to compare different designs. The restrictions or conditions that must be satisfied to produce a feasible design are called constraints. A meaningful constraint must be a function of at least one design variable. There are a lot of techniques to solve constraint minimization problem reported by various researcher (Arora, et al, 1996). Fadaee and Grierson (1998) presented their computer based model for reinforced concrete frame which implements optimality criteria (OC) method. They studied the influence of constraints with an example

problem. Two types of problem formulation have been studied, one with biaxial shear and second without biaxial shear. Luisa et al (2006) have presented a method that is designed oriented for improving the overall stability and strength. The method is implemented on moment-resisting frame structure. The condition of structural instability (or buckling) is approximated as a linear function of the displacements. The design process can easily be visualized because this method is implemented story-by-story. Sandoval et al (2005) have studied the columns of reinforced concrete tall building for optimization point of view. They have proposed a formulation for the optimization of reinforced concrete columns. Columns cross sectional dimensions and amount of longitudinal reinforced are chosen as design variables. With an intention to reduce the size of this class of problem, method of decomposition has been brought into play. The large problem also called a global problem is decomposed into number of sub-problems.

The technique used in this study is gradient-base techniques. Optimal design of frames typically involves finding cross sectional dimensions to minimize an objective function (e.g. weight or cost of a RC frame) subject to one or more constraints (e.g. performance requirements) for a fixed structural layout and loading (Grierson, 1997).

In Pakistan, very little amount of work has been done in the field of structural optimization and it was the aim to add somewhat in this area. The main objectives of this study were to determine the objective function for 2-dimensional frame structures keeping the lateral deflection as a main constraint. Member grouping and its role in structural optimization was also studied. The effectiveness of Generalized Reduced Gradient method for structural optimization was also studied.

MATERIALS AND METHODS

For problem formulation the elastic behavior of the structure is assumed under design loads. The frame geometry or layout and loads acting on it are considered as a given parameters. The main design requirements are assumed to be the control of lateral displacements

Structural optimization program mainly consists two parts

- 1- Programming for Structural Analysis
- 2- Programming for Optimization algorithm

Microsoft Excel has been used for the programming of the proposed problem. Matrix Stiffness method is implemented for Structural analysis using Microsoft Excel programming capabilities like matrix algebra functions. Three spreadsheets for One Bay 8 Story (Figure-1), Two Bay 6 Story (Figure-2) and Three Bay 4 Story (Figure-3) RC frames having structure stiffness matrices of 48x48, 54x54 and 48x48 respectively were prepared with minimum input like nodal coordinates for frame geometry, material properties, loads, seismic parameters and initial member sizes. Microsoft Excel Solver is used for optimization which implements Generalized Reduced Gradient (GRG) method.

The design optimization problem of the proposed study may be stated in mathematical form as, Minimize:

$$W = \gamma_{con} \sum_{i=0}^{nsec} (B_i H_i) L_i \quad (1)$$

Where:

W = objective function, it is summation of the weight of concrete of all the members

γ_{con} = unit weight of concrete.

The design variables "B" and "H" are member width and depth respectively, L is member length and "nsec" means no. of sections

Optimization algorithm changes the initial design by improving the objective function. Several optimization models were prepared for each frame in order to study how optimization works. A limit of 1/350 is proposed for inter-story drifts and same 1/350

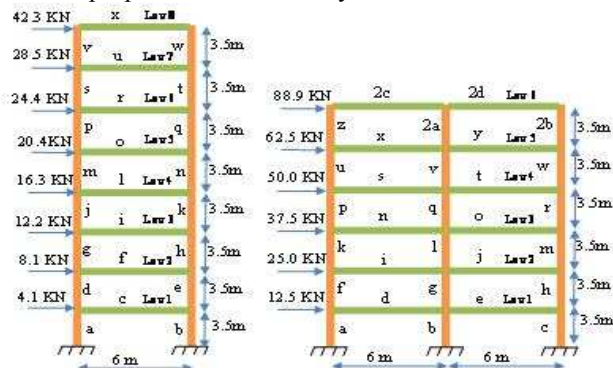


Fig-1: Frame-1 Labeling, Dimensions and Loading

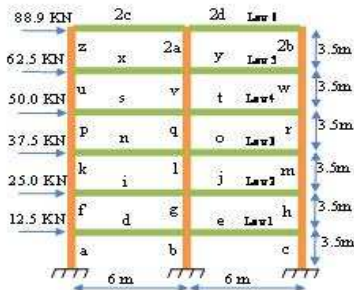


Fig -2: Frame-2 Labeling, Dimensions and Loading

for overall Lateral displacement. For columns 0.3 m and 0.9 m are upper and lower bounds respectively. For beams width (0.2 m and 0.7 m) and for height (0.325 m and 0.7) m are upper and lower bounds respectively.

(a) Material Properties: The following material properties are assumed for the proposed framed structures and modulus of elasticity E is determined according to

ACI code as $4700 \sqrt{f'_c}$

$$f'_c = 28000 \text{ KN/m}^2$$

$$f_y = 420000 \text{ KN/m}^2$$

Modulus of elasticity of steel $E_s = 2.00 \times 10^8 \text{ KN/m}^2$

Unit wt of concrete $\gamma_{con} = 2.36 \times 10^1 \text{ KN/m}^3$

Modulus of elasticity of concrete $E_c = 2.49 \times 10^7 \text{ KN/m}^2$

(b) Seismic Parameters: The following seismic parameters are assumed for the proposed framed structures.

$C_t =$	0.073
Zone =	2B
Soil profile =	S_E
$C_a =$	0.34
$C_v =$	0.64
R =	5.5
I =	1

(c) Illustrative Example Frames: Three frames have been used in this study. Frame-1 is one bay, eight stories frame; frame-2 is two bays, six stories and frame-3 is three bays, four stories. Dimensions, loading and labeling of all the frames are shown in Fig-1 to Fig-3. The main constraints are inter-story drift and overall lateral displacement. The frame geometry is fixed and lateral loads are calculated as per UBC-97. The bay width is 6 m and story height is 3.5 m for all frames. The overall heights of the frame-1 (Fig-1), frame-2 (Fig-2) and frame-3 (Fig-3) are 28 m, 21m and 14m respectively. The story dead load is taken 24.9 kN/m. The member grouping options for all the frames are presented in Table-1.

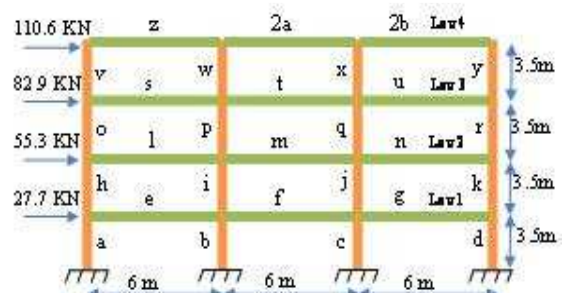


Fig -3: Frame-3 Labeling, Dimensions and Loading

Table-1: Member Grouping for Different Options

Frame	Option	columns	Beams
Frame-1	1.1	No member grouping	No member grouping
	1.2	C1(a,b),C2(d,e), C3(g,h), C4(j ,k), C5(m,n), C6(p,q),C7(s,t),C8(v,w)	B1(c), B2(f), B3(i), B4(l), B5(o), B6(r) ,B7(u), B8(x)
	1.3	C1(a,b,d,e),C2(g,h,j,k), C3(m,n,p,q), C4(s,t,v,w)	B1(c,f), B2(i,l), B3(o,r), B4(u,x)
	1.4	C1(a,b,d,e,g,h),C2(j,k,m,n,p,q), C3(s,t,v,w)	B1(c,f,i), B2(l,o,r), B3(u,x)
	1.5	C1(a,b,d,e,g,h,j,k,m,n,p,q,s,t,v,w)	B1(c,f,i,l,o,r,u,x)
Frame-2	2.1	No member grouping	No member grouping
	2.2	C1(a,c), C2(b), C3(f,h), C4(g), C5(k,m), C6(l), C7(p,r), C8(q), C9(u,w), C10(v), C11(z,2b), C12(2a)	B1(d,e), B2(i,j), B3(n,o), B4(s,t), B5(x,y), B6(2c,2d)
	2.3	C1(a,c,f,h),C2(b,g), C3(k,m,p,r), C4(l,q), C5(u,w,z,2b),C6(v,2a)	B1(d,e,i,j), B2(n,o,s,t), B3(x,y,2c,2d),
	2.4	C1(a,c,f,h,k,m),C2(b,g,l),C3(p,r,u,w,z,2b), C4(v,2a,,q)	B1(d,e,i,j,n,o), B2(s,t,x,y,2c,2d)
	2.5	C1(a,c,b, f,h, g, k,m, l,p,r,q,u,w, v, z,2b,2a)	B1(d,e, i,j, n,o, s,t, x,y, 2c,2d)
Frame-2	3.1	No member grouping	No member grouping
	3.2	C1(a,d),C2(b,c), C3(h,k), C4(i,j), C5(o,r), C6(p,q),C7(v,y),C8(w,x)	B1(e,f,g), B2(l,m,n), B3(s,t,u), B4(z,2a,2b)
	3.3	C1(a,d,h,k),C2(b,c,i,j),C3(o,r,v,y), C4(p,q,w,x)	B1(e,f,g,l,m,n), B2(s,t,u,z,2a,2b),
	3.4	C1(a,d,h,k,o,r,v,y),C2(b,c,i,j,p,q,w,x)	B1(e,f,g,l,m,n,s,t,u,z,2a,2b)
	3.5	C1(a,d,b,c,h,k,i,j,o,r,p,q,v,y,w,x)	B1(e,f,g,l,m,n,s,t,u,z,2a,2b)

Columns are grouped as C1, C2, C3 etc and in the same way beams are grouped as B1, B2, and B3 etc. For example, C1(a, b) means column “a” and column “b” are in group C1. There are five options for all frames. Only the detailed designs of option 1.1 and option 1.3 are discussed. For frame-2 (Fig-2) and frame-3 (Fig-3) only the summary of results showing initial design, initial objective function, optimized objective function and top story displacement are presented. All dimensions are in meter.

RESULTS AND DISCUSSION

The lateral displacement limiting value of frame-1 for level-1, level-2, level-3, level-4, level-5, level-6, level-7 and level-8 are 0.01 m, 0.02 m, 0.03 m, 0.04 m, 0.05 m, 0.06 m, 0.07 m and 0.08 m respectively as given in Table-2b. The initial design for all the options to get optimized design is shown in Table-2a and Table-2b. Table-2a shows the columns and beams sizes used as an initial estimate during optimization and Table-2b shows overall lateral displacement limits and actual lateral displacements. In Option 1.1, member grouping is not considered while constraints are specified in Table-2b. Fig-4 shows the lateral displacement profile of this option. As no member grouping is considered in this option that is why columns sizes distribution is uneven from level to level and even at the same level. For example, column “a” of size 0.300x0.300 m and column “b” of size 0.003x0.488 m are at the same level but their sizes are different. Objective function value of initial design is 574 but after optimization objective function value is 319 and there is 44% reduction in the objective function. It can be seen that lateral displacements are exactly equal to the limiting value. For example, top story

lateral displacement limiting value is 0.08 m and actual value is also 0.08 mas given in Table-3b.

For option 1.3, optimized design is presented in Table-4. In Option 1.3, members are grouped in such a way that there are four groups of columns C1, C2, C3, C4 and four groups of beams B1, B2, B3 and B4. Member of each two stories are place in one group of columns and beams. In Story level 1 and level 2, column “a”, column “b” column “d” and column “e “are place in group C1; beam “c” and beam “f” are placed in group B1 and so on as given in Table-1. Objective function value of initial design is 574 but after optimization objective function value is 337. Lateral displacement profiles of initial designs, optimized designs and limiting values are shown in Fig-5. During optimization using different options the lateral displacements improve as compared with the initial displacements but remain within the specified limits and sizes of the beams and columns changes so as to get minimum value of objective function.

The GRG optimization method as well as other optimization methods converges to the neighborhood of the initial design point giving local minimum. Keeping in view the above phenomenon optimization has been carried out for different design points and multiple objective functions are obtained depending upon the initial design. To study this behavior 128 initial designs are optimized. Eight initial design point scattered in the design space are chosen for all frames. For frame-1 and frame-2, design point “1”and “5” are feasible designs and rests of the design points are infeasible designs. For frame-3, design points “1”, “3”, “5” and “7” are feasible design and other remaining points are infeasible designs. Table-5 presents the results of optimized design of frame-1 for option 1.1 and option 1.3 for various design points scattered in the design space. Optimized objective function value of option 1.1 for design points “1”, “2”,

“4”, “5”, “7” and “8” is 319 but they do not converges to same design . Design points “2”, “4”, “5”, and “8” converges to the same design. In option 1.3 design points

“4”, “5”, “6” and “8” converges to the same design with objective function value of 337.

Table-2a: Initial Design for Option 1.1, 1.3

Element				Objective Function
Columns		Beams		
Width	Height	Width	Height	
0.400	0.700	0.300	0.600	574

Table-2b: Lateral Displacements Initial Design

Story Level	Lateral Displacement Limits	Actual Lateral Displacements	Remarks
0	0	0	OK
1	0.010	0.004	OK
2	0.020	0.010	OK
3	0.030	0.018	OK
4	0.040	0.025	OK
5	0.050	0.032	OK
6	0.060	0.037	OK
7	0.070	0.042	OK
8	0.080	0.045	OK

Table-3a: Optimized Design Option 1.1

Story Level	Columns			Columns			Beams			Objective Function
	Label	Width	Height	Label	Width	Height	Label	Width	Height	
1	a	0.300	0.300	b	0.300	0.488	c	0.200	0.667	319
2	d	0.300	0.671	e	0.300	0.367	f	0.210	0.700	
3	g	0.300	0.314	h	0.300	0.715	i	0.210	0.700	
4	j	0.300	0.616	k	0.300	0.300	l	0.210	0.700	
5	m	0.300	0.300	n	0.300	0.615	o	0.202	0.675	
6	p	0.300	0.521	q	0.300	0.300	r	0.200	0.665	
7	s	0.300	0.300	t	0.300	0.441	u	0.200	0.606	
8	v	0.300	0.374	w	0.300	0.300	x	0.200	0.372	

Table-3b: Lateral Displacements Option 1.1

Story Level	Lateral Displacement Limits	Actual Lateral Displacements	Remarks
0	0	0	OK
1	0.010	0.010	OK
2	0.020	0.020	OK
3	0.030	0.030	OK
4	0.040	0.040	OK
5	0.050	0.050	OK
6	0.060	0.060	OK
7	0.070	0.070	OK
8	0.080	0.080	OK

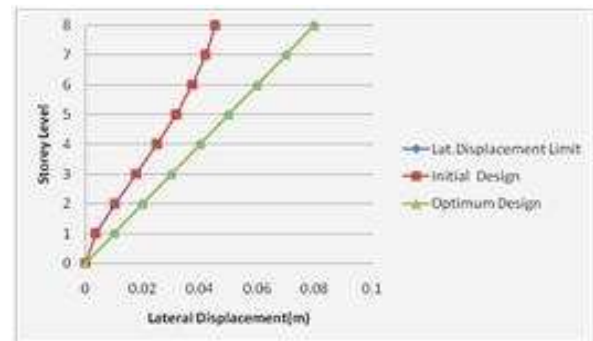
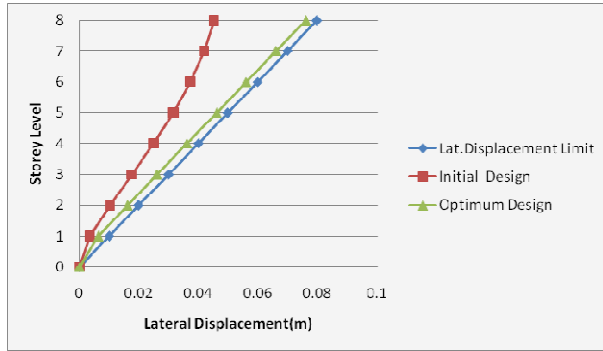


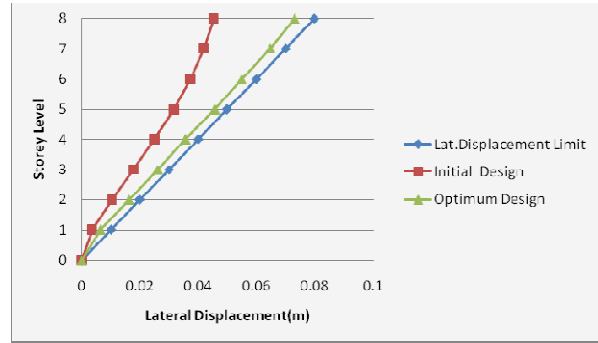
Fig-4: Lateral Displacement Profile Option 1.1

Table-4: Optimized Design Option 1.3

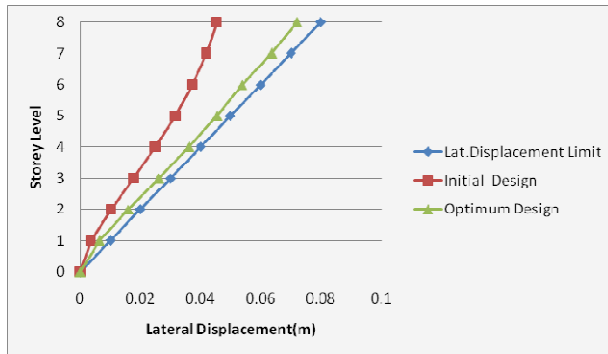
Story Level	Colmns			Beams			Objective Function
	Member Grouping	Width	Height	Member Grouping	Width	Height	
1	a = b=d=e	0.300	0.511	c = f	0.210	0.700	337
2		0.300	0.511		0.210	0.700	
3	g = h=j=k	0.300	0.511	l = l	0.210	0.700	
4		0.300	0.511		0.210	0.700	
5	m=n=p=q	0.300	0.462	o = r	0.202	0.674	
6		0.300	0.462		0.202	0.674	
7	s=t=v=w	0.300	0.400	u = x	0.200	0.500	
8		0.300	0.400		0.200	0.500	



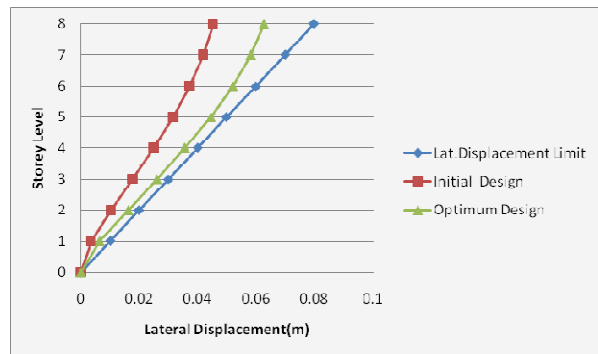
(a) Option 1.2



(b) Option 1.3



(c) Option 1.4



(d) Option 1.5

Fig-5: Lateral Displacement Profiles.

Table-5: Optimized Design for Various Design Points of Frame-1 Option 1.1 and Option 1.3

Frame	Option	Design Point	Initial Design				Initial Objective Function	Optimized Objective Function	Initial Top story displacement(m)	Optimized Top story displaceme nt(m)	Top story displacement Limit(m)
			Columns		Beams						
			Width	Height	Width	Height					
Frame-1	1.1	1	0.900	0.900	0.700	0.700	1626	319	0.012	0.080	0.080
		2	0.300	0.300	0.200	0.350	198	319	0.383	0.080	0.080
		3	0.900	0.900	0.200	0.350	1150	323	0.120	0.075	0.080
		4	0.300	0.300	0.700	0.700	674	319	0.124	0.080	0.080
		5	0.400	0.700	0.300	0.600	574	319	0.045	0.080	0.080
		6	0.350	0.400	0.250	0.400	298	330	0.188	0.078	0.080
		7	0.900	0.900	0.250	0.350	1170	319	0.106	0.080	0.080
		8	0.350	0.350	0.350	0.600	400	319	0.097	0.080	0.080
	1.3	1	0.900	0.900	0.700	0.700	1626	340	0.012	0.072	0.080
		2	0.300	0.300	0.200	0.350	198	460	0.383	0.061	0.080
		3	0.900	0.900	0.200	0.350	1150	460	0.120	0.061	0.080
		4	0.300	0.300	0.700	0.700	674	337	0.124	0.072	0.080
		5	0.400	0.700	0.300	0.600	574	337	0.045	0.072	0.080
		6	0.350	0.400	0.250	0.400	298	337	0.188	0.072	0.080
		7	0.900	0.900	0.250	0.350	1170	404	0.106	0.073	0.080
		8	0.350	0.350	0.350	0.600	400	337	0.097	0.072	0.080

The summary of results of all the three frames is shown in Table-6. This table shows the sizes of members, initial objective function, optimized objective function values and top story displacements before and after optimization. Five options with different member

grouping are studied for frame-1 eight story building. It can be seen that for same structural performance objective function values are different. In option 1.1 where there is no restriction of member grouping, objective function value 319 is the least as compared with

other options frame of eight story building because feasible region for this option is more as compared with other options. In Option 1.5 members are grouped as same column sizes same beam sizes for all story level and feasible region for this option is less as compared with other options and objective function value of 369 is the greatest as compared with other options. There is difference of about 16% between the largest and smallest value of objective function. Similarly, there is difference of about 22 % for frame-2 and 23 % for frame-3 between the largest and smallest value of objective function.

It can be concluded from the results obtained that lateral displacement are very close to the specified limit and the algorithm used is very effective to control the lateral displacements due to lateral loads. Control of lateral displacements very close to specified limits is very Table-6: Summary of Results of All Three Frames

much difficult or nearly impossible in conventional design methods so this method is very useful and applicable to control the lateral displacements. It can be seen if optimization is started with initial infeasible design (when constraints are not satisfied) the algorithm used changes it into a feasible design. It is concluded that in RC frame greater the feasible region lesser will the objective function. Moreover structural optimization is very useful and effective to decide better member grouping for large buildings.

It can be seen that if the optimization is started with initial feasible design there is 44% to 35% reduction in weight of the frame. If optimization is started with initial infeasible design (when constraints are not satisfied) the algorithm used changes it into a feasible design.

Frame	Option	Design Point	Initial Design				Initial Objective Function	Optimized Objective Function	Initial Top story displacement(m)	Optimized Top story displacement(m)	Top story displacement Limit(m)
			Columns		Beams						
			Width	Height	Width	Height					
Frame-1	1.1	5	0.350	0.350	0.350	0.600	574	319	0.045	0.080	0.080
	1.2	5	0.350	0.350	0.350	0.600	574	328	0.045	0.074	0.080
	1.3	5	0.350	0.350	0.350	0.600	574	337	0.045	0.072	0.080
	1.4	5	0.350	0.350	0.350	0.600	574	340	0.045	0.072	0.080
	1.5	5	0.350	0.350	0.350	0.600	574	369	0.045	0.063	0.080
Frame-2	2.1	5	0.400	0.700	0.300	0.600	722	379	0.029	0.060	0.060
	2.2	8	0.350	0.350	0.350	0.600	539	402	0.073	0.057	0.060
	2.3	4	0.300	0.300	0.700	0.700	966	414	0.098	0.054	0.060
	2.4	5	0.350	0.400	0.250	0.400	722	426	0.029	0.052	0.060
	2.5	5	0.350	0.400	0.250	0.400	722	462	0.029	0.045	0.060
Frame-3	3.1	6	0.350	0.400	0.250	0.400	355	306	0.054	0.040	0.040
	3.2	6	0.350	0.400	0.250	0.400	355	329	0.054	0.038	0.040
	3.3	6	0.350	0.400	0.250	0.400	355	342	0.054	0.036	0.040
	3.4	6	0.350	0.400	0.250	0.400	355	366	0.054	0.030	0.040
	3.5	6	0.350	0.400	0.250	0.400	355	376	0.054	0.030	0.040

Conclusions: The following conclusions are drawn from the study

1. The application of optimization techniques coupled with Matrix Stiffness Method is very useful to control the lateral displacement in the structure and to optimize the member sizes.
2. The algorithm used is convergent and can bring the design from infeasible region to feasible region and minimizes the objective function. The results are satisfactory even though it converges to local optimum.
3. For the same performance criteria (lateral displacement), member grouping plays an important role. It affects the objective function. It is concluded that in RC frame greater the feasible region lesser will the objective function.
4. Member grouping helps to control the member sizes distribution, without member grouping

member sizes distribution will not practicable and it will be random.

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