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Optimum Participation of Beams and Columns in Lateral Resistance of Steel Moment Frames

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Abstract

For the purpose of understanding the behavior of steel moment frames, optimum participation of beams and columns in lateral resistance of moment frames subjected to earthquake force is represented in terms of lateral displacement of stories depends on height of the building. This optimum participation will be introduced in terms of the ratio of story drift over maximum allowable drift. As the height of a building rises, the structural designer can take beams into participation in lateral resistance more by choosing the bigger ratio for story drift. Five steel moment frames 2, 3, 4, 5 and 10 steel frames by different bays are subjected to earthquake load which are modeled in ETABS2000 to work on. Since the lateral displacement is usually the main concern in the design of multistory buildings, the smaller lateral displacement is the favorable in this paper. Relative tables are presented and general advices in the design of steel moment frames are given which can be applied in the design of proposed structural system with regard to the ratio of flexural stiffness of beams over the flexural stiffness of columns in each story.

Keywords: Flexural stiffness, lateral displacement, optimum participation, optimum ratio and steel moment frame.

1. Introduction

The popularity of medium height buildings have made the structural designers to work on the behavior of efficient structural systems and consequently the innovative method which helps the designers to consider the final sections of structural elements easier and faster is becoming favorable. The main objective of this study is to control the optimum ratio of story drift over maximum allowable drift with regard to the ratio of stiffness of beam-to-column in order to have the most stable and economic steel moment resistant frame system. This study focuses on developing a method by which designers come out the final section as efficient as possible and in the shortest time. To obtain the optimum ratio five steel frames, with a various number of stories and bays (Figure 1), have been considered. The structures are subjected to carry the earthquake load estimated by using Eurocode 8 and it is assumed that all of the structures are located in high seismicity zone (A=0.35g) and will be designed based on Eurocode 3. ETABS2000 is the software to analyze and design the structures.

2. Literature Review

Nowadays, many studies have been done in the literature on optimization of structural components by different methods (Baker, 1990; Chan and Grierson, 1993; Park and Park, 1997; Park and Adeli, 1997). A number of studies have conducted on optimization of structures to detect solutions with regard to satisfying the dynamic response constraints (Hsieh and Arora, 1984; Tzan and Pantelides, 1996; Mahmoud et al., 2000; Kang et al., 2001) as well.

Park and Kwon have introduced an optimum drift design method for multi-story building with moment frames as structural system. Since the inspiration of this study comes from this literature, so it will be reviewed with regard to this study title. The main aim of the litrerature is achieving to minimum weight structure which is named “the optimal drift design model” consists of three main components;

1) Optimizer; an optimizer is a mathematical function consists of three parts;
    - Design variable is a pair of function which relates cross-sectional area of beam and column to the moment of inertia of them;
    - Objective function is the function of weight of the structure which sums up the weight of each element by multiplying the mass density, cross-sectional area and length of the members;
    - Constraint function is a function to limit the lateral displacement at the top of the structure, inter-story drift and stress ratio in members;

2) Response spectrum analysis module; The responses of the multi-story structure are computed by linear response spectrum analysis and inter-story drift, lateral displacement at the top, and combined stresses in members will be calculated.

3) Sensitivity analysis module; in sensitivity analysis, the change in system response with respect to parameter variations will be performed. The adjoint variable method and direct differentiation method can be used.

The combined optimization procedure consists of 9 steps is provided and it describes how to combine the result of different functions and how to reach to the final design. At the end of the paper, in order to state the application of the method, 4 frames are designed. The first one is a 3-bay 4-story steel frame and the second one is 4-bay 5-story steel frame. The third example is a 6-bay 20-story steel frame and the final example is a 6-bay 40-story steel frame.

Although all of the cited papers are successfully applied to drift optimization of multistory buildings and all methods are totally applicable and clear, the methods doesn't discuss about optimum ratio of story drift over maximum allowable drift (Main Ratio) with regard to the ratio of stiffness of beam-to-column (Control Ratio) in order to have the most stable and economic steel moment resistant frame system.

3. Problem Statement

Generally, when designers are going to design a structural system due to lateral forces two requirements must be satisfied. The first one is providing enough sectional resistance to carry the shear and flexural forces resulted from lateral loads (First step in this study). The second one is providing enough resistance against lateral displacement induced by earthquake load (Second and third step in this study). In fact the lateral displacement usually governs the design process of multistory building in which can result in the different amount of construction materials which are going to consume.

Therefore the above idea needed to be worked on, it can be changed into the optimization of structural resistant regarding to the Control Ratio and economic parameters (weight). To obtain the optimization (Main Ratio) in each story by consideration of lighter components (column and beam), five steel frames with a various number of stories and bays as shown in Figure 1, have been considered. The number of stories is assumed to be two (2S), three (3S), four (4S), five (5S) and ten (10S) in the two-bay frame (2B), three-bay frame (3B), four-bay frame (4B), five-bay frame (5B) and five-bay frame (5B), respectively. The height of each story is 3.6 m and length of each bay is 5 m in all frames and the ground type is assumed to be B in high seismicity zone (A=0.35g). The distributed dead and live loads are considered 20 and 10 kN/m applied to the beams at all the stories. In the tables and figures, "S" denotes the number of story and "B" denotes the number of bays.

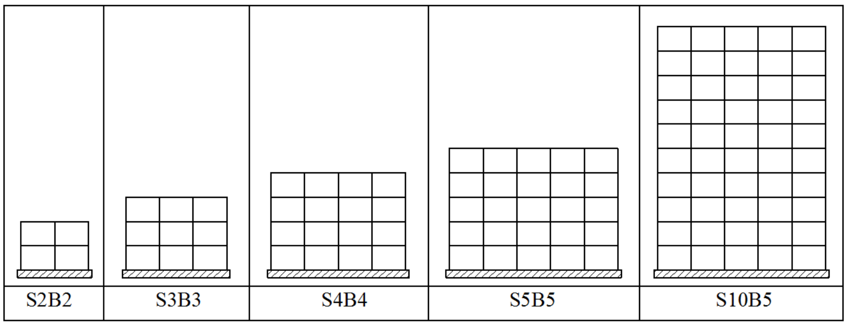
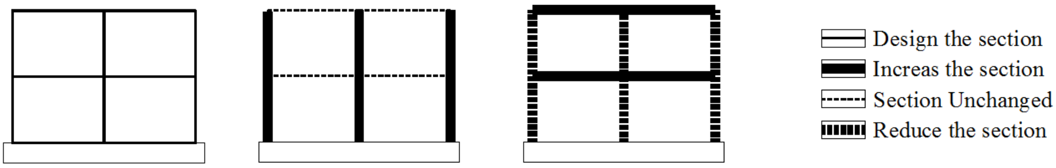


Figure 1. Geometry and names of studied frames

4. Research Methodology

This study is based on a computer modeling (Analytical). Different frames are modeled in ETABS2000 and required result is compared by using different tables to develop the general idea. For realizing the effect of beam and column stiffness separately on optimum ratio of story drift over maximum allowable drift (Main Ratio), as the Figure 2 shows, after designing whole structures without drift control, the properties of the columns are changed while the beams are kept unchanged. The efficiency of columns and beams in lateral resistance of the frame is compared separately (the ratio of flexural stiffness of beams over the flexural stiffness of columns in each story=Control Ratio). In the next stage the properties of the beams are changed while the stiffness of columns is reduced with smaller second moment of inertia.



Step 1
(Designing without drift control)

Step 2
(Columns are incresed and Beams are kept ungانged)

Step 3
(Beams are increased and Columns are simultaneously will decrease)

Figure 2. Design and analysis process to capture the idea

5. Data Collection and Analysis

The required strength of a frame to restrict its lateral displacement to the specified limit is called "required lateral stiffness". Flexural stiffness of columns, I/L, is the most crucial parameter in lateral stiffness. Although columns play an important role in lateral stiffness of a moment frame, the role of beams cannot be neglected. In the following, the effect of beams on lateral stiffness is shown and the effective contribution of beams and columns stiffness in lateral resistance is discussed.

Consider five frames by different bays as shown in Figure 1. At first step, the frames are designed for the specified combination of applied load (vertical and horizontal loads) to satisfy the sectional resistance. Selected sections for beams are those with the smallest second moment of inertia (Minimum Ix (beam)) and the lighter weight per length unit; for columns are those with the smallest sectional area (Minimum Acol) and the lighter weight per length unit. As it can be seen in Table 2, after analysis and design without drift story control, the stories drift are higher than the allowable story drift (Table 1 shows the allowable story drift for each model).

Table 1. Allowable story drift and relevant T1 and Sd(T1)

Models	2S2B	3S3B	4S4B	5S5B	10S5B
Design Spectrum T1	0.374	0.506	0.628	0.743	1.25
Fundamental Period Sd(T1)	1.592	1.573	1.268	0.69	0.69
Allowable Story Drift de/h	**0.0031**	**0.0031**	**0.0031**	**0.0031**	**0.0031**

At second step, in order to satisfy the allowable limit of drift, the sections of columns are replaced by the section with higher second moment of inertia while the section of beams is kept constant. It is obvious that between two sections with same second moment of inertia and different weight per length unit, the lighter one is preferred. This increment will be continued until stories drift are smaller than the allowable limit (allowable story drift=0.0031). The procedures for 2S2B have been shown in Table 3. As the last row of Table 3 for final trying (7th trying) shows, maximum story drift (0.00296) is less than 0.0031 and total weight is 2.83 ton.

Table 2. The smallest required section and story drift for all modles

Model	Story	Column Section	Beam Section	story drift	Allowable Story Drift
2S2B	2	UC203x203x46	UB305x102x28	0.00508	0.0031
	1	UC203x203x46	UB305x102x28	0.00503	
3S3B	3	UC203x203x52	UB305x102x33	0.00554	
	2	UC203x203x52	UB305x102x33	0.00886	
	1	UC203x203x52	UB305x102x33	0.0074	
4S4B	4	UC203x203x71	UB305x102x28	0.00403	
	3	UC203x203x71	UB305x102x28	0.00639	
	2	UC203x203x71	UB305x102x33	0.00763	
	1	UC203x203x71	UB305x102x33	0.00551	
5S5B	5	UC203x203x46	UB305x102x28	0.00483	
	4	UC203x203x46	UB305x102x28	0.00832	
	3	UC254x254x73	UB305x102x33	0.00714	
	2	UC254x254x73	UB305x127x37	0.00772	
	1	UC254x254x73	UB305x127x37	0.00539	
10S5B	10	UC152x152x37	UB305x102x25	0.00579	
	9	UC203x203x52	UB305x102x25	0.00663	
	8	UC203x203x52	UB305x102x33	0.00846	
	7	UC203x203x52	UB305x127x37	0.01007	
	6	UC254x254x73	UB305x165x40	0.00844	
	5	UC254x254x73	UB305x165x40	0.00904	
	4	UC254x254x73	UB305x165x46	0.00947	
	3	UC254x254x107	UB305x165x46	0.00863	
	2	UC254x254x107	UB305x165x46	0.00832	
	1	UC254x254x107	UB305x165x46	0.00508	

At third step, sections of beams are replaced by the new section which has a bigger second moment of inertia (with the smallest possible weight per length unit). This will allow reducing the stiffness of columns by replacing the new section with smaller second moment of inertia (with the smallest possible weight per length unit and sectional area not less than what is required) not until the drift story is bigger than allowable limit. In the other word, increments in beams stiffness can make it possible to have smaller columns until

Table 3. 2nd step, replacing of column by stronger section until the story drift is adequate

Try	Story	NO.	Column			NO.	Beam			ΣB/ΣC	dei(mm)	Story Drift	Total Weight (ton)
			Section	Height (cm)=	360		Section	Height (cm)=	500				
				Ix(cm4)	I / L			Ix(cm4)	I / L				
1st	2	3	UC203x203x46	4570	12.694	2	UB305x102x28	5370	10.740	0.564	36.380	0.00508	1.53
	1	3	UC203x203x46	4570	12.694	2	UB305x102x28	5370	10.740	0.564	18.110	0.00503	
2nd	2	3	UC203x203x52	5260	14.611	2	UB305x102x28	5370	10.740	0.490	33.530	0.00456	1.66
	1	3	UC203x203x52	5260	14.611	2	UB305x102x28	5370	10.740	0.490	16.430	0.00443	
3rd	2	3	UC203x203x60	6130	17.028	2	UB305x102x28	5370	10.740	0.420	30.730	0.0041	1.83
	1	3	UC203x203x60	6130	17.028	2	UB305x102x28	5370	10.740	0.420	14.770	0.0041	
4th	2	3	UC203x203x71	7620	21.167	2	UB305x102x28	5370	10.740	0.338	27.450	0.0045	2.07
	1	3	UC203x203x71	7620	21.167	2	UB305x102x28	5370	10.740	0.338	12.870	0.00358	
5th	2	3	UC203x203x86	9450	26.167	2	UB305x102x28	5370	10.740	0.274	24.570	0.00371	2.4
	1	3	UC203x203x86	9450	26.167	2	UB305x102x28	5370	10.740	0.274	11.210	0.00311	
6th	2	3	UC254x254x89	11400	26.250	2	UB305x102x28	5370	10.740	0.273	20.300	0.00319	2.44
	1	3	UC254x254x89	11400	26.250	2	UB305x102x28	5370	10.740	0.273	8.820	0.00245	
7th	2	3	UC254x254x107	17500	48.611	2	UB305x102x28	5370	10.740	0.147	18.450	0.00296	2.83
	1	3	UC254x254x107	17500	48.611	2	UB305x102x28	5370	10.740	0.147	7.800	0.00217	

the stories drift are still adequate. The procedure can be followed in Table 4. As the row column of Table 4 for final trying (4th trying) shows, maximum story drift (0.00301) is less than 0.0031 and total weight is 2.33 ton while the section area is more than final section in step one.

Table 4. 3rd step, replacing of beam by stronger section and replacing of column by weaker section

Try	Story	NO.	Column			NO.	Beam			ΣB/ΣC	dei(mm)	Drift	Total Weight (ton)
			Section	Height (cm)=	360		Section	Height (cm)=	500				
				Ix(cm4)	I / L			Ix(cm4)	I / L				
1st	2	3	UC254x254x107	17500	48.611	2	UB305x102x28	5370	10.740	0.147	18.450	0.00296	2.83
	1	3	UC254x254x107	17500	48.611	2	UB305x102x28	5370	10.740	0.147	7.800	0.00217	
2nd	2	3	UC203x203x86	9450	26.250	2	UB305x127x42	8200	16.400	0.417	20.220	0.00292	2.66
	1	3	UC203x203x86	9450	26.250	2	UB305x127x42	8200	16.400	0.417	9.720	0.0027	
3rd	2	3	UC203x203x71	7620	21.167	2	UB356x171x45	12100	24.200	0.762	19.760	0.00268	2.39
	1	3	UC203x203x71	7620	21.167	2	UB356x171x45	12100	24.200	0.762	10.120	0.00281	
4th	2	3	**UC203x203x60**	**6130**	**17.028**	2	UB406x178x54	18700	37.400	1.464	19.990	0.00255	2.33
	1	3	**UC203x203x60**	**6130**	**17.028**	2	UB406x178x54	18700	37.400	1.464	10.820	0.00301	

Meanwhile the section of beams is being replaced by the new one, the negative moment at supports needs to be controlled. Eurocode 3 prefers fixed beams with bigger moment at supports and smaller moment at mid span; it is because of the location of first plastic hinge that is preferred to occur at supports by Eurocode 3. Therefore, increment in beam stiffness must be stopped before the moment at supports goes to be smaller than moment at mid span.

There is still one more traditional idea to check at this step. Structural designers usually prefer a frame in which columns are stronger than beams (Comparison of ratio SB/SC relative column in Tables 3 and 4 for last trying, increases from 0.147 to 1.464 which shows strong beam, weak column rule). It is a very debatable topic and designers have different opinions. Some believe that it would be better if stress ratio of columns are not bigger than 0.9; regardless of whatever stress ratio in beams are. Therefore, it must also be controlled that replacing sections of columns does not lead to the stress ratio bigger than 0.9. At the end of third step, it can be seen that there is a noticeable decrease in the total weight of the frames (from 2.83 to 2.33 ton) because of participation of beams in the lateral stiffness (Comparison of weight at the last row of table 3 and 4). It means that the final frame at this step is the most economical frame in terms of steel consumption. In the other word, the selected sections of beams and columns are the best composition.

Table 5: Efficient columns and Ave drift ratio for all frames

Model	Story	Column Section	Beam Section	story drift	Drift Ratio	Ave
2S2B	2	**UC203x203x60**	UB305x102x28	0.00443	1.43	**1.38**
	1	**UC203x203x60**	UB305x102x28	0.00411	1.33	
3S3B	3	**UC254x254x73**	UB305x102x33	0.00429	1.38	**1.62**
	2	**UC254x254x73**	UB305x102x33	0.00626	1.62	
	1	**UC254x254x73**	UB305x102x33	0.00455	1.47	
4S4B	4	**UC254x254x107**	UB305x102x28	0.00342	1.10	**1.39**
	3	**UC203x203x71**	UB305x102x28	0.00494	1.59	
	2	**UC254x254x107**	UB305x102x33	0.0055	1.77	
	1	**UC254x254x107**	UB305x102x33	0.00342	1.10	
5S5B	5	**UC305x305x97**	UB305x102x28	0.00316	1.02	**1.44**
	4	**UC305x305x97**	UB305x102x28	0.00459	1.48	
	3	**UC254x254x73**	UB305x102x33	0.00553	1.78	
	2	**UC305x305x97**	UB305x127x37	0.00564	1.82	
	1	**UC305x305x97**	UB305x127x37	0.00333	1.07	
10S5B	10	**UC356x406x287**	UB305x102x25	0.00353	1.14	**1.58**
	9	**UC356x406x287**	UB305x102x25	0.00414	1.34	
	8	**UC356x406x287**	UB305x102x33	0.00479	1.55	
	7	**UC356x406x287**	UB305x127x37	0.00536	1.73	
	6	**UC356x406x287**	UB305x165x40	0.00584	1.88	
	5	**UC356x406x287**	UB305x165x40	0.00612	1.97	
	4	**UC356x406x287**	UB305x165x46	0.00618	1.99	
	3	**UC356x406x287**	UB305x165x46	0.00593	1.91	
	2	**UC356x406x287**	UB305x165x46	0.00491	1.58	
	1	**UC356x406x287**	UB305x165x46	0.00229	0.74	

It is desired to find out how this composition can be selected without going through the above procedure which is very time-consuming. It can be said that although increasing in columns stiffness can reduce the stories drift but there is a point after that, stronger columns are not efficient anymore and stronger beams can provide the required lateral resistance with lighter frame. To find out that point, two ratios will be kept for final conclusion:

1. The ratio of flexural stiffness of beams over the flexural stiffness of columns in each story at the last composition of the third step.
2. The ratios of stories drift over the allowable story drift when the columns' sections are those in last composition of the third step and the beams' sections are those in first step (Table 5).

5. Discussion of results

Study of several multi story moment frames has showed that flexural stiffness of beams play an important role in the total lateral resistant of frame. Although most of the lateral resistant is provided by flexural stiffness of columns, but there is an optimum ratio for beam-to-column in order to have the lightest frame while the drift limitation is adequate. This optimum ratio depends on many parameters such as height of the story, length of the beam span and number of beams and columns in every story. In other worlds, this ratio is unique for every single moment frame but the final participation of beam in lateral stiffness is almost the same value in different moment frames. This optimum participation will be introduced in terms of the ratio of story drift over maximum allowable drift. As it can be seen in the last provided table (Table 5) for all models, the efficient participation of columns in lateral resistant is achieved when the drift ratio is between 1.4 and 1.6. This ratio ranges from 1.4 to 1.6 because the participation of beams in lateral resistance varies among several moment frames. For instant, in higher frames participation of beams in lateral resistance can be more than what they have in a shorter frame. In the other world, as the height of a building rises, the structural designer can take beams into participation in lateral resistance more by choosing the bigger ratio for story drift.

Here is a simple procedure which leads the designer to that optimum ratio:

First Step: Try to design the frame due to the different load combinations provided by the code. The final selected section for every element of beams or columns must be the smallest possible section with the lightest weight per length unit. (Figure 3)

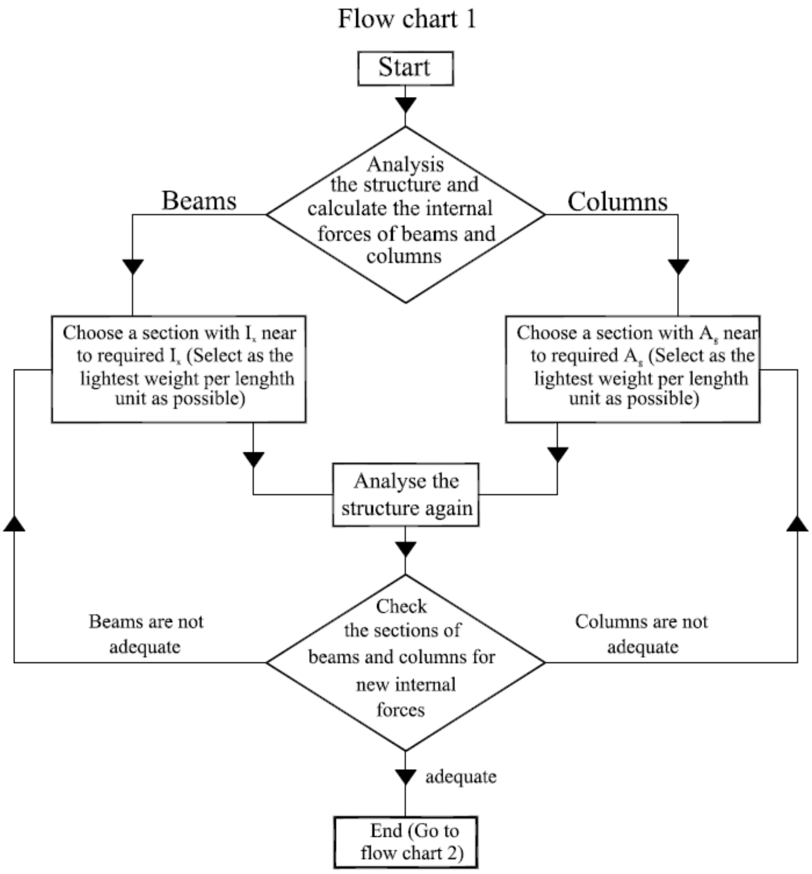


Figure 3. First step control flowchart

Second Step: Try to increase the section size of the columns only, until the ratio of stories drift over maximum allowable drift reaches to the value of 1.4 to 1.6. In multi-story frames the average of stories drift can be also considered. This is the very important stage. In the other hand, the designer is considering the efficient participation of columns in total lateral stiffness of the frame. This is the point in which if section of columns increases, only slight decrease in story drift will be appeared. Therefore, the way can make the designer be sure of final section of columns is to check the decrease in story drift after replacing section of columns by new bigger one. If the change in story drift was not considerable, the chosen section would be satisfactory. (Flowchart 2 in Figure 4)

Third Step: While the section of columns kept constant, try to replace the section of beams by the new section with bigger moment of inertia until the stories drift are adequate. (Flowchart 3 in Figure 4)

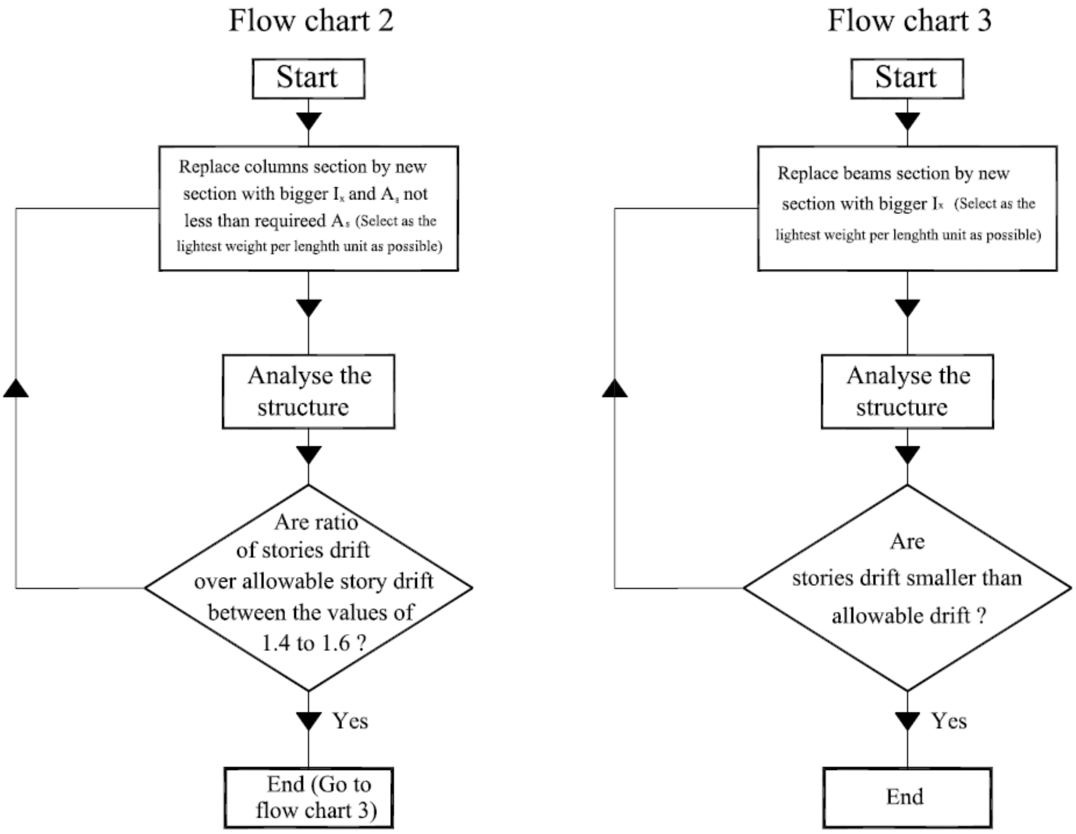
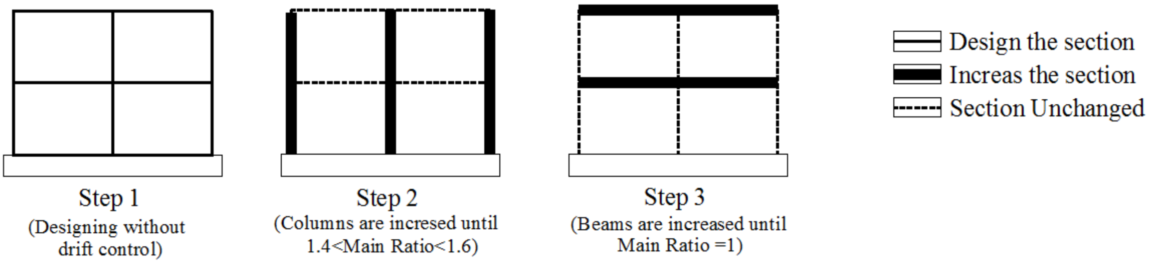


Figure 4. Second and third step control flowchart

In other words, as the Figure 5 shows, after designing, the columns section are increase till the value of main ratio decrease between 1.4 and 1.6. At next step the beams section increase till the value of main ratio reduce to 1.



Step 1 (Designing without drift control)
Step 2 (Columns are incresed until 1.4<Main Ratio<1.6)
Step 3 (Beams are increased until Main Ratio =1)

Figure 5. Design and analysis process for faster method

Tip: It is shown that a multi-story moment frame in which the values of stories drift are close together has the best structural behavior. Therefore, reaching to the point in which story drift changes slightly among height of the frame is desired.

6. Conclusion

By study on several moment frames subjected to vertical and horizontal loads, efficient contribution of beams and columns is introduced in terms of story drift over maximum allowable drift specified by the relevant code. Efficient participation of columns in lateral resistance of moment frame is almost the same value for moment frames with different story height or span length. If story drift defined as the lateral displacement of story (which is the difference between displacement of top and bottom of the story) over height of the story, efficient contribution of columns would be represented by ratio of story drift over maximum allowable story drift. This ratio is called “the ratio of story drift”.

Participation of columns in lateral resistance of a moment frame is efficient when they are strong enough to decrease the ratio of story drift to a value between 1.4 and 1.6. The rest of required resistance will be provided by flexural stiffness of beams to decrease the ratio of story drift to 1.0. Participation of beams in lateral resistance of a moment frame goes up when height of moment frame increases. Therefore the ratio of story drift in short frame is near to 1.4 and by increase in height of moment frame this ratio also changes to higher values to let the beam take more part of lateral resistance than before.

In some moment frames with longer span of beams than typical spans (between 4 and 6 meter), it might be found that participation of beams in lateral resistance of frame is not valuable so much and it might also increase the usage of steel drastically. It is because of reduced stiffness of beams made by longer span. Therefore in such that cases the ratio of story drift may be taken lower than 1.4 to introduce efficiency of columns' participation.

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