Selection of optimum structural systems and materials

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Abstract

This paper proposes procedures and guidelines for the selection of optimum structural systems and materials in two stages. Stage one is based on a list of criteria, including architectural considerations. Stage two evaluates selected systems and materials for optimum performance of criteria considered critical for a given project. A tall office building in Dammam, Saudi Arabia is used as a case study to compare three structural systems: moment frame, braced frame, and shear wall; as well as two materials: concrete and steel. The case study considers four building heights: 10, 20, 30, and 40 stories. The STAAD Pro 2005 software is used to analyze these systems according to allowable stress requirements for an objective function to minimize drift, at minimal cost for a wind speed of 90 mph. Shear wall is the optimum structural system and concrete the optimum material to minimize lateral drift at minimum material and labor costs.
Keywords: lateral drift, wind load, IBC 03, allowable stress, STAAD Pro.

1 Introduction

The selection of structural system and material is often done according to personal experience or perception without being evaluated as it should be for optimum performance. The proposed selection process provides a methodology to determine the selection of the optimum structural system. Since in Saudi Arabia wind load is more critical than seismic load, this paper investigates wind effect on tall buildings. Since wind load increases with height on tall buildings and causes lateral deflection (drift), minimizing lateral drift is an important criterion to select structural systems for tall buildings. Controlling drift is vital

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to provide occupant comfort and avoid motion sickness. Furthermore, large drift may endanger life and incur loss of property or even cause building collapse.

2 Methodology

Stage one includes, among others, consideration of the following criteria: gravity load, lateral load (wind and seismic), climate conditions, labor and material costs, code requirements, building location, building height limit, sustainability (durable and recyclable), strength, stiffness, stability, and synergy. For example, building location is a significant criterion which affects the selection of material. In Saudi Arabia, the most popular building material is concrete; while wood is not available and steel is very expensive.

Stage two is defined by the process shown in Figure 1. For example, considering two materials (steel and concrete), three structural systems (moment frame, braced frame, and shear wall); this process implies four combinations of structural systems and materials for each building height. Each material and system combination is passed through a criteria process to minimize lateral drift (main criterion) as well as minimizing labor and material costs (secondary criterion). All material and structural system combinations are entered to the design evaluation of STAAD Pro 2005. Comparing all results leads to the selection of the optimum structural system and material.

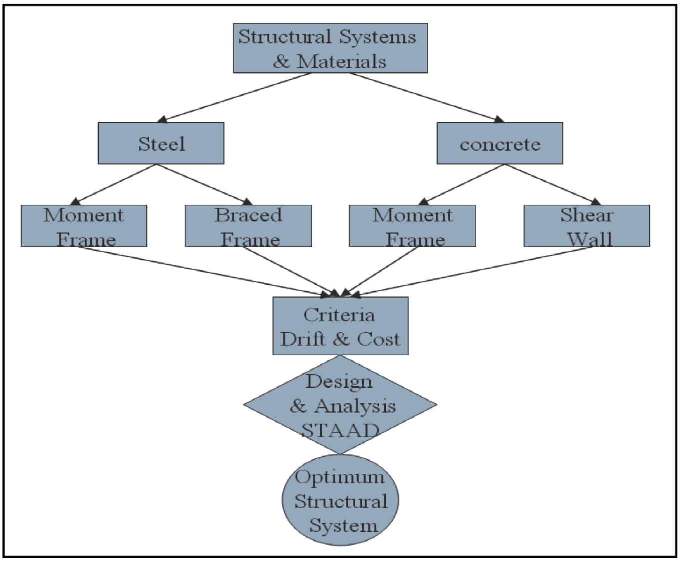

Figure 1: Selection of the optimum structural system process.

3 Assumptions

Using the structural design and analysis software (STAAD Pro), the case study assumed: International Building Code IBC 03; 90 mph maximum wind speed; allowable stress design method for schematic structural design; material strength: concrete 9.0 ksi, steel: 50 ksi. Structural members are designed to meet the allowable stresses, using safety factors of 45% for concrete and 60% for steel (4 ksi concrete, 30 ksi steel beam; 25 ksi steel columns due to buckling) and maximum allowable lateral drift (h/200). Gravity load was applied simultaneously with wind load, assuming combined dead and live loads uniform distributed loads of 1.7 kip/ft. Lateral wind load per level (in kips) was assumed acting on wind and lee sides as shown in Figs. 2–5.

Variables investigated in the case study:

- Building height (10, 20, 30, and 40 stories)
- Structural systems (moment frame, braced frame, and shear wall)
- Structural materials (concrete and steel)

Those variables combined create 16 cases.

The lateral drift is measured at each level after defining member size for strength to assure the actual lateral drift is less than the maximum allowable. Labor and material cost for each system is based on current costs in Saudi Arabia. The tested case study consists of 3 bay frames of 33x33 ft (10×10 m) column spacing and 13 ft (4 m) story height. Member sizes are based on combined wind and gravity loads. Beam and column sizes vary every two floors as shown in the tables.

4 10-story building

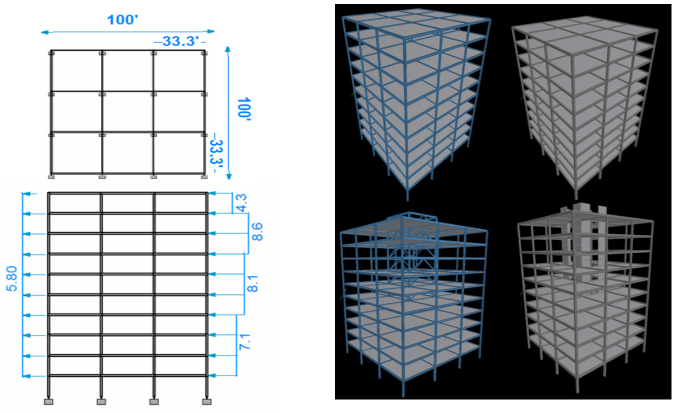

Figure 2: Wind loads in kips and perspective of 10-story building, (130') height with different structural systems.

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Table 1: Beams schedule for 10-story building for different structural systems.

Steel Moment Frame		Steel Braced Frame		Conc. Moment Frame.		Concrete Shear wall	
Beam Size	Floor No.	Beam Size	Floor No.	Beam Size	Floor No.	Beam Size	Floor No.
W 18× 50	9,10	W 18× 50	9,10	17.5"×12"	9,10	18.0"×12"	9,10
W 18× 60	7,8	W 18× 50	7,8	19.0"×12"	7,8	18.5"×12"	7,8
W 18× 76	5,6	W 18× 55	5,6	21.5"×12"	5,6	21.0"×9.5"	5,6
W 18× 76	3,4	W 18× 60	3,4	22.0"×12"	3,4	21.5"×9.5"	3,4
W 18× 86	1,2	W 18× 65	1,2	24.0"×12"	1,2	24.0"×9.5"	1,2

Table 2: Columns schedule for 10-story building for different structural systems.

Steel Moment Frame		Steel Braced Frame		Conc. Moment frame		Concrete Shear wall	
Column Size	Floor No.	Column Size	Floor No.	Column Size	Floor No.	Column Size	Floor No.
W 14× 159	9,10	W 14× 145	9,10	17.5"×17.5"	9,10	17.5"×17.5"	9,10
W 14× 176	7,8	W 14× 159	7,8	19.0"×17.5"	7,8	18.0"×18.0"	7,8
W 14× 211	5,6	W 14× 176	5,6	20.5"×19.0"	5,6	19.0"×19.0"	5,6
W 14× 283	3,4	W 14× 193	3,4	20.5"×20.5"	3,4	19.0"×20.5"	3,4
W 14× 342	1,2	W 14× 233	1,2	24.0"×24.0"	1,2	21.0"×20.5"	1,2

5 20-story building

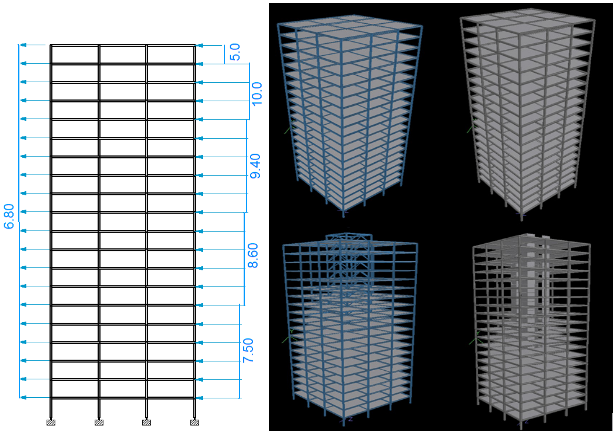

Figure 3: Wind load in kips and perspective of 20-story building, (260') height with different structural systems.

Table 3: Beams schedule for 20-story building for different structural systems.

Steel Moment Frame		Steel Braced Frame		Conc. Moment Frame		Concrete Shear wall	
Beam Size	Floor No.	Beam Size	Floor No.	Beam Size	Floor No.	Beam Size	Floor No.
W 18 × 55	19,20	W 18× 60	19,20	18.0" × 12.0"	19,20	20.4" x 12.0"	17-20
W 18 × 71	17,18	W 18× 65	16-18	20.5" × 12.0"	17,18	21.0" x 13.2"	14-16
W 18 × 86	15,16	W 18× 71	14,15	21.6" x 13.2"	15,16	22.2" x 13.2"	12,13
W 18 × 97	13,14	W 18× 76	1-13	24.0" x 13.2"	13,14	22.8" x 13.2"	10,11
W 18 × 106	11,12	------------	-------	24.0" x 14.4"	11,12	24.0" x13.2"	1-9
W 18 × 119	9,10	------------	-------	25.2" x 14.4"	9,10	----------	------
W 18 × 130	5,6,7,8	------------	--------	27.0" x 14.4"	6,7,8	----------	------
W 18 × 143	1,2, 3,4	------------	---------	28.2" x 14.4"	1-5	-----------	------

Table 4: Columns schedule for 20-story building for different structural systems.

Steel Moment Frame		Steel Braced Frame		Conc. Moment Frame.		Concrete Shear wall	
Column Size	Floor No.	Column Size	Floor No.	Column Size	Floor No.	Column Size	Floor No.
W14 x 159	18,19,20	W14 x 159	18,19,20	18.0" x 18.0"	17-20	18.0" x 12.8"	17-20
W14 x 211	16,17	W14 x 176	16,17	19.0" x 19.0"	15,16	20.4" x 12.0"	15,16
W14 x 283	14,15	W14 x 233	14,15	21.5" x 20.5"	13,14	20.4" x 20.4"	13,14
W14 x 342	12,13	W14 x 257	12,13	22.8" x 22.8"	11,12	22.2" x 22.2"	11,12
W14 x 426	10,11	W14 x 311	10,11	25.2" x 24.0"	9,10	22.8" x 22.8"	9,10
W14 x 500	8,9	W14 x 342	8,9	25.2" x 26.4"	7,8	18.0" × 18.0"	7,8
W14 x 550	5-7	W14 x 370	5,6,7	27.6" x 27.6"	5,6	19.0" × 19.0"	5,6
W14 x 605	3,4	W14 x 426	3,4	28.8" x 28.8"	3,4	19.0" × 20.5"	3,4
W14 x 730	1,2	W14 x 605	1,2	32.4" x 32.4"	1,2	21.0" × 20.5"	1,2

6 30-story building

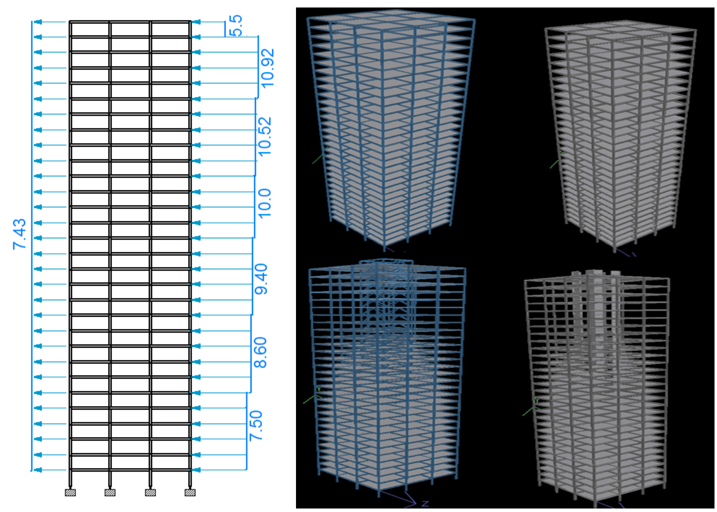

Figure 4: Wind loads in kips and perspective of 30-story building, (390') height with different structural systems.

Table 5: Beams schedule for 30-story building for different structural systems.

Steel Moment Frame		Steel Braced Frame		Conc. Moment frame		Conc. Shear wall	
Beam Size	Floor No.	Beam Size	Floor No.	Beam Size	Floor No.	Beam Size	Floor No.
W18 x 55	29,30	W18 x 71	29,30	18.6" x 12.0"	29,30	19.8"x 14.4"	29,30
W18 x 71	27,28	W18 x76	27,28	21.0" x 12.0"	27,28	21" x 14.4"	27,28
W18 x 86	25,26	W18 x 86	24,25,26	21.6" x 14.4"	25,26	21" x 15.6"	24-26
W18 x 106	23,24	W18 x 97	22,23	24.0" x 14.4"	23,24	23.4"x 15.6"	22,23
W18 x 119	21,22	W18 x 106	19,20,21	25.2" x 14.4"	21,22	27" x 15.6"	19-,21
W18 x 130	19,20	W18x 119	17,18	27.0" x 14.4"	19,20	28.8"x 16.8"	13-18
W18 x 143	16,17,18	W18x 130	15,16	27.0" x 15.6"	17,18	29.4"x 16.8"	11,12
W18 x 158	13,14,15	W18x 119	1 TO 14	28.4" x 15.6"	15,16	30" x 16.8"	1TO 10
W18 x 175	9 TO 12	------------	--------	29.0" x 16.8"	10-14	----------	------
W18 x 192	6-8, 1-3	------------	---------	30.6" x 18.0"	1 T0 9	-----------	------
W18 x 211	4,5	------------	---------	28.2" x 14.4"	1-5	-----------	------

Table 6: Columns schedule for 30-story building for different structural systems.

Steel Moment Frame		Steel Braced Frame		Conc. Moment frame.		Conc. Shear wall	
Column Size	Floor No.	Column Size	Floor No.	Column Size	Floor No.	Column Size	Floor No.
W14 x 176	27-30	W14 x 176	27-30	18.4" x 18.4"	27 - 30	18.6" x 18.6"	27-30
W14 x 257	25,26	W14 x 193	25,26	19.8" x 19.8"	25,26	19.6" x 19.6"	25,26
W14 x 342	23,24	W14 x 233	23,24	21.7" x 21.7"	23,24	22.0" x 22.0"	23,24
W14 x 426	21,22	W14 x 283	21,22	23.5" x23.5"	21,22	23.4" x23.4"	21,22
W14 x 455	19,20	W14 x 342	19,20	25.2" x25.2"	19,20	24.6" x24.6"	19,20
W14 x 550	16,17,18	W14 x 370	17,18	26.6" x 26.6"	17,18	26.4" x 26.4"	17,18
W14 x 605	14,15	W14 x 398	15,16	28.2" x 28.2"	15,16	27.6" x 27.6"	15,16
W14 x 665	12,13	W14 x 426	13,14	29.4" x29.4"	13,14	28.2" x 28.2"	13,14
W14 x 730	10,11	W14 x 500	11,12	30.6" x 30.6"	11,12	29.4" x29.4"	11,12
W14 x 825	8,9	W14 x 550	9,10	32.4" x 32.4"	9,10	30.0" x30.0"	7-10
W14 x905	6,7	W14 x605	7,8	33.0" x 33.0"	7,8,	30.6" x 30.6"	5,6
W14 x1025	3,4,5	W14 x665	5,6	33.6" x 33.6"	5,6	31.2" x 31.2"	3,4
W14 x 1105	1,2	W14 x 730	3,4	34.8" x 34.8"	3,4	33.6" x 33.6"	1,2
---------	-------	W14 x 825	1,2	39.3" x 39.3"	1,2	-----------	------

7 40-story building

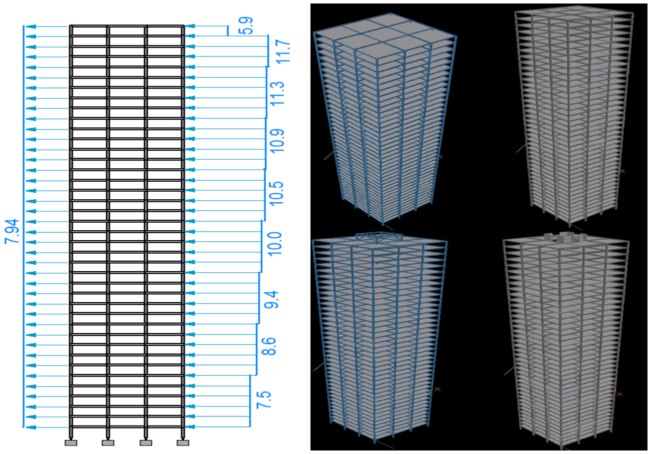

Figure 5: Wind loads in kips and perspective of 40-story building, (520') height with different structural systems.

Table 7: Beams schedule for 40-story building for different structural systems.

Steel Moment Frame		Steel Braced Frame		Conc. Moment frame		Concrete Shear wall	
Beam Size	Floor No.	Beam Size	Floor No.	Beam Size	Floor No.	Beam Size	Floor No.
W18 x 55	39,40	W18 x 71	39,40	18.6" x 12"	39,40	19.2"x 14.4"	38-40
W18 x76	37,38	W18 x76	37,38	21" x 12"	37,38	20.4"x 14.4"	36,37
W18 x 97	35,36	W18 x 86	35,36	21.6" x14.4"	35,36	22.2" x15.6"	34.35
W18 x 106	33,34	W18 x 97	33,34	24" x 14.4"	32,33	23.4"x 15.6"	32,33
W18x 119	31,32	W18 x 119	30,31,32	25.8" x14.4"	30,31	24" x 16.8"	30,31
W18x 143	29,30	W18x 130	28,29	28" x 14.4"	28,29	25.2"x 16.8"	27-28
W18x 158	25 - 28	W18x 43	7 TO 10	28" x 15.6"	26,27	30" x 16.8"	25,26
W18x 175	23,24	W18x 158	23-27	28.8" x15.6"	24,25	32.4" x16.8"	21-24
W18x 192	20-,22	W18x 175	18 TO 22	29.4" x 16.8"	22,23	33.6" x 18"	15-20
W18x 211	16 -19	W18x 192	15-17	31.2" x16.8"	18-20	32.4" x16.8"	11-14
W18x 234	12 -15	W18x 158	11-14	32.4" x 18"	11 -17	33.6" x 18"	6-10
W18x 258	1 TO 11	W18x 130	1 TO 6	35.4" x18"	1 - 10	32.4" x16.8"	1 TO 5

Table 8: Columns schedule for 40-story building for different structural systems.

Steel Moment Frame		Steel Braced Frame		Conc. Moment Frame		Concrete Shear wall	
Column Size	Floor No.	Column Size	Floor No.	Column Size	Floor No.	Column Size	Floor No.
W14 x 176	37 TO 40	W14 x 193	37 TO 40	18.4" x 18.4"	37 TO 40	19.2" x 19.2"	37- 40
W14 x 257	35,36	W14 x 211	35,36	20" x 20"	35,36	20" x 20"	35,36
W14 x 342	33,34	W14 x 283	33,34	22" x 22"	33,34	21" x 21"	33,34
W14 x 426	31,32	W14 x 342	31,32	24" x24"	31,32	22.5" x22.5"	31,32
W14 x 500	29,30	W14 x 370	29,30	25.6" x25.6"	29,30	24" x24"	29,30
W14 x 550	27,28	W14 x 426	27,28	27" x 27"	27,28	25.2" x 25.2"	27,28
W14 x 605	25,26	W14 x 500	23 TO 26	28.8" x 28.8"	25,26	27.4" x 27.4"	25,26
W14 x 730	21 TO 24	W14 x 550	21,22	30" x 30"	23,24	29.4" x 29.4"	23,24
W14 x 865	19,20	W14 x 605	17 TO 20	31.2" x31.2"	21,22	30" x 30"	21,22
W14 x 905	17,18	W14 x 665	15,16	32.4" x32.4"	19,20	31.2" x31.2"	19,20
W14 x 985	15,16	W14 x730	13,14	33.6" x33.6"	17,18	32.4" x32.4"	17,18
W14 x 1065	13,14	W14 x825	11,12	34.2" x 34.2"	15,16	33" x 33"	15,16
W14 x 1145	11,12	W14 x 1225	9,10	35.4" x 35.4"	13,14	33.6" x 33.6"	11to14
W14 x 1265	9,10	W14 x 1305	7,8	36.4" x 36.4"	10,11,12	34.2" x 34.2"	9,10
W14 x 1305	7,8	W14 x 1385	5,6	37.4" x 37.4"	7,8,9	34.6" x 34.6"	7,8
W14 x 1385	5,6	W14 x 1465	3,4	38.7" x38.7"	5,6	35.4" x35.4"	5,6
W14 x 1465	3,4	W14 x 1545	1,2	39.6" x 39.6"	3,4	36" x 36"	3,4
W14 x 1545	1,2	-------------	---------	46" x 46"	1,2	38.4" x 38.4"	1,2

8 Lateral drift comparison

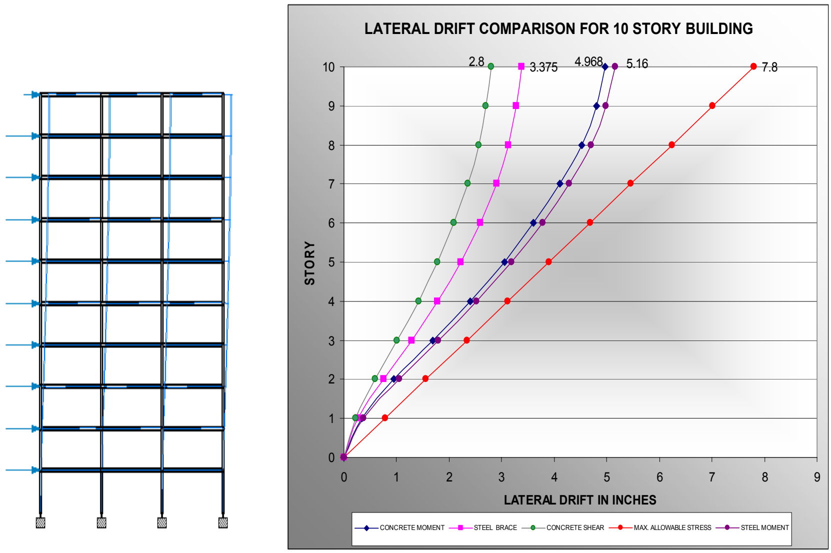

Figure 6: Lateral drift comparison for 10-story building.

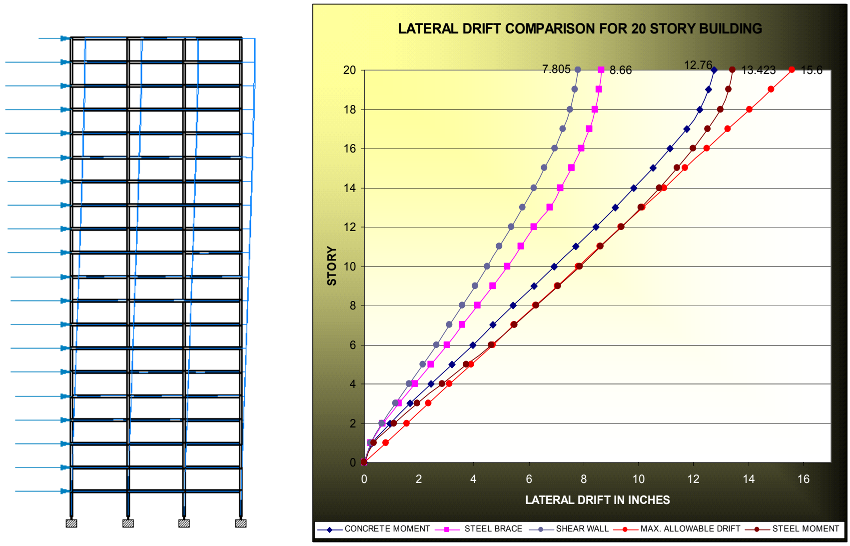

Figure 7: Lateral drift comparison for 20-story building.

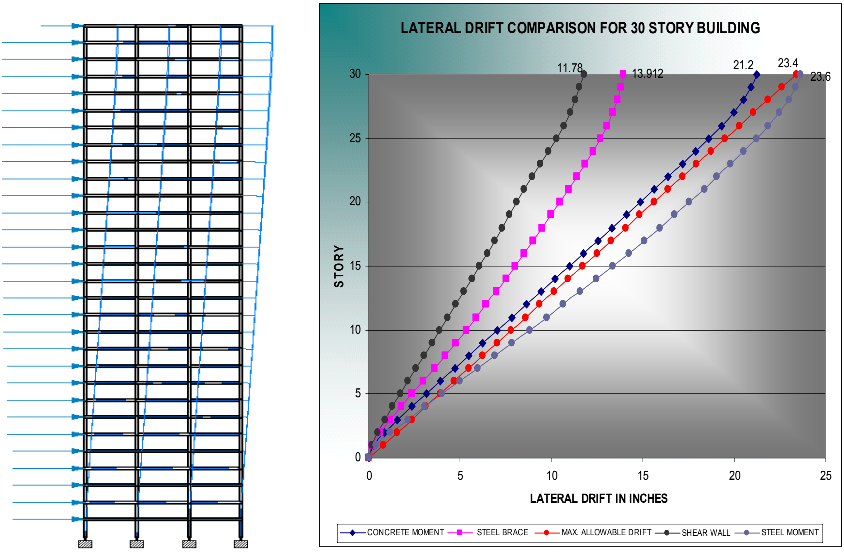

Figure 8: Lateral drift comparison for 30-story building.

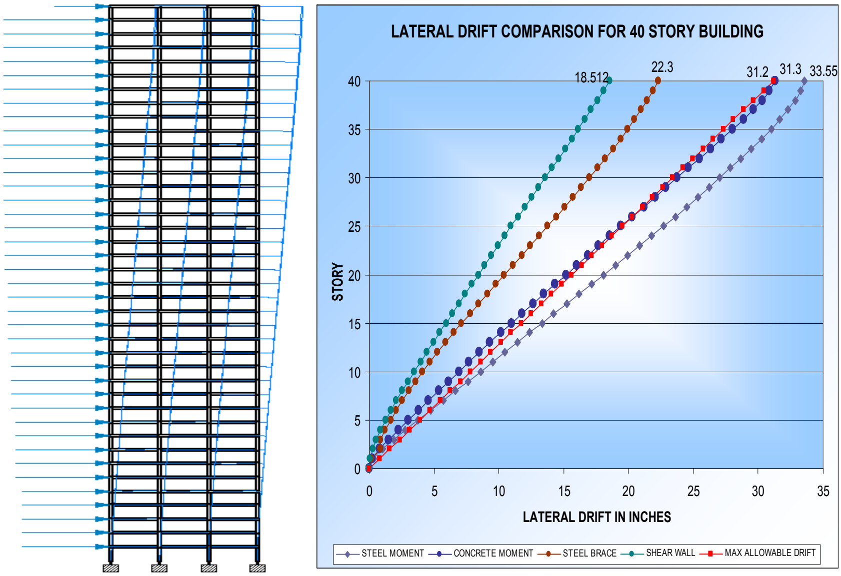

Figure 9: Lateral drift comparison for 40-story building.

9 Cost comparison

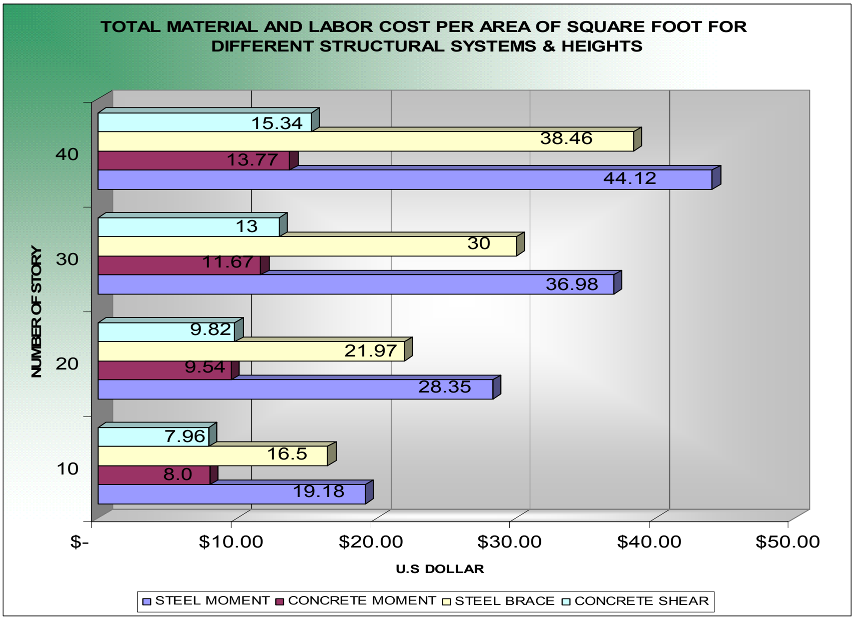

Figure 10: Cost comparison for structural systems.

10 Results

Comparing lateral drift and the cost for various structural systems at different heights shows the following results:

Figure 6 shows that the optimum structural system for a 10-story building is concrete shear wall with lateral drift (2.8"). The concrete shear wall minimizes drift in comparison to the maximum allowable drift by 64%, steel braced (3.4") reduces the drift by 57%, concrete moment (4.9") reduces by 37%, steel moment (5.6") reduces by 34% in comparison to the maximum allowable drift (7.8").

Figure 7 shows that the optimum structural system for a 20-story building is concrete shear wall with lateral drift (7.8"). It minimizes lateral drift by 50%, steel braced (8.7") reduces by 44%, concrete moment (12.8") reduces by 18%, steel moment (13.4") reduces by 14% in comparison to the maximum allowable drift (15.6").

Figure 8 shows that the optimum structural system for a 30-story building is concrete shear wall with lateral drift (11.8"). It minimizes lateral drift in comparison to the maximum allowable drift by 50%, steel braced (13.9") reduces the drift by 41%, concrete moment (21.2") reduces by 9%, steel moment (23.6") exceeds drift by (-1%) in comparison to the maximum allowable drift (23.4").

Figure 9 shows that the optimum structural system for a 40-story building is concrete shear wall with lateral drift (18.5") minimizes lateral drift in comparison to the maximum allowable drift by 41%, steel brace (22.3") reduce 28%, concrete moment (31.3") exceeds drift by (-0.5%), steel moment (33.5") exceeds drift by (-8%) in comparison to the maximum allowable drift (31.2").

Figure 10 shows that the optimum structural system for a 10-story building to minimize the cost is shear wall (7.96 $/ft²). It reduces the cost by 59% in comparison steel moment which has the highest cost, (19.18 $/ft²).

The optimum structural system for 20-, 30-, and 40-story building is concrete moment (9.54 $/ft²), (11.67 $/ft²), and (13.77 $/ft²). It reduces the cost by 66%, 68%, and 69% as follows in comparison to the highest cost, steel moment (28.35 $/ft²), (36.98 $/ft²), and (44.12 $/ft²).

A steel braced frame reduces the cost by 14%, 23%, 19%, and 13% for 10, 20, 30, and 40 stories in comparison to steel moment frame.

For a 10-story building in Saudi Arabia, steel building costs twice more than concrete building.

For 20-, 30-, and 40-story building in Saudi Arabia, a steel building costs three times more than concrete building.

11 Conclusions

Using the proposed process is a vital method to select the optimum structural system to minimize lateral drift and cost. In Saudi Arabia shear wall is the optimum structural system. Concrete proves to be the optimum structural material to minimize lateral drift and reduce material and labour costs in comparison to steel. Adding shear walls in the concrete building is important to reduce lateral drift. This investigation shows that adding shear wall to concrete moment frame reduces lateral drift by 50% of the maximum allowable drift. Adding braces to steel moment frame minimizes the lateral drift, the cost, and the building mass. Drift governs the design when the height exceeds 30 stories for the steel moment frame and 40 stories for the concrete moment frame.

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