Multiple Outrigger Systems

Introduction

The design of the hat truss and outriggers added to the optimized frame resulted in reducing the overall drift by 9” in the N-S direction with only a 10% increase in steel tonnage. The resulting N-S drift is very near the allowable drift in that direction which caused some inter-story drifts to be unacceptable. Cracking over interior partitions, damage to non-structural materials and possible cladding issues can arise from excessive movements caused by drift. The structure will still be safe; however, visual signs of cracking or actual performance issues can develop while the building is in service necessitating constant renovation and maintenance.

The third structural redesign builds upon the hat truss and roof-level outriggers scheme; however additional horizontal outriggers will be used at middle-level mechanical plants to further help limit the excessive drifts in the N-S direction. Design assumptions and goals will be made during the redesign to focus the study on mainly the N-S lateral system. The concept and behavior of the combined system of horizontal outriggers and hat trusses with lower belt trusses and outriggers will be discussed. The design results of the 2-outrigger performance will be compared to the design criteria and conclusions will be made.

Methodology

The methodology of a multiple outrigger system is practically the same as the single hat truss and outrigger at the roof-level. In a combination system though, outriggers are used throughout the building; one in the level 22 mechanical plant, another in the level 3 mechanical space, and the other hat truss and outriggers remain unchanged from the structural scheme before.

The addition of an outrigger lower in the braced core causes the rotational stiffness of the outrigger to increase since the length of columns (L) in the equivalent spring stiffness equation (6-10) decreases on page 35. This causes also caused less axial force to be applied to the columns in resisting the rotation of the core.

By locating the outrigger in a mechanical space lower in the tower, the braced frame cannot rotate freely; therefore, the drift is lessened at the upper levels before the second outrigger is engaged.

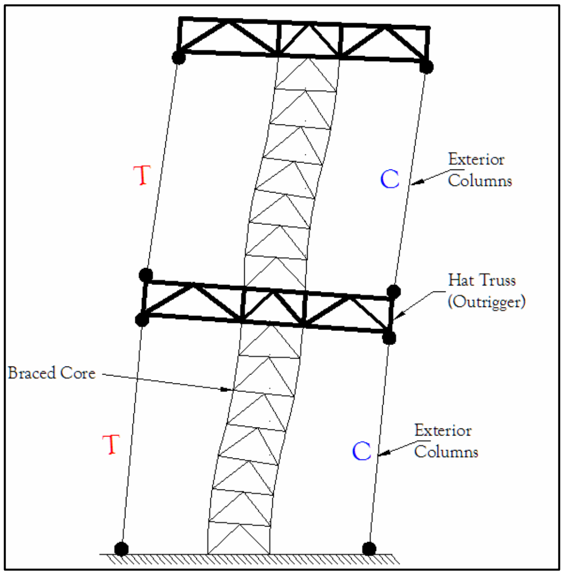


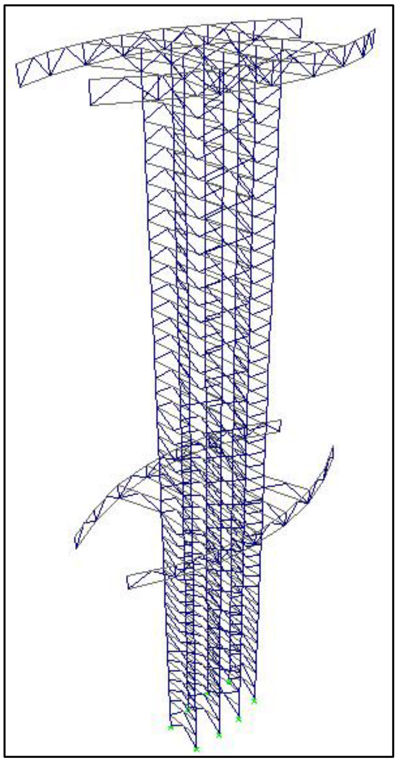
Figure 6.12: Multiple Outrigger System

Assumptions and Design Goals

To effectively evaluate the validity of the multi-outrigger system many factors and limiting assumptions must be made. The assumptions made in the design of multiple outrigger systems is the same as the assumptions made in the hat truss and outrigger system and are as follows:

<u>Assumptions:</u>

1. The optimized braced frame design shall be used as the core structure.
2. Members shall be redesigned if insufficient after incorporation of the additional outriggers in mechanical plant levels.
3. Only the N-S direction will be analyzed in this study.
4. Outriggers will be designed for BF #2, #3, #4 and #5.
5. Calculated ASCE 7-02 wind loads control the strength of N-S frames. See Appendix A.
6. Limiting slenderness ratios for braces: Tension KL/r <= 300 Compression <=200.
7. P-Delta effects shall be accounted for in deflection and strength design.
8. Mechanical equipment can be moved without significant impacts on the building.



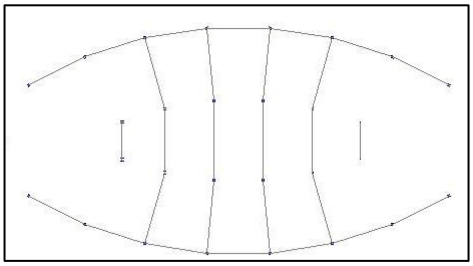


**Figure 6.13a,b: (a) 2-Outrigger System Geometry (b) Outrigger Locations in Plan view:
Outriggers on BF #2, #3, #4 and #5 (from left to right)**

<u>Design Goals:</u>

1. Design an efficient and least weight alternative reduce drift in the N-S direction.
2. Compare performance between a 2-outrigger and 3-outrigger systems
3. Further reduce inter-story and total drift to H/480 in N-S direction by use of outrigger and hat truss systems.
4. Minimize impact on interior spaces and layouts by placing outriggers in mechanical plant spaces.
5. Conclude on which system is best suited for an alternative to the reinforced concrete core structure in resisting lateral loads.

Design Process

The design of the multiple outrigger system starts with using the optimized braced frame and hat truss design from the previous structural scheme. The design of the outrigger system stayed the same with only minor changes in column sizes at the 21st and 22nd levels to account for increased axial loads by the 2-outrigger system.

The scope of this study did not include the design of the heavy bracing connections in either the outrigger or the braced frame column due to the immense size of the structure. Only two outrigger combinations were researched where outriggers are placed in the top two mechanical spaces, and where all three mechanical spaces exist. The results of the two systems will conclude the structural redesign and a recap of information will conclude this report section with conclusions and recommendations on what system to use.

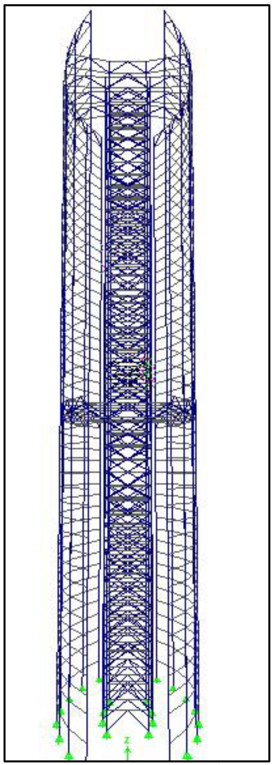


Figure 6.14: 2-Outrigger Side Elevation (MEP Levels: Roof & 22nd)

Results

The drift results of the 2-outrigger system and 3-outrigger system can be seen below in Table 6.5. The utilization of two outrigger trusses (roof and mid-level) resulted in a further reduction in total building drift. The building drift is now well within the allowable in both directions. The resulting increase in tonnage for the 2-outigger system is approximately 1.5% more than the hat truss only, and only 7% more than the original braced only design scheme investigated further.

The addition of a third outrigger in 3rd level mechanical space did not reveal more significant drift reductions as can be compared to Table 6.5 and 6.6. This indicates the outriggers are sufficiently flexible and do no contribute as much compared with the overall stiffness of the braced frame core. The braced frame structure is very stiff at lower levels due to heavy structural members and the braced configuration.

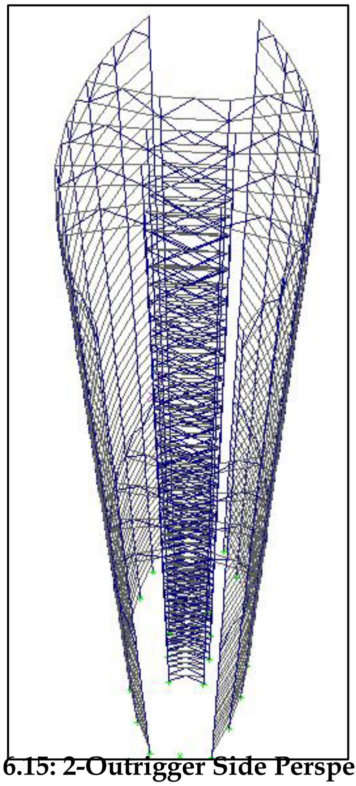


Figure 6.15: 2-Outrigger Side Perspective

2-Outrigger Drifts		No P-Delta			Including P-Delta Effects		
	Load	**UX**	**UY**	**RZ**	**UX**	**UY**	**RZ**
N-S	WINDY	0.1753	18.7478	0.00037	0.1895	19.3223	0.00041
	TUNNELNS	0.103	11.1462	0.00019	0.1111	11.4772	0.00022
	EQY	0.2935	13.8783	0.00432	0.3162	14.2843	0.00454
	H/480		**17.0825**			**17.0825**	
E-W	WINDX	8.2933	0.0748	0.00037	8.5829	0.08	0.0004
	TUNNELEW	2.8408	0.0239	0.00014	2.936	0.0256	0.00015
	EQX	17.8611	0.118	-0.00085	18.4371	0.1254	-0.00087
	H/1000	**8.1996**			**8.1996**		

Table 6.5: 2-Outrigger System Total Drift (inches)

3-Outrigger Drifts		No P-Delta			Including P-Delta Effects		
	Load	**UX**	**UY**	**RZ**	**UX**	**UY**	**RZ**
N-S	WINDY	0.1649	18.455	0.00034	0.1913	18.8764	0.00028
	TUNNELNS	0.0977	10.9997	0.00018	0.1115	11.2505	0.00011
	EQY	0.2888	13.7152	0.00429	0.3586	13.9794	0.00478
	H/480		**17.0825**			**17.0825**	
E-W	WINDX	8.2857	0.0704	0.00038	6.3056	0.0712	0.00065
	TUNNELEW	2.7012	.02013	0.00012	2.0852	0.0233	0.00023
	EQX	16.9852	.1013	-0.00052	12.5628	0.1379	-0.00064
	H/1000	**8.1996**			**8.1996**		

Table 6.6: 3-Outrigger System Total Drift (inches)

It can be seen in the above tables that the difference in drift reduction between a two outrigger system and 3-outrigger system is nearly negligible. The outrigger at the lowest level mechanical space has the least effect on resisting the rotation of the core. This behavior is consistent with how a braced frame deforms due to lateral load. A braced frame resists the large shear forces at the base of the building through axial forces in the bracing members at this location. And since the columns are very large near the base, only small axial deformations due to chord drift can be expected. Therefore, the primary source of deflection is shear racking, not a rotation of the core due to chord drift.

The two determinates of the effectiveness of an outrigger stated earlier were the magnitude of the core rotation and the stiffness of the spring element. Since the rotation is small and the stiffness of the spring is also relatively small compared to the core structure, the lowest outrigger is the least effective in contributing to drift. The best solution would be to use the 2-outrigger system since the drift values are approximately equal, and savings in steel tonnage would result in the most efficient structural system for the Hyatt Center. A closer look into the dynamics and torsional effects of the 2-outrigger system is required to make a final judgment on the validity of this solution.

Results (continued)

Taking another look at the 2-outrigger design and the design goals it can be seen that the drift meets allowable limits, the total weight of the system is lower and minimal impact on office layouts was achieved by incorporating mechanical spaces as the outrigger locations. Table 6.7 below summarizes the overall drift, including P-Delta effects, as well as the total cost, steel tonnage and increase in steel tonnage from the braced frame core structure with no outriggers. Figures 6.16a and 6.16b graphically display the deflection of each system compared to the allowable drift limits in both directions.

	N-S Drift	E-W Drift	Steel Tonnage	% Steel Increase	Total Cost
Shear Wall	14.64	0.84	11305	N/A	**$17,914,271**
Braced Frame	24.0347	3.2926	19095	0.0%	**$19,972,758**
Hat Truss	15.9389	3.0997	20210	5.5%	**$21,281,477**
2-Outrigger	11.4772	2.936	20528	7.0%	**$21,369,834**
3-Outrigger	11.2505	2.0852	20847	8.4%	**$21,577,731**
Allowable	17.0825	8.1996			

Table 6.6: Summary of System Performances

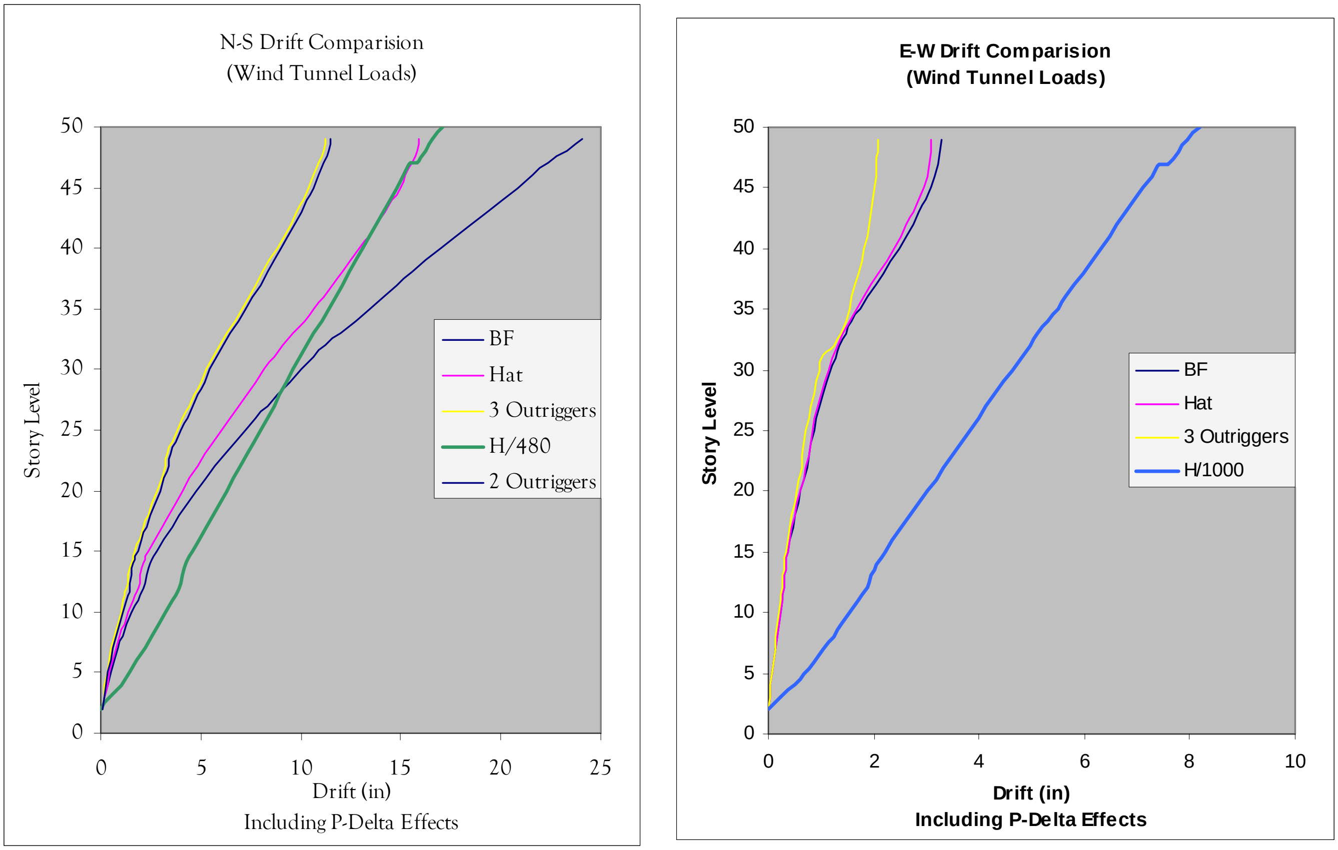


Figure 6.16a, b: N-S and E-W System Deflection Summary

Taking a closer look at the initial design when modeled, however, deliberate torsion was incorporated into the building by asymmetrical elevator openings in the rigid diaphragm as seen below in Figure 6-16. A tall building with only a central core to resist lateral loads can develop torsion problems due to loads acting at an eccentricity to the center of rigidity of the core structure.

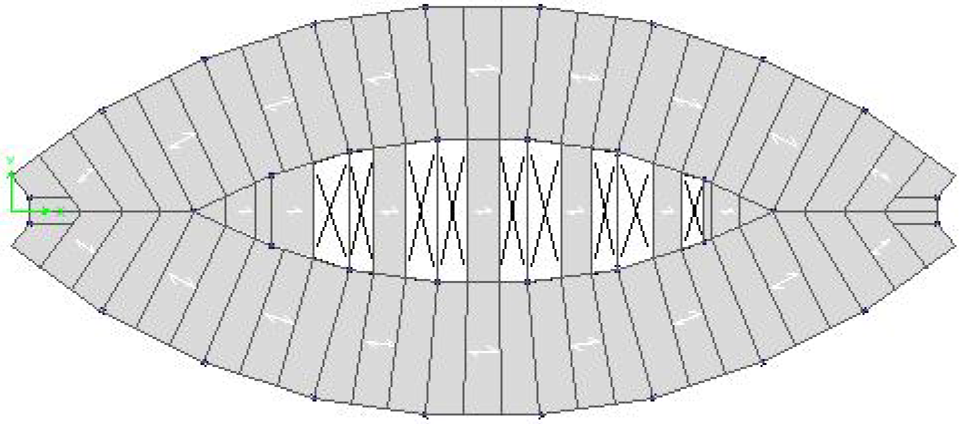


Figure 6.16: Plan with Offset Opening in Diaphragm

The arrangement of elevator cores was deliberate to model how the building will perform torsionally. Results of the calculated rigidities and torsional moments applied to the structure can be found in Appendix E. The calculated center of mass for the structure varies along the height, however the values are approximately X=158 feet, Y= 0 feet. This corresponds to the geometric center in the Y-direction and 12 feet towards the east-side of the diaphragm in the X-direction. The center of rigidity was offset by a maximum of 6 feet to the north or south and 1 foot to the east or west. This eccentricity is very close to the 5% accidental eccentricity required for seismic lateral distribution.

The increased loads on the braced frames and outriggers to resist the torsional moment were applied to the frames during the initial analysis of each system. The inherent effects of torsion can be seen in the modal shapes of the model which will be discussed in the final conclusion.

Since the Hyatt Center has a slender aspect ratio of 15:1 and all the framing has been designed in the core to resist lateral loads, the building is torsionally flexible. The drift caused by the twisting effects of torsion can be calculated by multiplying the maximum diaphragm rotation by the distance to the furthest edge of the diaphragm.