1 Shear Wall Analysis

Introduction

The current lateral system in the Medical Office Building consists of cast-in-place (CIP) concrete moment frames and torsion beams. Although the frame system is effective for the Filigree beam system, it detracts from some of the benefits of the Filigree beams and suffers certain inefficiencies because it has to work around the Filigree beams. In particular, the frame beams, which are up to 48" deep, divide the channeled plenums created by the Filigree system. These same beams are also 30" lower than the floor system beams, which generally means that the ceilings most be hung lower to hide the frames. In addition, the frames themselves are placed in such ways that lateral loads can generate significant torsion in the building. A careful redesign could alleviate some torsion and lead to a more efficient system.

Solution Overview

One alternative to moment frames as a lateral system is shear walls. Properly located shear walls would reduce the number of plenum channels that are interrupted, eliminate the deep beams and thus potentially increase usable space, and move the center of stiffness of the building to alleviate torsion. Another notable feature of shear walls is that they are typically located at the building's edges or around the stairwells. Because the current frame system is located along the stairwells there are already several bays that could have shear walls added without affecting the rest of the Filigree system.

Design Criteria

When considering the effectiveness of the shear wall system, there are several factors that need to be addressed:

- Can the shear walls meet code?
- Can the shear walls be constructed at no greater cost?
- Will the shear walls introduce more problems than they correct?

The first question will be addressed by designing the shear walls based on the IBC 2003 Building code. The second question will be addressed by running a cost analysis based on data provided by RS Means. The last question will be addressed by comparing and contrasting the utility of the building with frames and with shear walls. Regardless of the final conclusion, if the shear walls cannot meet the code requirements, they will be discarded as a solution. The majority of the conclusion will be weighted on the answers to the latter two questions. A savings in cost and schedule in addition to the introduction of few problems will be considered a great success. Combinations of higher costs and fewer problems or lower costs, but more problems will be considered successes based on the relative severity of the costs and benefits.

Preliminary Analysis

One of the major considerations in the design of any lateral system is trying to keep the center of rigidity near the center of gravity to limit the torsional moment generated by uneven wind loads. In considering the use of shear walls, it is necessary to evaluate not only the center of rigidity, but the effects on the architectural design and the other building systems. In the case of the Medical Office Building, the architecture of the façade makes the use of exterior shear walls impossible. However, a sound lateral system should include resistance along the exterior surfaces to efficiently resist torsion. For this reason, the two moment frames on the exterior walls were retained and shear walls were investigated for several internal locations.

In order to minimize the impact on the other building systems and the architecture, the shear wall locations were chosen to be around the stairwells and bathrooms (Figure 1-1). Based on these locations it was possible to determine the height and maximum depth of the shear walls. Once the heights of the walls were determined, the required thickness could be calculated based on the slenderness criteria that the thickness be greater than or equal to 1/30 the height. Knowing the dimensions of the shear walls it was possible to determine their stiffness. A STAAD analysis of the two existing moment frames also revealed their stiffness, the full details of these analyses appear in Table 1-1.

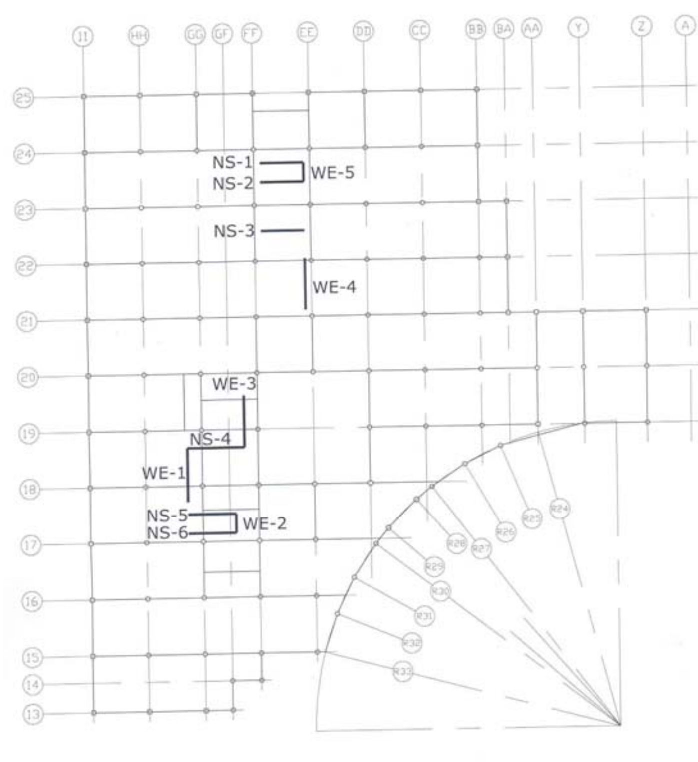


Figure 1-1 The schematic showing the potential shear walls in plan

Wall	b (in.)	d (ft.)	h(ft.)	I (in^4)	Aw(in^2)	k (k/in.)
N-Frame	-	-	-	-	-	111.00
S-Frame	-	-	-	-	-	36.00
NS-1	16.00	21.75	37.50	23706108.00	4176.00	1707.90
NS-2	16.00	21.75	37.50	23706108.00	4176.00	1707.90
NS-3	16.00	21.75	37.50	23706108.00	4176.00	1707.90
NS-4	16.00	28.46	37.50	53101997.83	5464.00	3370.93
NS-5	20.00	23.82	50.00	38938326.51	5717.50	1261.20
NS-6	20.00	23.82	50.00	38938326.51	5717.50	1261.20
WE-1	16.00	27.00	37.50	45349632.00	5184.00	2963.40
WE-2	20.00	9.58	50.00	2534791.67	2300.00	92.69
WE-3	16.00	26.08	37.50	40885729.33	5008.00	2719.79
WE-4	16.00	26.00	37.50	40495104.00	4992.00	2698.13
WE-5	16.00	9.58	37.50	2027833.33	1840.00	172.43

Table 1-1 Summary of shear wall and moment frame properties

Using the properties of the shear walls and moment frames it was possible to perform a stiffness analysis to determine the center of rigidity for various combinations of shear walls. The full excel spreadsheets detailing this analysis appear in Appendix I. A summary of the walls utilized in the analysis and their respective eccentricities appear in Table 1-2. Based on these results it can be seen that the least eccentricity results from the use of shear walls at the inside edges of the stairwells and around the bathroom walls. These walls were chosen for further analysis.

Walls	X-eccentricity	Y-eccentricity
All	-10.18’	1.22’
NS-1,2,5,6 & WE-2,5	-8.77’	-8.42’
NS-3,4 & WE-1,4	-10.08’	12.49’
NS-2,3,4,5 & WE-1,4,5	-9.21’	5.04’
NS-2,3,4,5 & WE-3,4	5.16’	5.04’

Table 1-2 Eccentricity Analysis of shear wall combinations

Secondary Analysis

Starting with the shear wall combination chosen from the preliminary analysis, a further evaluation of the least eccentric combination was performed to test the actual strength and size of the walls needed. Shear walls resist lateral loads on a building, predominantly those from wind. Earthquake forces also produce lateral loads, but the columns in the building would assist in carrying this load, and thus not be the controlling value in the design. The wind loads (Figure 1-2) on the Medical Office Building, as determined by guidelines in ASCE 7-02, are 267 kips in the North-South direction and 192 kips in the West-East direction.

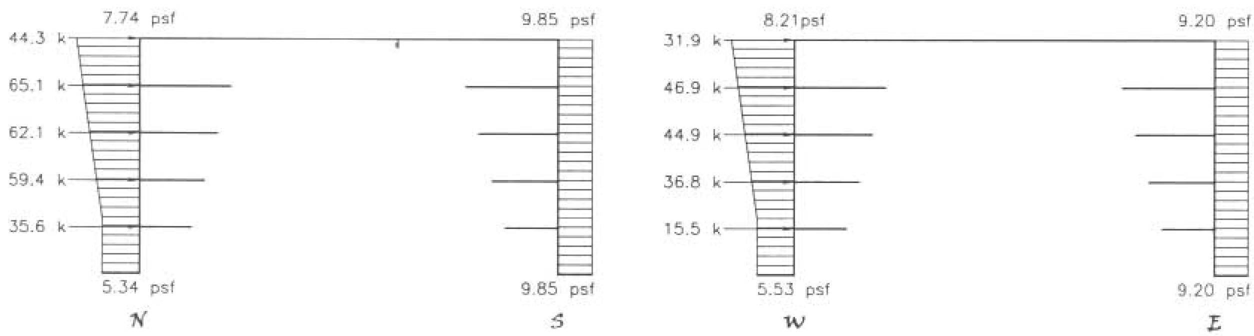


Figure 1-2 Wind profiles for The Medical Office Building

These loads were distributed to the shear walls and frames through a stiffness analysis. The loads in the shear wall were then evaluated against the strength of an unreinforced masonry wall, using 3000 psi CMU blocks fully grouted:

$$\phi V_n = 0.8 * 3.8 A_n \sqrt{f_m^{'}} \quad (1\text{-}1)$$

The walls were then resized to more closely match the depth required for strength. This redesign resulted in a change of stiffness, and thus the need for another distribution of the loads. Inevitably the process of redistributing the loads would result in the elimination of the shear walls altogether, as the reduced depths would mean more of the load enters the frames. For this reason, the frames were limited to carrying 10% of the shearing force from a symmetric load. In addition, the shear walls could not exceed an in-plane stress due to bending greater than 250 psi without reinforcing. With these requirements in place, several sizes of shear walls were checked using excel, the final results being shown in Table 1-3.

Wall	V_ult	f (psi)	ΦV_n
N-Frame	13.59	-	-
S-Frame	3.91	-	-
NS-2	75.48	54	174.56
NS-3	29.01	31	67.10
NS-4	118.05	230	273.01
NS-5	45.41	123	105.01
WE-3	109.14	231	252.40
WE-4	63.64	139	147.18

Table 1-3 Summary of shear wall analysis showing the carried load, the bending stress and the allowable shear

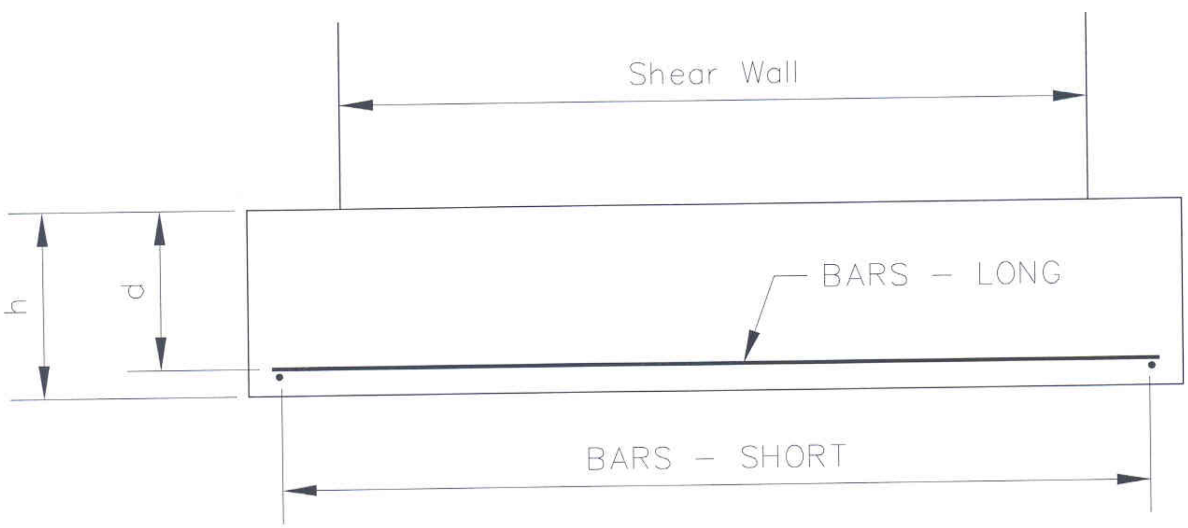
Final Design

In order for the shear walls to perform effectively they must have a proper foundation. In this case it was assumed that the shear walls would take a portion of the floor loads, as determined by tributary area, in addition to the lateral loads. Moments of overturning were approximated by applying the final shear at 2/3 the height of the shear wall. Based on the maximum stress due to the gravity loads and the moments, the initial size of the footings was determined. Once the initial size was known, an analysis of overturning was performed (Table 1-4).

Wall	M_o (ft-k)	P (k)	e (ft)	B (ft)	L (ft)	q (ksf)	kern
NS-2	1887.06	221.87	8.51	24.00	6.00	4.82	4.00
NS-3	725.36	158.48	4.58	15.00	6.00	4.98	2.50
NS-4	2951.34	253.57	11.64	26.00	7.50	4.79	4.33
NS-5	1513.60	304.98	4.96	24.00	6.00	4.75	4.00
WE-3	2728.54	316.96	8.61	30.00	6.00	4.79	5.00
WE-4	1591.04	253.57	6.27	23.00	6.00	4.85	3.83

Table 1-4 Overturning analysis of footings

Based on this analysis it becomes clear that overturning becomes a serious issue with the shear wall footings. There are several means of remediation for this problem, including using underpinning, increasing the size of the footing, or burying the footing. Increasing the footing size would be inefficient, and burying the footing would require excessive excavation, therefore, the best solution is to underpin the footings. The analysis of the necessary underpinning was not conducted as part of this work, but the footings were designed using the above loads after modification for strength design. A general schematic of the slab design, and the results of the analysis for each shear wall appear in Figure 1-3.



Wall	q_design (ksf)	d (in)	h (in)	A_s (in^2) Long	A_s (in^2) Short	Bars – Long	Bars -Short
NS-2	8.62	36	39	0.84	0.84	#6's @ 6"	#6's @ 6"
NS-3	6.60	17	20	0.44	0.43	#6's @ 12"	#6's @ 12"
NS-4	7.85	45	48	1.04	1.04	#6's @ 5"	#6's @ 5"
NS-5	6.11	27	30	0.69	0.65	#6's @ 7"	#6's @ 8"
WE-3	7.07	29	32	0.73	0.69	#6's @ 7"	#6's @ 7"
WE-4	6.38	21	24	0.60	0.52	#6's @ 8"	#6's @ 9"

Figure 1-3 Footing Design for shear walls

Conclusions

The proposed shear wall design requires the construction of six masonry walls and their foundations. Each wall was designed using applicable code, and therefore meets the legal requirements for use. The existing system that can be removed as a result of the redesign includes 60 beams, from the moment frames, and their reinforcing. The columns and footings would be retained as party for the gravity structure, therefore, no savings can be recovered from the existing footings. A cost comparison through R.S. Means is presented in Table 1-5. This data shows that there is a $70,000 benefit from the use of the shear wall system.

	Shear Wall	Moment Frame
CMU Block	$35,728	$0
Footing Formwork	$4,301	$0
Footing Rebar	$2,895	$0
Footing Concrete & Placement	$21,904	$0
Beam Formwork	$0	$3,960
Beam Rebar	$0	$33,780
Beam Concrete & Placement	$0	$96,540
TOTAL	$64,828	$134,280

Table 1-5 Cost Comparison of Shear Walls to Moment Frames

Before drawing a final conclusion though, it is necessary to consider the effects the shears walls have on other systems. Although the shear walls were placed to avoid impact, they still represent an impenetrable barrier between certain areas. In one respect, this creates additional sound damping, particularly important around bathrooms and stairwells, where the walls were located. In another respect, the shear walls around the bathroom may interfere with runs of pipe, electrical lines, and mechanical ducts. There is no clear cost benefit to the improved sound damping, but there is a calculable deficit if additional amounts of mechanical, electrical, and plumbing work are required. The cost estimate also ignores the cost of underpinning the shear wall foundations to prevent overturning.

Despite the possible related costs to the shear walls, they are still the more economical system and are recommended as a replacement system for the moment frames.