FINITE ELEMENT MODELING EFFICIENCY OF MASONRY SHEAR WALLS IN A FIVE-STOREY BUILDING

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ABSTRACT
Shear walls are used in buildings to resist lateral loads applied to the building by wind, seismic and other effects through in-plane action. These walls are often constructed from masonry because masonry does not require the use of form work, making it ideal for the construction of elevator shafts, stairwells and infill walls. The calculation of the in-plane forces acting on these masonry shear walls can be quite complicated when considering three dimensional analyses of the walls. Without the aid of software, two simplifying assumptions are required. The first is that the floors and roofs behave as rigid diaphragms, constraining the in-plane (x and y direction) translations to be the same for all the walls and preventing top of wall rotation of all walls. The second assumption is that the floors do not restrain the top of wall rotation for out-of-plane bending [1].

In the engineering consulting industry, time is money. If the building is small it can often be quicker to perform calculations using spreadsheets, MathCAD, or other calculation tools, than to create an elaborate finite element model. For the purposes of such a comparison, the lateral forces generated from wind on a hypothetical five-storey building were distributed using both traditional methods of hand calculation found in many masonry text books [1, 4] and also using a Finite Element Model in SAP2000. The time required by each of the two methods to obtain the design forces on the shear walls (shear and bending moment at wall bases) and the differences between the results are discussed.

KEYWORDS: masonry shear walls, finite element model, lateral loads

INTRODUCTION
Shear walls are used in buildings to resist lateral loads applied to the building by wind, seismic and other effects through in-plane action. These walls are often constructed from masonry because masonry does not require the use of form work, making it ideal for the construction of elevator shafts, stairwells and infill walls. If the floors are considered flexible or semi-rigid and not considered rigid diaphragms a simple tributary area distribution can be used. Figure 1 uses a simple numerical example to illustrate the distribution of forces to shear walls in a single storey building based on the assumptions of rigid, semi-rigid and flexible diaphragms. However, when considering three dimensional analysis of multi-storey buildings if the floors act as rigid

diaphragms the calculation of the in-plane forces acting on these masonry shear walls can be quite complicated.

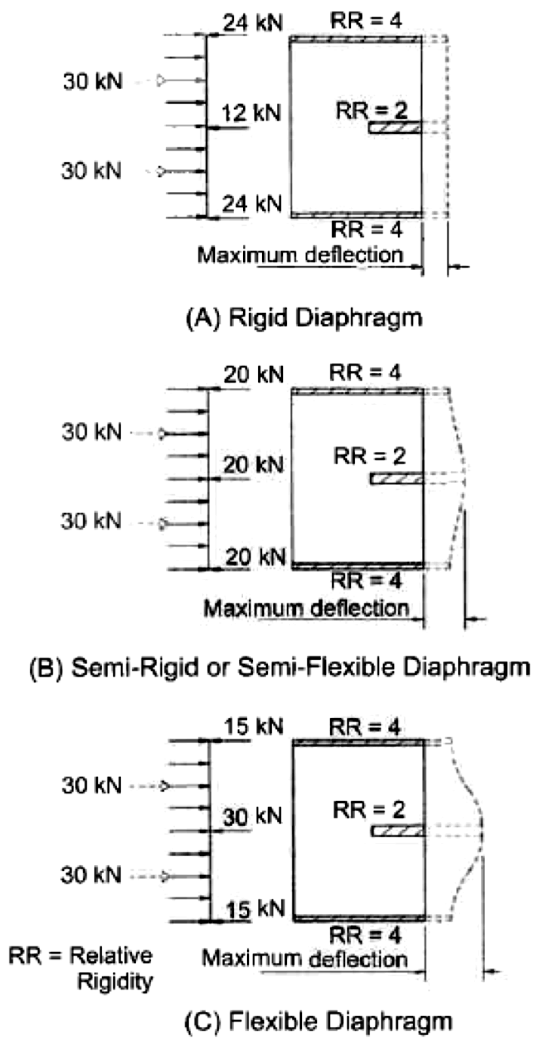

Figure 1: Analysis of shear walls under different assumptions [1]

Depending on the size of the building being designed it may be less time consuming to model the building using software than using traditional hand calculations to distribute lateral loads to the shear walls. For the purposes of such a comparison, the lateral forces generated from wind on a hypothetical five-storey building were distributed using both traditional methods of hand calculation found in many masonry text books and also using a Finite Element Model in SAP2000. One parameter of interest was the time required for each of the two methods to obtain the design forces on the shear walls in the first floor (Base Shear and Bending).

FIVE STOREY BUILDING

The sample building used for the exercise was taken from "Masonry Design for Engineers and Architects" problem 7-1 [2]. The elevation and plan of the building are illustrated in Figure 2 below.

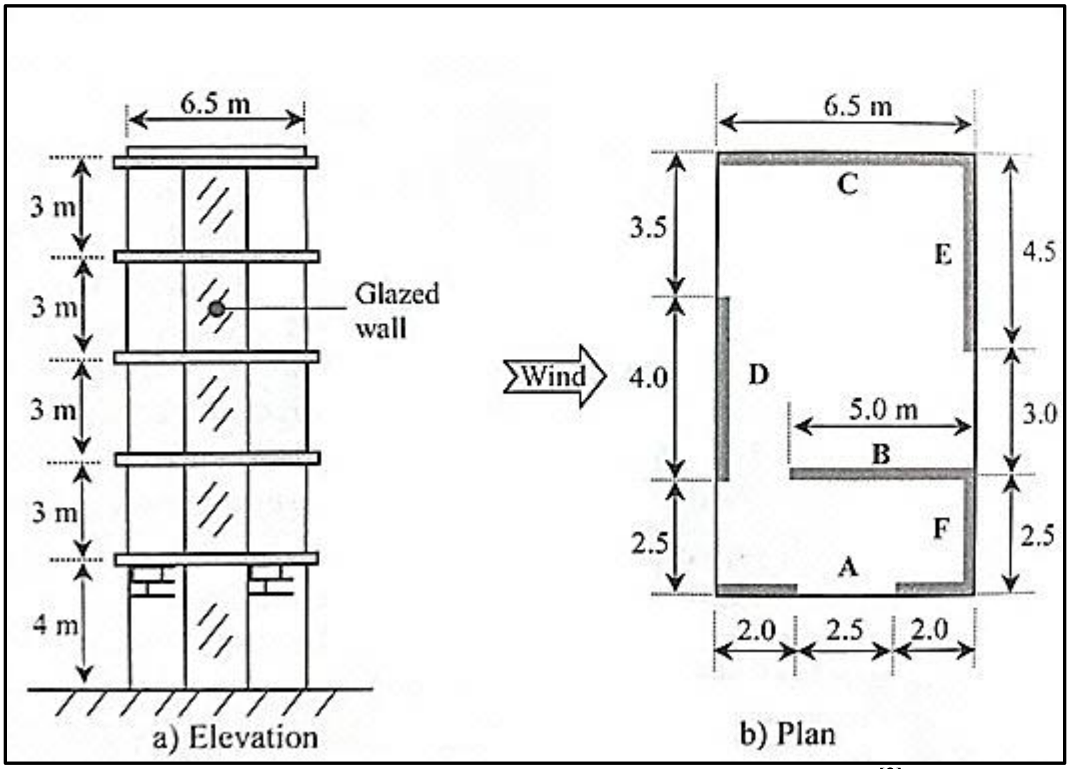

Figure 2: Five Storey Building under Consideration [2]

In the example, the building is to be constructed of 200 mm (8") precast hollow core concrete slab floors supported on 20 cm (190 mm actual thickness) concrete block masonry walls in Calgary, Alberta, Canada and in open terrain. The climatic data for the building were obtained from the National Building Code of Canada 2010 [3].

For both models, calculation of the wind load distribution to the floor levels is required and is independent of the efficiency of the method of analysis of distribution of lateral forces to the shear walls generated by the wind loads. Using the climatic data for Calgary the wind pressure was determined using

$$p = I_w q_{1/50} C_e C_g C_p \tag{1}$$

Where p is the wind pressure (kPa), I_w is the importance factor, $q_{1/50}$ is the 1 in 50 year wind pressure, C_e is the exposure factor, C_g is the gusting factor, and C_p is the external pressure coefficient averaged over the area of the surface.

This resulted in a wind load of: $p = 1.32$ kPa .

Distributing this load based on tributary area of the walls and the height between floors yielded the following table:

Table 1: Wind Distribution to the Floor levels of the Building

Level (i)	Height h_i (m)	Width (m)	Tributary Height (m)	Wind Load F_i (kN)	Base moment F_i x h_i (kN-m)
Roof	16	10	1.5	19.8	316.8
4th	13	10	3.0	39.6	514.8
3rd	10	10	3.0	39.6	396
2nd	7	10	3.0	39.6	277.2
1st	4	10	3.5	46.2	184.8
Σ				**184.8**	**1689.6**

The summation of the floor loads yields a base shear of 184.8 kN and a base moment of 1689.6 kN-m. With this information, the traditional and finite element methods for distributing these loads based on the assumption of rigid diaphragm action were explored.

TRADITIONAL METHOD

Distribution of the lateral forces described in the previous section were first calculated using traditional methods of hand calculation based on the relative rigidities of the shear walls as found in many masonry text books [2,4]. Since rigidity can be expressed as the inverse of deflection assuming all walls are constructed of the same materials, the rigidity of cantilever walls and be calculated from :

$$K_c = \frac{E_m t_e}{4\left(\frac{h_w}{l_w}\right)^3 + 3\left(\frac{h_w}{l_w}\right)} \tag{2}$$

Where K_c is the rigidity of the wall E_m is Modulus of Elasticity (MPa), t_e is the thickness (mm), h_w is the height of the wall (mm) and l_w is the length of the wall (mm). Equation 2 assumed the floors for this building were incapable of transferring significant vertical shear between shear walls and the shear walls were conservatively assumed to behave as cantilevers [4]. Using EXCEL 2010 the following table was created to distribute the shear force to the walls on the first floor, treating the Wall A as two separate walls A_1 and A_2.

Table 2: Shear and Bending Forces Calculations at the Base Floor

Wall	l_w (m)	h_w (m)	(h_w / l_w)	K_i	$K_i / \Sigma K_i$	Shear (kN)	Bending (kN-m)
A_1	2.0	3.0	1.5	0.0556	0.0530	9.25	87.3
A_2	2.0	3.0	1.5	0.0556	0.0530	9.25	87.3
B	5.0	3.0	0.600	0.3754	0.3579	66.0	480
C	6.5	3.0	0.462	0.5625	0.5362	100.4	617
Σ				1.0490	1.00		

Table 3 contains the forces calculated in the shear walls on floors 2 to the roof

Table 3: Shear Forces from the Wind Load obtained by Traditional Methods

Floor \ Wall	A_1 (kN)	A_2 (kN)	B (kN)	C (kN)
Base	9.25	9.25	66.0	100
1st	9.25	9.25	66.0	100
2nd	7.34	7.34	49.6	74.3
3rd	5.24	5.24	35.4	53.1
4th	3.15	3.15	21.3	31.9
roof	1.05	1.05	7.09	10.6

Table 4: Bending Moments from the Wind Load obtained by Traditional Methods

Floor \ Wall	A_1 (kN-m)	A_2 (kN-m)	B (kN-m)	C (kN-m)
Base	87.3	87.3	601	913
1st	50.4	50.4	338	511
2nd	28.4	28.4	190	288
3rd	12.6	12.6	84.6	128
4th	3.15	3.15	21.2	32.0
roof	0.00	0.00	0.00	0.00

The time required to distribute the forces and arrive at the design forces for the shear walls was seven (7) hours by a designer with an advanced understanding of structural analysis. It is interesting to note that the design forces in the tables above did not include torsional effects. Torsional effects result when the centre of rigidity does not coincide with the centre of gravity which would be the case for the shear walls in the asymmetric floor plan in the example (Figure 2). However, problem 7-1 instructed that torsional effects be neglected. Including the calculations for torsional effects would likely have taken an additional 1 to 4 hours.

FINITE ELEMENT MODEL

A Finite Element Model using SAP2000 was used to calculate the forces exerted on the five storey building. SAP2000 was chosen because it is widely used in the consulting engineering industry. SAP2000 is user-friendly and requires very little post-processing to obtain the forces acting on the walls. The walls were modeled using nominal 20 cm block. The modulus of elasticity was calculated to be 8.5 GPa according to Clause 6.5 of the CSA-S304.1-04 for a compressive strength, f'_m of 10 MPa. To simplify the post-processing analysis, the shear walls were modeled as beam elements while floors were modeled as shell elements. Figure 3a below illustrates the extruded version of the beam model. The lateral loads were applied to the structure in the SAP2000 model as they would have been using the traditional methods, as point loads at each floor level at the center of the west elevation. Figure 3b) illustrates how the lateral wind loads were applied in the model.

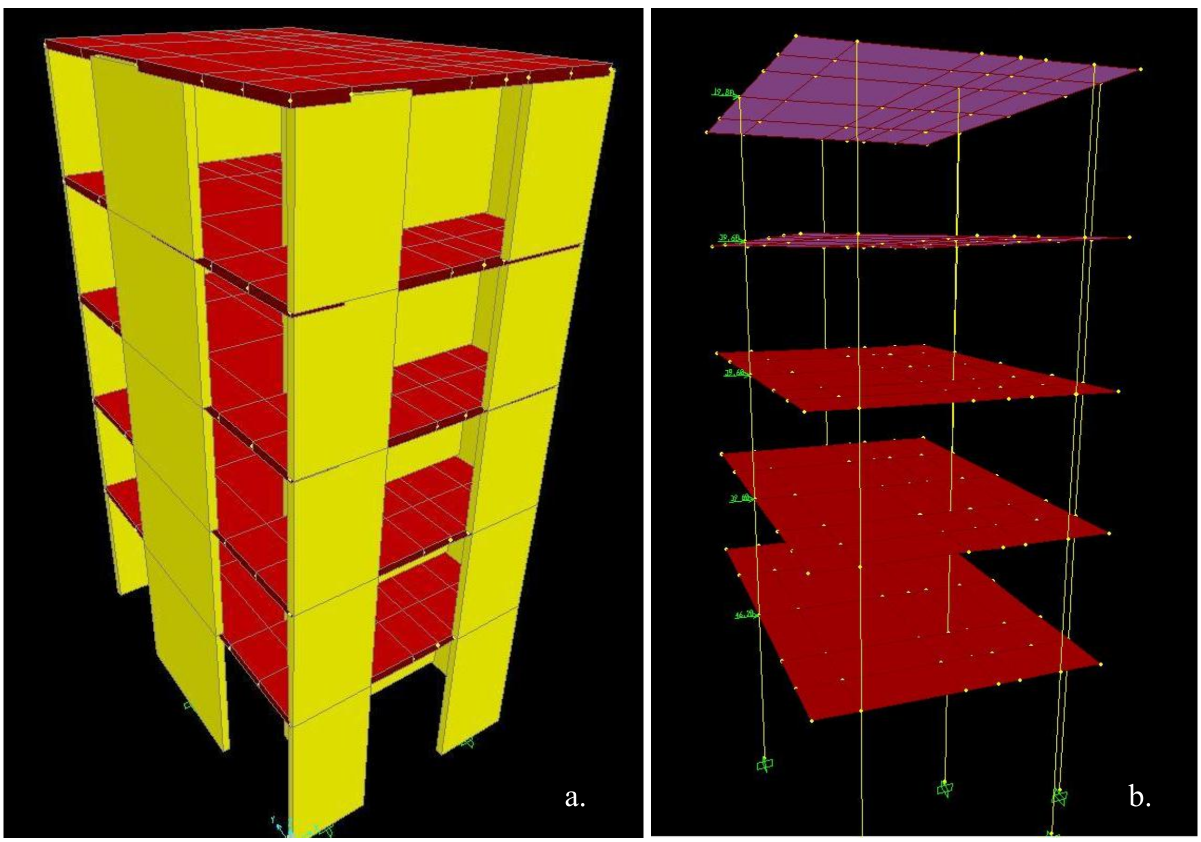

Figure 3: a) Finite Element Model of the Five Storey Building Using Beam Elements b) Lateral Wind loading assigned to the floor levels

Beam elements were selected to model the shear walls because in SAP2000 the output for beam elements is in the form of shear force diagrams, bending moment diagrams and reactions at the supports reducing the time required to obtain the required design forces. Figure 4 illustrates the shear force diagram for shear wall C generated by the model in SAP2000. In Figure 5, the bending moment diagram for shear wall C is illustrated.

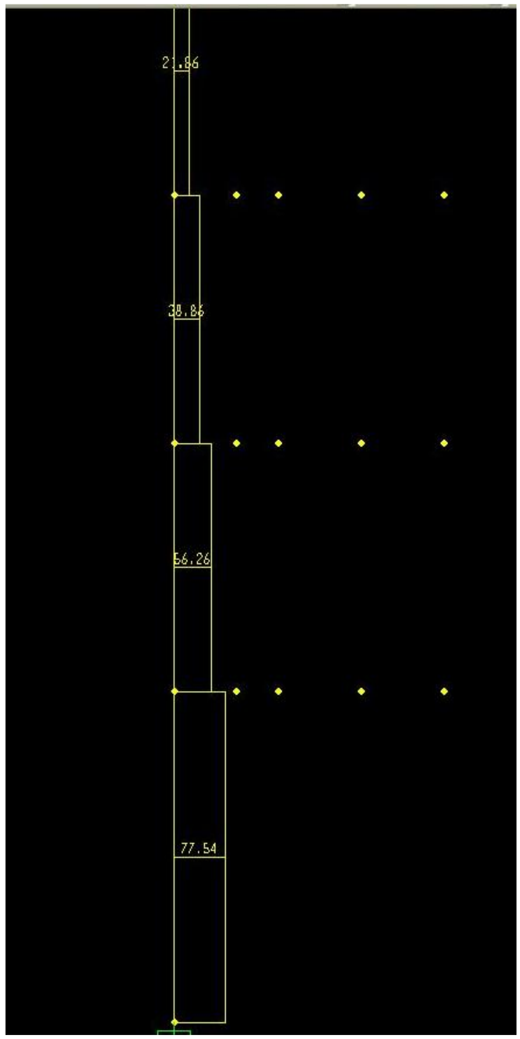

Figure 4: Shear Force Diagram with Beam Elements for Shear Wall C

Table 5: Shear Forces from the Wind Load obtained by SAP2000

Wall / Floor	A_1 (kN)	A_2 (kN)	B (kN)	C (kN)
Base	11.9	12.1	81.2	77.8
1^{st}	11.9	12.1	81.2	77.8
2^{nd}	6.01	6.06	64.6	58.2
3^{rd}	4.44	4.64	44.9	40.9
4^{th}	3.07	3.25	25.3	23.7
roof	1.38	1.51	5.57	6.52

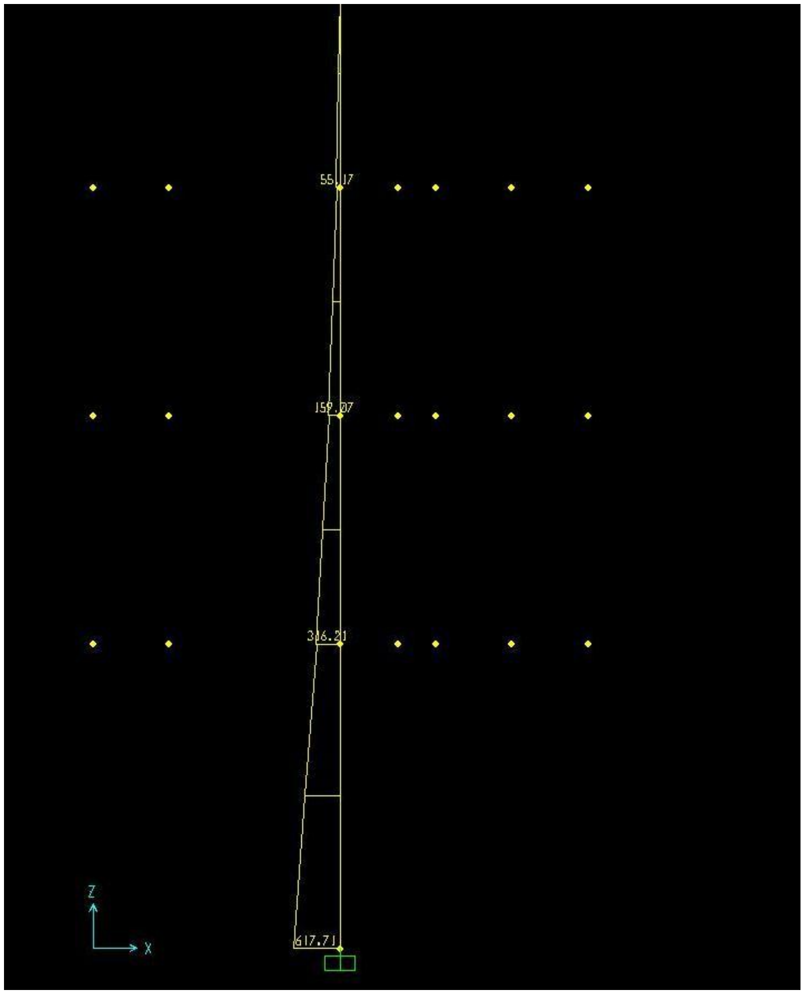

Figure 5: Bending Moment Diagram with Beam Elements for Shear Wall C

Table 6: Bending Moments from the Wind Load obtained by SAP 2000

Floor \ Wall	A_1 (kN-m)	A_2 (kN-m)	B (kN-m)	C (kN-m)
Base	70.1	70.1	682	688
1^{st}	22.6	22.6	366	378
2^{nd}	8.10	8.10	185	206
3^{rd}	-1.01	-1.01	64.8	85.8
4^{th}	-4.60	-4.60	3.1	17.2
roof	-5.20	-5.20	-13.6	-2.40

For comparison purposes, shell elements were used to model the walls. Once again the walls were modeled using nominal 20 cm block and the same material properties were used. Figure 6 illustrates the model.

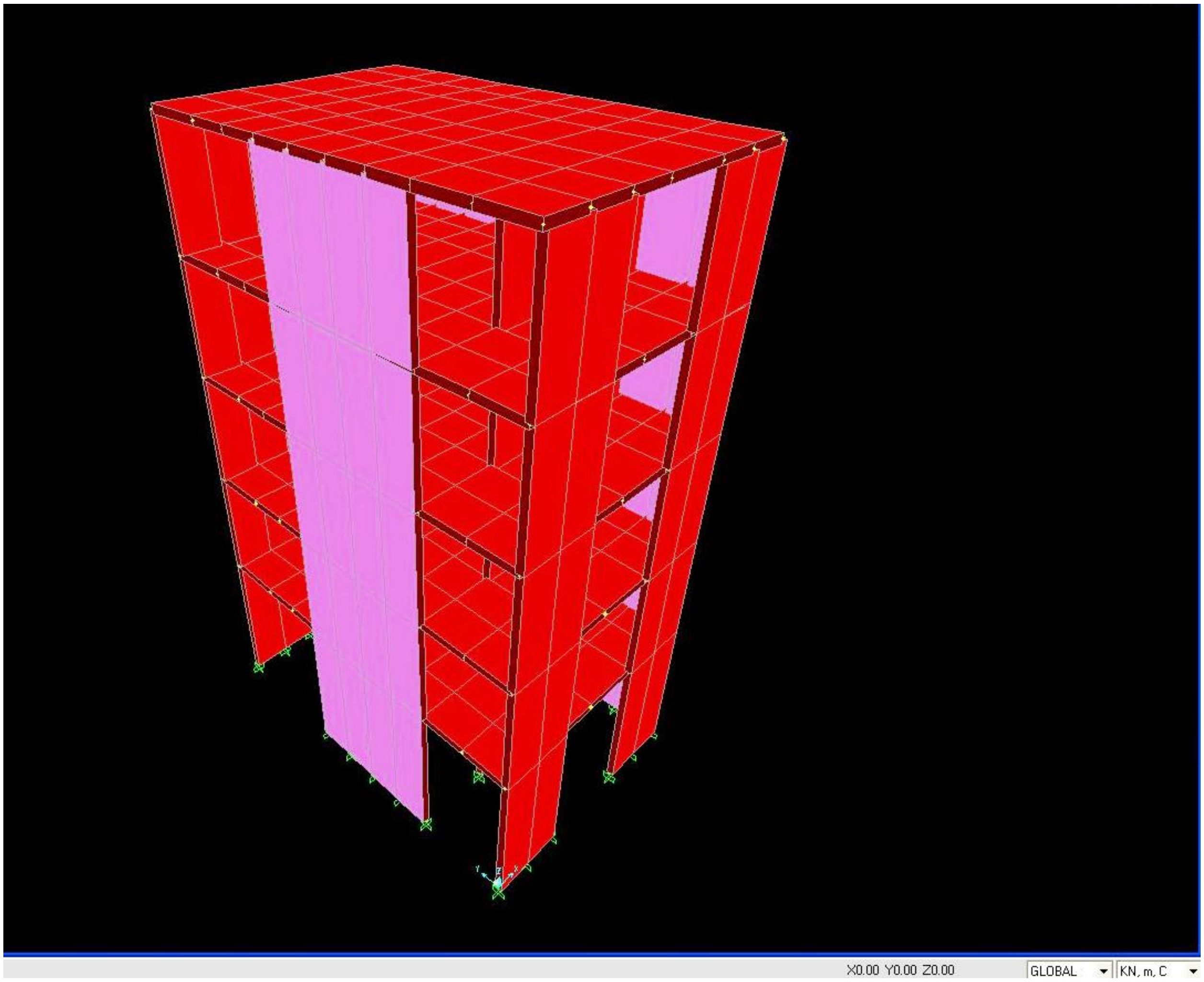

Figure 6: Finite Element Model of the Five Storey Building Using Shell Elements

The design forces on the shear walls were not as easily obtained when the shear walls were modeled with shell elements. At each floor level, the nodal forces from the shell elements above and below the floor level had to be exported to EXCEL and manipulated. This required tracking of the node labels and the shell labels corresponding to the wall under investigation, and then re-ordering the exported data in EXCEL for summation to arrive at the total shear and moment generated at the wall base. After the shear and moment forces were obtained for wall A at floor 1, this labour intensive post-processing was abandoned without further investigation. It is mentioned here only to note that when using SAP2000, shell elements should be avoided in favour of beam elements from which the design forces are much more easily obtained. The SAP 2000 model using beam elements took only three (3) hours to create and obtain the design forces of the shear walls from a user who would classify their proficiency with SAP2000 as proficient but not advanced.

DISCUSSION

The finite element method appeared to be a quicker and more accurate than the traditional method for distributing the lateral forces from the wind to the shear walls in the sample building. The traditional method did not account for the minor axis shear walls absorbing small amounts of shear force and bending moment, the absorption of a portion of the shear force and base moment by the floor slabs or the effects of the building self-weight. For simplicity of calculation, the traditional method did not account for torsional forces on the shear walls resulting from the asymmetric floor plan creating a centre of rigidity that was not coincident with the centre of gravity. Conversely these items were all accounted for in the finite element model

As a result, there were often large differences between the SAP2000 model and the traditional method as can be seen by comparing Table 3 with Table 5 and Table 4 with Table 6. The traditional method does however produce larger design forces and therefore conservative results. It was interesting to note that a comparison of the lateral wall deflections at the top of the structure (see Table 7) show that the assumption of the floor slabs behaving as a rigid diaphragm was not that accurate. Although the deflections are small, the deflections of Wall A1 and A2 are 47.4% greater than the deflection of Wall C. So it appears that the true nature of rigidity of the floor slabs is better modelled with SAP2000 than an assumption of rigidity.

Table 7: Lateral Deflections from the Wind Load obtained by SAP 2000

Wall	Location from base (m)	Lateral Deflection (mm)
A1	14	1.74
A2	14	1.74
B	14	1.60
C	14	1.18

Under the assumption of rigid diaphragm action the lateral deflections should be equal. This would also account for some of the discrepancies between the traditional method of calculation and SAP2000 results. One advantage of the traditional method was that the documentation generally required for use with the designers notes is automatically generated by EXCEL whereas the SAP2000 output must be manipulated (either exported to EXCEL and manipulated or copied by hand).

CONCLUSIONS

Using SAP2000 for distributing the lateral wind loads to the shear walls when modelled using beam elements appears to be a fast, efficient, and accurate method to obtain the shear forces for the five storey building in Figure 2. This method is easily adapted for more or less stories or change in floor plan, once all the beam elements had been defined, and accounted for self-weight, torsional effects and absorption of lateral forces by minor axis shear walls.

Although the traditional method was fairly straight forward, it overestimated the shear forces and bending moment forces, and in the simpler form of calculation used in the comparison, did not account for torsional effects. In addition to this it is less easily adapted for the addition or reduction of floors or addition or removal of shear walls. The traditional method was more labour intensive, especially when calculating the overturning moment at each floor level. For a building of the size and complexity of the example in Figure 2, SAP2000 appears to be the best method for lateral load distribution to the shear walls.

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