Modeling Effects on Forces in Shear Wall-Frame Structures*

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Abstract. Shear walls are added to a structural system to reduce lateral deformations in moment resisting frames and are designed to carry a major portion of lateral load induced by an earthquake. A small percentage error in the shear wall calculation will have a significant effect on the frame forces. The results show that even a slight difference in structural assumption, or modeling, results in significant differences. Some of these differences are beyond the values that are covered by safety factors for errors in modeling. The differences are more obvious in the upper stories. It is not recommended to overestimate shear wall stiffness, nor underestimate frame stiffness.

Keywords: *boundary beam; bending deformation; equivalent frame; free-standing shear wall; shear deformation; shear distribution.*

1 Introduction

This paper is based on shear wall-frame interaction calculations that were discussed by Surahman [1]. Due to their rigidities, shear walls take most of the lateral loads exerted on a building during the earthquake. A small error in force calculations on the shear wall results in higher percentage errors in the frame forces calculations. More in-depth discussions are elaborated upon in this paper.

Three different shear wall models are discussed. The first is the free-standing shear wall, which is corrected by resisting moments from the boundary beams. The second is the equivalent frame model, where the shear wall is treated and modeled as a column. At every story, there is a rigid beam connecting the center of the shear wall and the boundary beam. To account for shear deformation, the bottom of the column is connected to the joint by a very short horizontal beam. The third is the more rigorous finite element (shell element) model. The effects of shear and axial deformations are also considered in this paper.

Two boundary beam models are considered. The first is a rigid beam that can provide a resisting moment to the shear wall, and the second is a simple beam (hinged beam) that does not provide a resisting moment. Three different

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structures are evaluated. Structure A is a five-storied shear wall-frame structure with hinged boundary beams, whereas structures B and C are four-storied and ten-storied shear wall-frame structures, respectively, both with rigid boundary beams.

2 Various Calculation Methods

The simplest method is the manual calculation developed by Muto [2], assuming that the resisting moments from the boundary beams are small compared to the moments carried by the shear wall. This method is derived from a free-standing shear wall that is subjected to horizontal forces, which undergo bending and shear deformations that induce force to the adjacent frames. Detailed calculation formulations are given in [1]. Manual calculations by Muto [2] were further developed by Khan and Sbarounis [3].

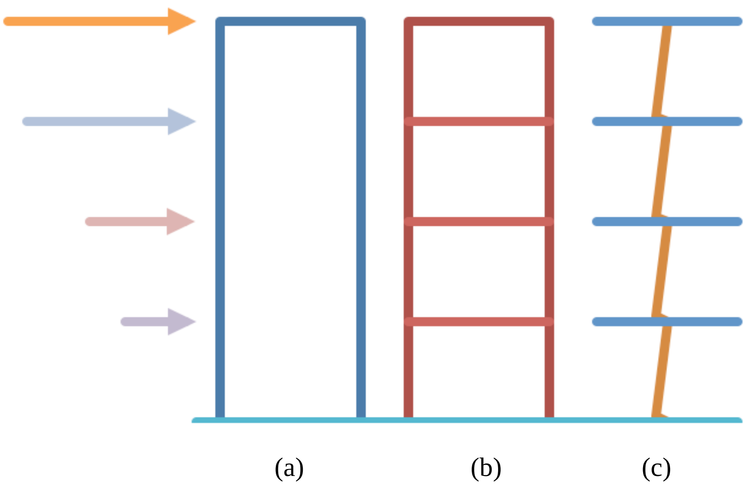


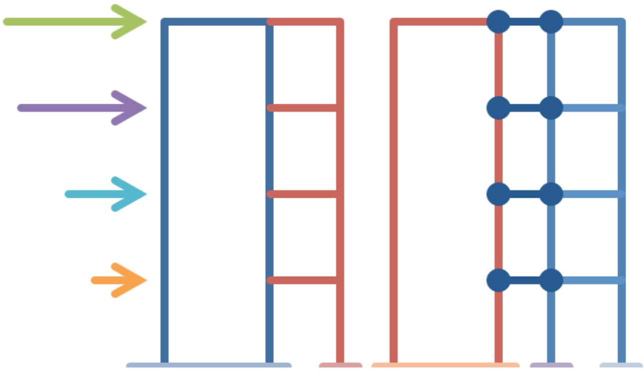
Figure 1 (a) Free-standing, (b) Shell Elements and (c) Equivalent Frame Models [1].

The second method is the matrix method using the equivalent frame model. In this method the shear wall panel is modeled as a column in the center line, with a rigid beam connecting the shear wall center line and the boundary beam at the edge of the shear wall, as shown in Figure 1(c). To accommodate for the shear deformation of the wall panel, the column is connected at the bottom to a short beam similar to the one connecting the shear wall centerline and the boundary beam, but with an area such that the axial stiffness is equal to the shear stiffness of the actual wall [1]. The calculation steps then follows the ordinary matrix structural analysis as given amongst others by Holzer [4].

The third method is the use of finite element models (Figure 1(b)), where in this paper the calculation are executed by the SAP and ETABS programs.

3 Result Comparisons

Structure A is a five-storied shear wall-frame structure with hinged boundary beams, as shown in Figure 2(b). This is analyzed by using the manual calculations for shear wall frame interaction using free-standing shear wall model (Figure 1(a)), and the matrix method using equivalent frame model (Figure 1(c)). In this example, the shear deformations are neglected in order to compare results given by the manual and the matrix methods [1] with the results compiled by Gutierez [5]: the approximate method by Khan and Sbarounis [3,5], story element method by Wang [6,5], and exact matrix and simplified methods as described by Gutierez [5].



(a) (b)

Figure 2 (a) Rigid and (b) Hinged Boundary Beam Models [1].

Structure B is a four-storied shear wall-frame structure with rigid boundary beams, as shown in Figure 2(a). It is calculated manually, based on the shear wall, as shown in Figure 1(a), and the matrix method where the shear wall is modeled with an equivalent frame shown in Figure 1(c). The structural dimensions are given in [1]. The calculations are compared with the results of commercially available computer programs, such as SAP and ETABS using finite element analyses and where the shear walls are modeled as shell elements shown in Figure 1(b). The finite element analyses were carried out by Gitomarsono [7].

Structure C is a ten-storied shear wall-frame structure with rigid boundary beams, shown in Figure 2(a). The comparison is between the use of the manual calculation for the free-standing shear wall model (Figure 1(a)) and the matrix method for the equivalent frame model (Figure 1(c)). The structural dimensions are given in [1 and 5]. Similar studies on ten-storied shear wall–frame structures are also carried out by Zai [8].

4 Results and Discussions

The results for Structure A are given in Tables 1-6. Table 1 shows horizontal deformations of shear wall-frame interaction. It is observed that there are some discrepancies: The manual calculation [1] should have been the same with the Khan-Sbarounis method [5], which is not the case here. Likewise, the matrix method [1] should have also been the same as the matrix exact method [5]. Whereas the manual calculation clearly showed that, where the axial deformations are restrained, results in a stiffer structure are indicated by smaller horizontal deformations compared to the matrix method [1], and this is not the case when comparing the exact and Khan-Sbarounis methods [5]. Nothing can be concluded from the Wang and simple methods [5] since they are just simplified methods analyses. Tables 1, 2 and 3 also show that structural rigidity depends on frame rigidity, which is shown by the smaller deflections and larger frame shear forces compared to the manual and matrix methods [1]. This case is not in agreement with the results derived from the exact, Wang, Khan and Sbarounis, and Simple methods, as compiled by Gutierez [5]. There are possibilities that there are some calculation or modeling differences that are not clearly explained. In some cases, the differences among frame shear forces exceed the commonly assumed modeling error of ten percent, whereas some of them result in sign reversals, particularly in the upper stories of the structure.

Table 1 Horizontal Deformation [m] for Structure A [1].

Story	Manual	Matrix	Exact	Wang	Khan	Simple
1	0.00175	0.00187	0.00167	0.00180	0.00167	0.00166
2	0.00605	0.00652	0.00559	0.00623	0.00598	0.00597
3	0.01170	0.01273	0.01175	0.01208	0.01178	0.01173
4	0.01785	0.01957	0.01807	0.01850	0.01814	0.01811
5	0.02402	0.02650	0.02447	0.02447	0.02463	0.02461

Tables 1 and 2 show that while the deformations do not display significant differences, the differences in the frame forces are quite significant. Table 3 shows that at the top story the shear force differences are significant percentagewise. To explore the validity of manual calculation by restraining the axial shortening of the column, a comparison with a longer frame span is carried out, as shown in Table 4. It is shown that when the frame span is doubled while doubling the beam moment of inertia to keep the beam stiffness the same, the matrix analysis results are getting closer to the results of manual calculation, and that of the frame with restrained axial deformations. By increasing the frame span as shown in Table 5, the resulting axial forces of the columns decrease significantly, thus reducing column axial deformation, making the differences between the manual calculation and the matrix analysis smaller. This means that manual calculation is more suitable for frames with longer beam spans. However, the manual calculation and matrix analysis of the frame with restrained axial deformations, practically give similar results regardless of the span length.

Table 2 Shear Forces Carried by Frame [kN] for Structure A [1].

Story	Manual	Matrix	Exact	Wang	Khan	Simple
1	151	142	131	133	192	189
2	339	308	327	327	332	331
3	434	388	413	432	429	425
4	447	394	419	473	469	470
5	564	484	559	481	477	480

Table 3 Shear Forces Carried by Shear Wall [kN] for Structure A [1].

Story	Manual	Matrix	Exact	Wang	Khan	Simple
1	1349	1358	1369	1367	1308	1311
2	1061	1092	1073	1073	1068	1069
3	766	812	787	768	771	775
4	453	505	481	427	431	430
5	-64	15	-59	19	23	20

Table 4 The Effects of Span Length on Horizontal Deformations and Shear Distributions for Structure A (Matrix Method).

Story	Standard Frame			Long Spanned Frame			Restrained Deformation		
	δ_h [m]	Q_w [kN]	Q_f [kN]	δ_h [m]	Q_w [kN]	Q_f [kN]	δ_h [m]	Q_w [kN]	Q_f [kN]
1	0.00187	1358	142	0.00179	1350	150	0.00175	1347	153
2	0.00652	1092	308	0.00619	1070	330	0.00605	1061	339
3	0.01273	812	388	0.01199	779	421	0.01171	766	434
4	0.01957	505	394	0.01833	465	435	0.01786	451	449
5	0.02650	15	484	0.02469	-40	540	0.02403	-61	561

Table 5 The Effects of Span Length on Beam Moments and Shears, and Column Axial Deformations for Structure A (Manual and Matrix Methods).

	Manual Moment [kN-m]	Standard Frame			Longer Spanned Frame			Restrained Moment [kN- m]
		Moment [kN-m]	Shear [kN]	Axial Def. [m]	Moment [kN-m]	Shear [kN]	Axial Def. [m]	
1	34878	31711	204	0.0028	34050	110	0.0015	34929
2	56310	50351	324	0.0052	54654	176	0.0028	56285
3	65644	57872	372	0.0070	65367	204	0.0039	65726
4	71436	61865	398	0.0082	68743	221	0.0045	71370
5	45921	39335	242	0.0086	43960	141	0.0048	45736

When the boundary beams are rigid, as shown in Figure 2(a), the shear wall-frame structure becomes significantly stiffer, as shown in Table 6, as compared to the one shown in Table 4. The force distribution between the shear wall and the frame also changes significantly. When shear wall shear deformations are instead considered, the shear wall–frame structure becomes more flexible and the frame columns carry larger shear forces than was previously assumed, with the pure bending only shear wall. Both of these simplified assumptions result in non-conservative frame forces.

Table 6 The Effects of Boundary Beam and Shear Deformation on Horizontal Deformation and Shear Distribution for Structure A (Matrix Method).

Story	Rigid Boundary Beam			Considering Shear Deformation		
	δ_h [m]	Q_w [kN]	Q_f [kN]	δ_h [m]	Q_w [kN]	Q_f [kN]
1	0.00125	1283	217	0.00244	1255	246
2	0.00429	1296	104	0.00723	1030	370
3	0.00819	832	368	0.01319	743	457
4	0.01235	492	408	0.01946	440	460
5	0.01643	-37	537	0.02548	-45	545

Table 7 Horizontal Deformations [m] For Structure B [1].

Story	Manual	Matrix	SAP	ETABS
1	0.00130	0.00131	0.00166	0.00112
2	0.00393	0.00395	0.00459	0.00354
3	0.00721	0.00726	0.00809	0.00662
4	0.01064	0.01064	0.01161	0.00990

The results for Structure B are shown in Tables 7-9, and 10. Table 7 shows that the manual calculation and the matrix method provide almost similar deformation values, particularly when compared to the results from SAP and ETABS programs, that were carried out by Gitomarsono [7]. The differences between SAP and ETABS are very significant, representing both extremes, despite using the same shell element models to represent the shear wall. To use these commercial programs a proper understanding of finite element modeling is necessary. Table 8 shows that the resulting forces are relatively closer to each other, as compared to their respective deformation results. In the ETABS software, the forces on the shell element are expressed through in-plane stresses. To obtain the shear forces, it is more accurate to just calculate from the horizontal equilibrium than simply taking the average of the stresses at the element nodes, as shown on the right hand side of Table 8. As close as the results for the shear wall are, it is not exactly the case for the frame forces as shown in Table 8 for the column base shear forces. In this case, SAP and ETABS also represent both extremes. Table 9 and 10 show the moments of the beams at the near end (at the shear wall) and at the far end (the opposite end). The differences are more obvious when measured in percentages. Table 10 shows significant differences between the SAP and ETABS results despite the use of the same shear wall models. These differences are clearly visible, as illustrated in Figure 3, where the column bottom moments are calculated. It is shown that the ETABS program results deviate significantly from those produced by other methods.

Table 8 Shear Forces for Four Story Model [kN] [1].

Story	Manual		Matrix		SAP		ETABS		
							Column	Wall	
	Col.	Wall	Col.	Wall	Col.	Wall		Stress	Equil.
1	9	1018	9	1018	12	1015	7	945	1019
2	12	910	11	911	11	911	11	870	910
3	13	699	14	701	13	701	12	660	701
4	22	377	21	381	20	381	21	360	380

Table 9 Beam Moments [kN-m] For Structure B, Near End.

Story	Manual	Matrix	SAP	ETABS
1	33	33	33	32
2	52	51	50	49
3	61	60	58	58
4	58	57	55	55

Table 10 Beam Moments [kN-m] For Structure B, Far End.

Story	Manual	Matrix	SAP	ETABS
1	34	33	35	28
2	50	49	49	43
3	60	59	57	51
4	51	50	48	44

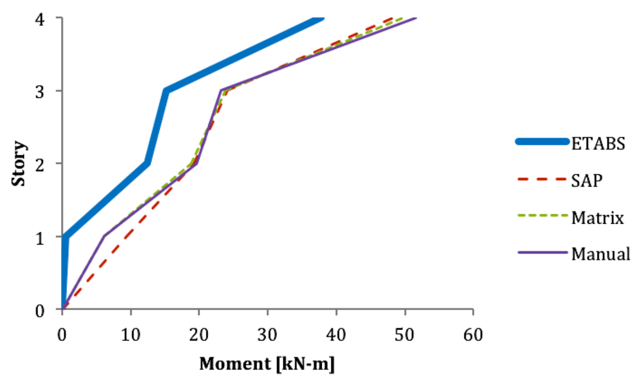


Figure 1 Bottom Column Moments.

The results from Structure C show that due to the axial shortening of the members, particularly columns, the difference between the manual calculation and the matrix method is significantly visible. The difference increases as the story increases as shown in Table 11. This is due to the cumulative effect of column axial shortening from bottom to the top story. Whereas the differences are negligible at the first story, at upper stories the differences become more significant. However, the design is determined by the bottom story, where the forces are critical.

Table 11 Deformations and Shear Forces for Structure C [1].

Story	Manual			Matrix		
	δ_h [m]	Q_w [kN]	Q_f [kN]	δ_h [m]	Q_w [kN]	Q_f [kN]
1	0.00235	1911	89	0.00243	1911	89
2	0.00645	1588	212	0.00678	1616	184
3	0.01132	1432	168	0.01210	1429	171
4	0.01667	1150	250	0.01817	1236	164
5	0.02249	894	306	0.02503	1032	168
6	0.02835	694	306	0.03220	823	177
7	0.03405	522	278	0.03938	632	168
8	0.03950	388	212	0.04647	467	133
9	0.04447	185	215	0.05319	276	124
10	0.04902	5	195	0.05953	50	150

5 Conclusions and Recommendations

According to the above discussions the following conclusions can be derived:

1. The manual calculation, which neglects axial shortening of the member, results in a more conservative frame force, can thus be used for design purposes without significantly sacrificing accuracy. As the beam spans become larger, the result differences decrease.
2. Neglecting axial column deformations mainly affect the upper part of the structure on the conservative side, thus it is reasonably acceptable for design purposes.
3. Ignoring moment resisting capabilities of boundary beams result in significantly less conservative frame forces. It is therefore not recommended for design purposes.
4. Ignoring the shear deformations of the walls results in significantly less conservative frame forces. It is therefore not recommended for design purposes.
5. It is not recommended to overestimate shear wall rigidity or underestimate frame rigidity.
6. The results show that there is a need for improving the formulation of finite element models for shear walls that are subjected to in-plane bending and used in the shear wall-frame interaction analysis.

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