Technical Note:

Effect of Shear Wall Cracking on Soft Storey Phenomenon

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Abstract: *According to the Iranian code of practice for seismic resistant design of buildings, soft storey phenomenon happens in a storey when the lateral stiffness of the storey is lower than 70% of the stiffness of the upper storey, or if it is lower than 80% of the average stiffness of the three upper stories. In the combined structural systems containing moment frames and shear walls, it is possible that the shear walls of the lower stories crack; however, this cracking may not occur in the upper stories. The main objective of this research is to investigate the possibility of having soft storey phenomenon in the storey, which is bellow the uncracked walls. If the tension stresses of shear walls obtained from ultimate load combinations exceed the rupture modulus of concrete, the walls are assumed to be cracked. For calculating the tension stresses of shear walls in different conditions, 10 concrete structures containing 15 stories were studied. Each of the structures was investigated according to the obligations of Iranian, Canadian, and American concrete building codes. Five different compressive strengths of 30, 40, 50, 60, and 70 MPa were assumed for the concrete of the structures. In other words, 150 computerized analyses were conducted in this research. In each analysis, 5 load combinations were imposed to the models. It means, the tension stresses of the shear walls in each storey, were calculated 750 times. The average wall to total stiffness ratios of the buildings were from 0.49 to 0.95, which was quite a wide range. The final conclusion was that the soft storey phenomenon did not happen in any of the structures investigated in this research.*

Keywords: *concrete, shear wall, rupture modulus, soft storey, crack, compressive strength.*

1. Introduction

Reinforced concrete shear walls are frequently used to improve the lateral stiffness of buildings for resisting horizontal forces such as wind and seismic loads. For seismic design, the main objective is to insure sufficient stiffness of shear walls at a given shear stress level, and to determine design parameters affecting the strength and stiffness of the walls such as cracking. Therefore, many experimental and analytical investigations for predicting the stiffness and nonlinear behaviour of reinforced concrete shear walls have been executed [1-3].

However, due to the complications in the modeling of reinforced concrete shear walls after cracking of concrete, numerical models for finite element analyses, which can provide accurate simulations of cracking behaviour under severe loading conditions such as seismic loadings are not regularly used [4]. In this context, reinforced concrete shear walls under cyclic loadings on the basis of a fixed crack model were analyzed by Sittipunt and Wood [3]. For modeling the concrete, independent hysteresis models for shear and normal stresses were suggested to accommodate the distortions, and special four-node quadrilateral elements incorporated with steel truss elements at each corner node were employed. Moreover, in another investigation [5], reinforced concrete shear walls were analyzed by means of the fixed crack model. Similar to the previous numerical approach by Sittipunt and Wood [3], two independent stress-strain equations for the shear and normal stress components were used. Because the application of these crack models is straightforward, they are commonly accepted in numerical modeling of concrete cracking. On the other hand, when a reinforced concrete shear wall is subjected to seismic loads, the fixed crack model can not explain the rotation of cracks stimulated by the interface shear beside the cracking surface [4].

Because the cracking of concrete elements during an earthquake is a complex destructive phenomenon, the Iranian code of practice for seismic resistant design of buildings [6], standard

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No. 2800-05, and the Iranian concrete building code [7] have introduced a simple suggestion for considering the cracking of elements in the analysis of structures. In fact, according to standard No. 2800-05 [6] and the Iranian concrete building code [7], the moment of inertia of cracked sections should be used in the analysis of reinforced concrete structures. These references suggest utilizing the values of 0.35Ig and 0.7Ig for the moments of the inertia of the beams and columns respectively, where Ig is the total moment of inertia of the sections. The suggestions of the references above for the moments of the inertia of cracked and uncracked shear walls are 0.35Ig and 0.7Ig respectively. It is worth noting that only if the maximum tensile stress of a shear wall in ultimate load combinations exceeds the flexural tensile strength of concrete, which is called rupture modulus, the shear wall is assumed to be cracked. The American [8] and Canadian [9] building codes have presented the same method for locating the cracked shear walls.

According standard No. 2800-05 [6], soft storey phenomenon happens in a storey when the lateral stiffness of the storey is lower than 70% of the stiffness of the upper storey, or if it is lower than 80% of the average stiffness of the three upper stories. In the combined structural systems containing moment frames and shear walls, it is possible that the shear walls of the lower stories crack; however, it may not occur in the upper stories. The main objective of this paper is to investigate the possibility of having soft storey phenomenon in the storey, which is bellow the uncracked shear walls.

2. Analytical Program

The main objective of the analytical part of the research is to investigate the possibility of having soft storey phenomenon in the storey, which is bellow the uncracked shear walls.

2.1. The Investigated Concrete Structures

In this research, 10 reinforced concrete structures were investigated, and each of these buildings contained 15 stories. The typical plan of the structures can be seen in Fig. 1. Although

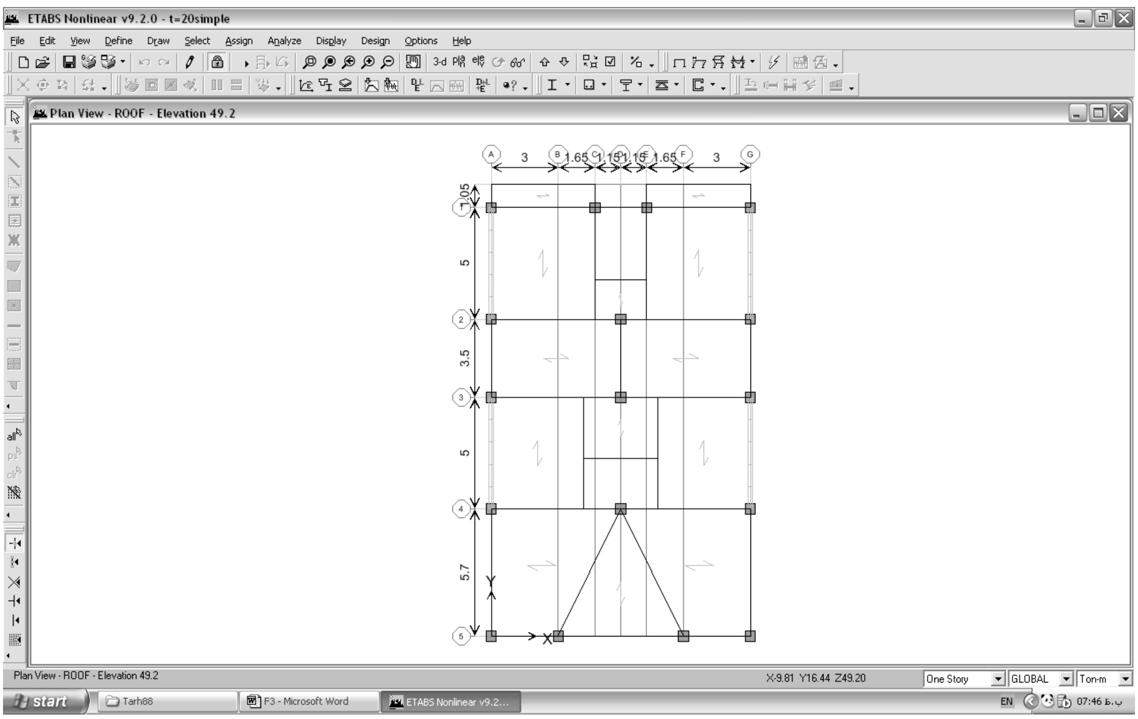

Fig. 1. Typical plan of the investigated structures

Table 1. Dimensions of the structural elements

Storey	Beams and Columns (cm^2)	Thickness of Shear Walls (cm)				
		Structures a_1 & a_2	Structures b_1 & b_2	Structures c_1 & c_2	Structures d_1 & d_2	Structures e_1 & e_2
12 to 15	45 x 45	25	30	35	40	45
8 to 11	55 x 55	35	40	45	45	50
4 to 7	65 x 65	45	50	55	50	55
1 to 3	75 x 75	55	60	65	55	60

the appearances of the plans were the same, the thicknesses of the shear walls were dissimilar. Therefore, the total stiffness, the wall to total stiffness ratio, and the wall to frame stiffness ratio of the structures were different. In other words, the structures of these buildings were quite diverse. The similarity of the appearances of the investigated buildings allowed the researcher to use constant equivalent lateral seismic loads; consequently, the effect of stiffness of the buildings on their seismic performance could be observed clearly.

The dimensions of different structural elements of the investigated structures can be seen in Table 1. In structures type a1, b1, c1, d1 and e1 of this table, the shear walls of the axes A and G are simple shear walls; however, in structures type a2, b2, c2, d2 and e2, the concrete walls of the axes A and G are coupled shear walls, and very strong coupling beams have connected the two shear walls of each axe. The heights of all the coupling beams were 1.2 m and their thicknesses were similar to the ones of the connecting shear walls. The average wall to total stiffness ratios of the investigated structures are presented in Table 2. According to this table, the ratios above are from 0.49 to 0.95, which is quite a wide range.

2.2. The Utilized Load Combinations

In this research, the obligations and load combinations of the ACI 318-89(92) [10], Canadian concrete building code [9] and Iranian concrete building code [7] were of interest. Because the equivalent seismic loads were imposed in y direction, the load combinations of this direction were used as follows.

a) The Iranian concrete building code:

1.25D+1.5L; D+1.2L+1.2Ey; D+1.2L-1.2Ey; 0.85D+1.2Ey; 0.85D-1.2Ey

where D is dead load, L is live load, and Ey is seismic load in y direction.

b) The Canadian concrete building code:

Table 2. The average wall to total stiffness ratios of the investigated structures

Type of Structure	The average wall to total stiffness ratios
a_1	0.49
a_2	0.88
b_1	0.51
b_2	0.90
c_1	0.53
c_2	0.92
d_1	0.54
d_2	0.93
e_1	0.56
e_2	0.95

1.25D+1.5L; D+L+Ey; D+L-Ey; D+Ey; D-Ey

c) The American concrete building code:
1.4D+1.7L; 0.75(1.4D+1.7L+1.87Ey); 0.75(1.4D+1.7L-1.87Ey); 0.9D+1.43Ey; 0.9D-1.43Ey

2.3. The Applied Gravity and Lateral Loads

Filler joist flooring system was used for all the floors of the investigated structures. The dead load and live load of the roof were assumed to be 650 kgf/m^2 and 150 kgf/m^2 respectively. These values in other floors were 620 kgf/m^2 and 200 kgf/m^2 respectively. The density of concrete used in the structure of the buildings was 2500 kgf/m^3. To calculate the equivalent seismic loads of the buildings, the method presented by Standard 2800-05 [6] was utilized and it was assumed that the type of the ground for estimating the seismic loads was type 2 as follows.

A=0.35, H=49.2 m, T=0.05H0.75=0.93, I=1, R=8
B=2.5(0.5/T)0.67=1.65, C=(A.B.I)/R=0.072,
Weff=WD+WL=7914.3 tonV=C.Weff=569.83 ton,
Ft=0.07T.V=37.1 ton (additional lateral load applied at roof)

According to Standard 2800-05 [6], Eq. (1) is utilized for distributing the base shear on the center of masses of the floors. The distributed lateral loads in each floor and their heights from the base level can be seen in Table 3.

$$Fi=[(W_i.h_i) /(\sum W_i.h_i)].(V-F_t) \qquad (1)$$

where Wi is the effective weight of each floor and hi is the height of each floor from the base level.

3. Studying the Soft Storey Phenomenon

Some researches have been executed on the application of shear walls in structures recently [11-15]. In this part of the research, the possibility of having soft storey phenomenon according to the obligations and load combinations of the Iranian, Canadian, and American concrete building codes were studied. For this purpose, the cracked shear walls of the investigated structures were clarified. Then, the structures having cracked shear walls in bottom stories and uncracked shear walls in top stories were considered. The main objective of this part was to investigate the possibility of having soft storey phenomenon in the storey, which is bellow the uncracked walls. For this purpose, in each of the 15 storey structures, 5 different compressive strengths of 30, 40, 50, 60 and 70 MPa were assumed for concrete. It means, for the 10 investigated structures, 10x5=50 analyses have been done according to each of the three concrete building codes. In other words, the total number of analyses was 50x3=150. As explained in part 5, each analysis contained five load combinations, which means each shear wall has been studied for 150x5=750 times.

3.1. Concrete Specifications

According to the experimental results, the tensile strength of concrete has been assumed to be $0.63\sqrt{fc}$ in MPa. As explained earlier, this value is the cracking border of shear walls, which means the concrete shear walls do not crack when their maximum ultimate tensile stress is lower than the cracking border. Because the compressive strength of the concrete mixes used in the structures were 30, 40, 50, 60, and 70 MPa, the rupture modulus of the concrete mixtures became 34.6, 40, 44.7, 49, and 52.9 MPa respectively. In fact, the effect of concrete strength on soft storey phenomenon has been studied too.

3.2. Shear Wall Cracks

In Figs. 2 to 7, the stiffness of different stories before and after considering the concrete cracks in shear walls can be seen. As explained earlier, the average wall to total stiffness ratios of the structures were from 0.49 to 0.95. It is worth noting that the stiffnesses of the structures containing the concrete strengths of 30 and 70 MPa can be observed in these figures. Using the other compressive strengths of 40, 50 and 60

Table 3. Lateral loads of the investigated structures and their distances from the base level

Storey	Lateral load at the center of mass (kN)	Height from the Base Level (m)
15	866	49.2
14	553	45.9
13	504	42.6
12	465	39.3
11	491	36
10	469	32.7
9	421	29.4
8	371	26.1
7	370	22.8
6	329	19.5
5	274	16.2
4	218	12.9
3	184	9.6
2	125	6.3
1	59	3

MPa did not change the total shape of the graphs, and the results were between the ones obtained from 30 and 70 MPa concrete mixtures.

3.3. Simple Shear Walls

In initial graphs of Figs. 2 to 4, all the walls were assumed to be uncracked, and the compressive strength of concrete was 30 MPa. The next graphs show the stiffness of the structures after considering the cracking of shear walls and the compressive strength of concrete. According to this figure, the soft storey phenomenon did not happen in any of the investigated structures. It should be mentioned that the cracking of lower floor shear walls decreased the total stiffnesses of these floors. Also it is clear that the stiffness values of the structures containing 70 MPa concrete after considering the cracking of shear walls are similar to that of the structures containing 30 MPa concrete before considering the cracking above. In other words, the cracking of the structural elements considerably affect the analytical results and can not be neglected.

3.4. Coupled Shear Walls

In initial graphs of Figs. 5 to 7, all the shear walls and the coupling beams were assumed to be uncracked, and the compressive strength of concrete was 30 MPa. The next graphs show the stiffness of the structures after considering the cracking of the coupling beams and the compressive strength of concrete. It is worth noting that only the shear walls of the first and second floors cracked in the worst conditions; however, almost all the coupling beams cracked in all conditions. According to this figure, the soft storey phenomenon did not happen in any of the investigated structures. It should be mentioned that the cracking of coupling beams decreased the total stiffnesses of the floors. Also it is clear that the stiffness values of the structures containing 70 MPa concrete after cracking of the coupling beams were more than that of the structures containing 30

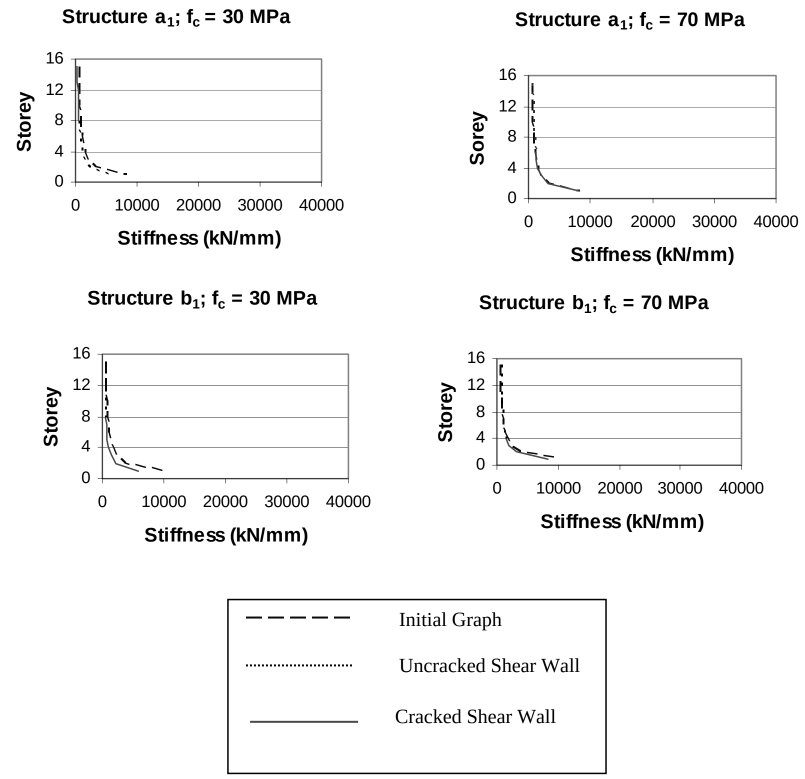

Fig. 2. Stiffness of the structures including simple shear walls and the obligations of the Iranian code

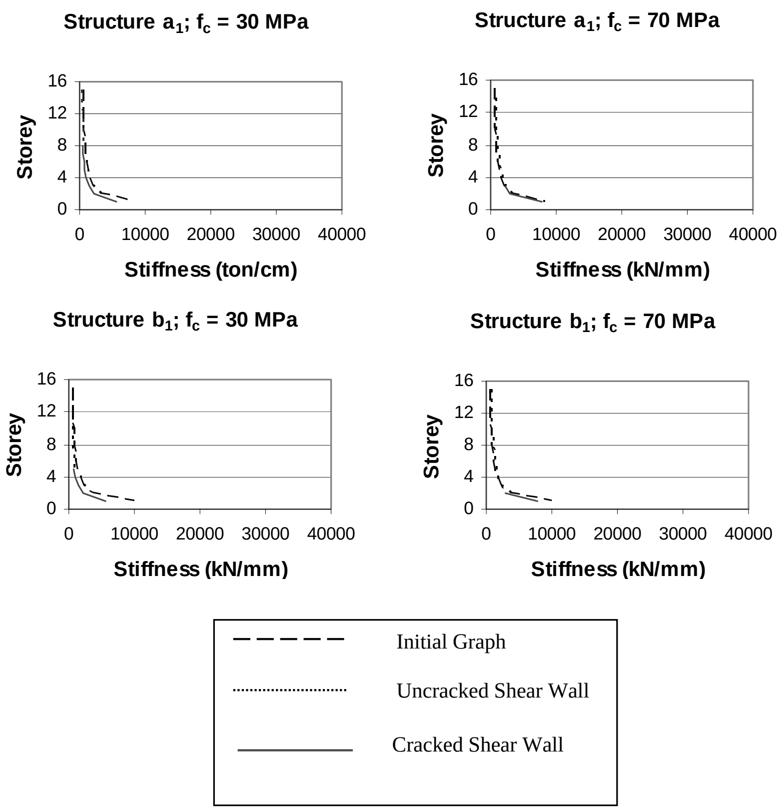

Fig. 3. Stiffness of the structures including simple shear walls and the obligations of the Canadian code

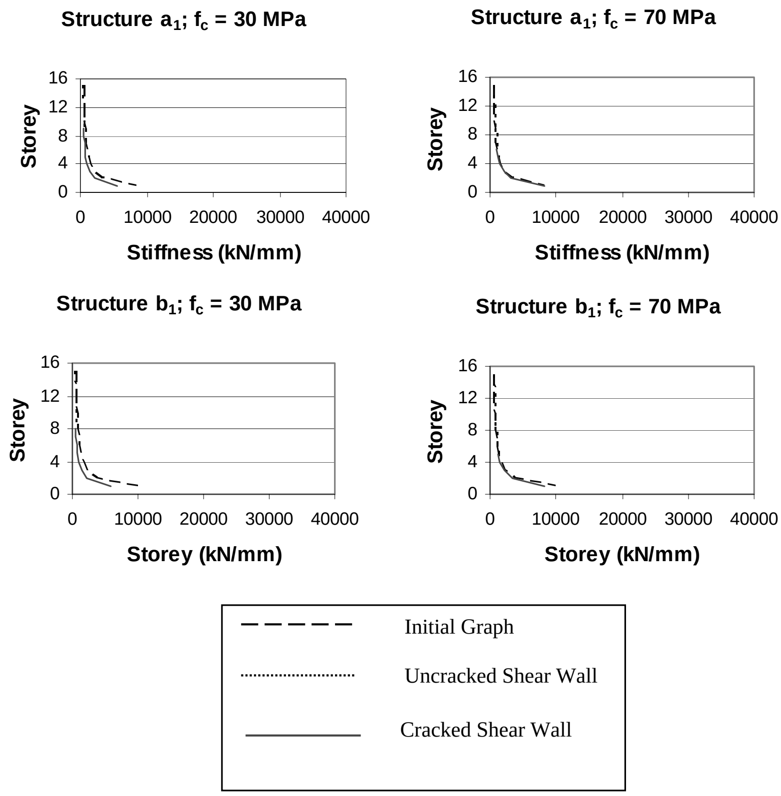

Fig. 4. Stiffness of the structures including simple shear walls and the obligations of the American code

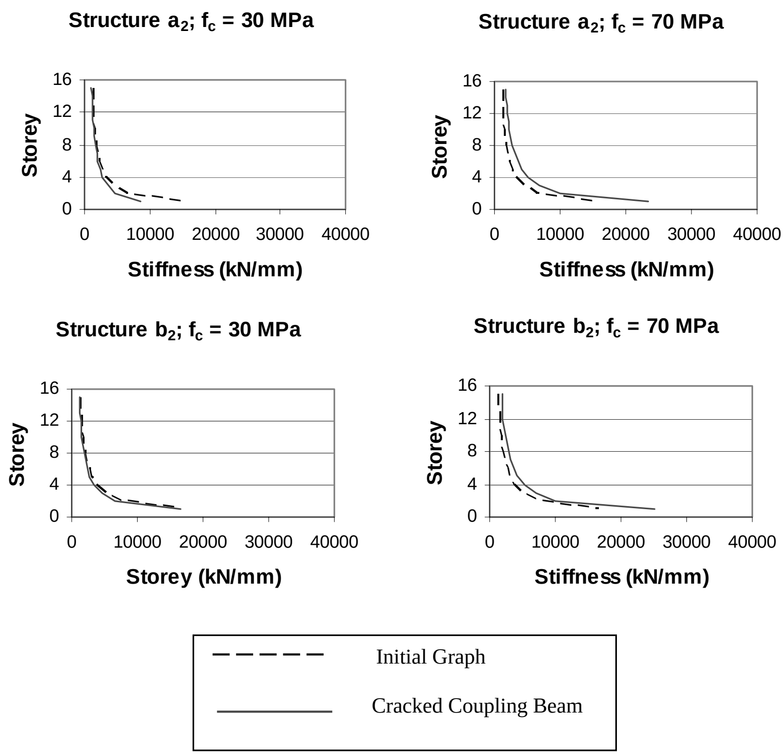

Fig. 5. Stiffness of the structures including coupled shear walls and the obligations of the Iranian code

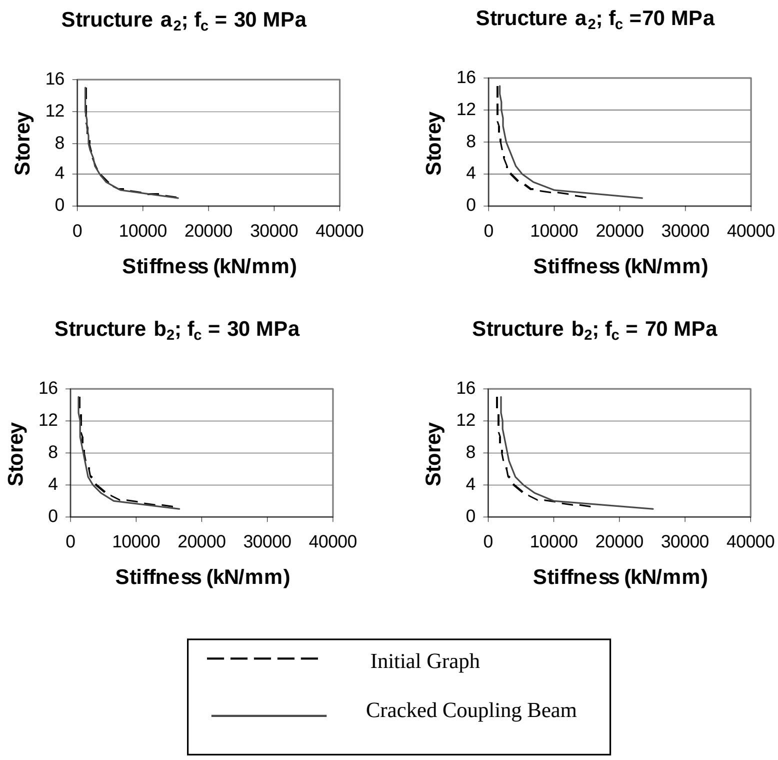

Fig. 6. Stiffness of the structures including coupled shear walls and the obligations of the Canadian code

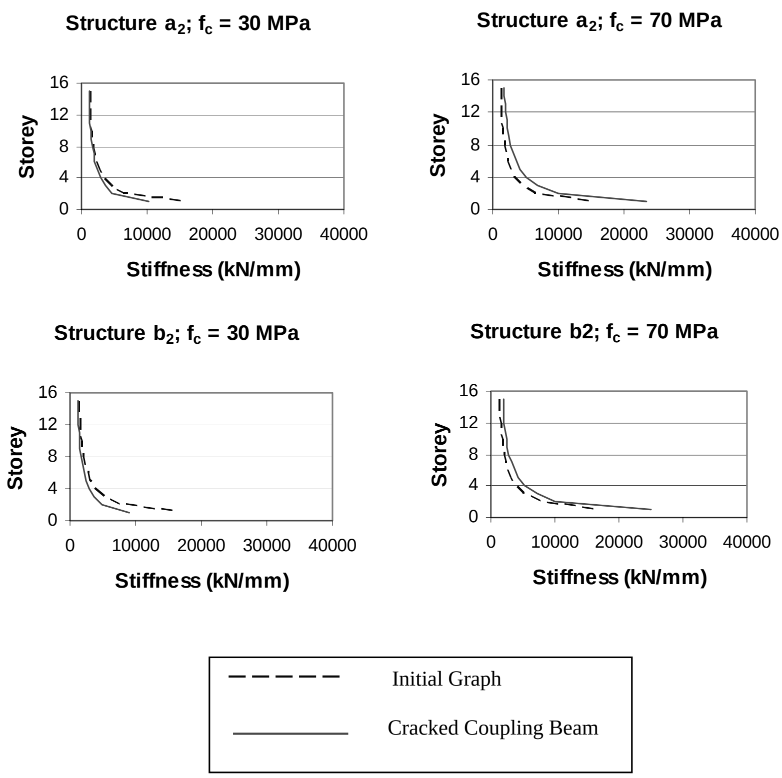

Fig. 7. Stiffness of the structures including coupled shear walls and the obligations of the American code

MPa concrete before considering the cracking of the beams. In other words, the compressive strength of concrete is more effective in coupled shear walls than in simple ones.

4. Conclusions

From the results presented in this paper the main conclusions are:

- Soft storey phenomenon did not happen in any of the investigated structures. The average wall to total stiffness ratios of these structures covered quite a wide range, which was from 0.49 to 0.95.
- In simple shear walls, the stiffness values of the structures containing 70 MPa concrete after considering the cracking of the shear walls were similar to that of the structures containing 30 MPa concrete before taking into account the cracking of the walls. In other words, the cracking of the structural elements affect the analytical results considerably and can not be neglected.
- Similar to ordinary concrete beams, almost all the coupling beams of coupled shear walls cracked in all load combinations containing seismic loads.
- In coupled shear walls, the stiffness values of the structures containing 70 MPa concrete after considering the cracking of the coupling beams were more than that of the structures containing 30 MPa concrete before taking into account the cracking of the beams. In other words, the compressive strength of concrete was more effective in the coupled shear walls than in the simple ones.

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