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The Effect of Cracking on Stiffness of Shear Walls under Lateral Loads

Anas M. Fares

***Abstract*—The lateral stiffness of buildings is one of the most important properties which define resistance to displacements under lateral loads. Moreover, it has a great impact on the natural period of the structures. Different stiffness's values can ultimately affect the behavior of the structure under the seismic load and the lateral forces that will be applied to it. In this study the effect of cracking is studied on 2D shell thin cantilever shear wall by using ETABS. Multi linear elastic analysis is conducted with the ACI stiffness modifiers for each analysis step. The results showed that the cracks affect the value of the drift especially at the top of the high rise buildings and this will change the lateral stiffness and so change the fundamental period of the structures which lead to change in the applied shear force that comes from the earthquake. Finally, this study emphasizes that the finite element method can be considered as a good tool to predict the tensile stresses in the elements.

***Keywords*—Lateral loads, lateral displacement, reinforced concrete, shear wall, Cracks, ETABS, ACI code, stiffness.

I. Introduction

SHEAR walls are the most vertical members that are used to resist the lateral loads especially those come from the earthquake. These members may take many forms according to their location in the buildings or to their functions such as the core, the coupled, and the planar walls [1]. According to Bungale, these members are suitable in low-rise constructions up to 20 floors [2]. Moreover, these members are not preferred in open spaced buildings or in the external glazed walls due to architectural functions [3]. The walls' members offer good stability for buildings because of small drift between floors and this will lead to both small natural frequency and small natural period of these buildings. The shear walls may be together with frames to form shear wall-frame interaction system and this system is one of the most popular system in the world for resisting the lateral loads in medium-to-high rise buildings [4]. The system has a preferred range to application from 10 floors to 50 floors or even taller buildings [5]. The interaction between shear wall and moment frame is shown in Fig. 1 [6]; the frame basically deflects in a shear mode while the shear wall responds by bending as a cantilever.

Compatibility of horizontal deflection introduces interaction between the two systems which tends to impose a reverse curvature in the deflection pattern of the system. It is not always easy to differentiate between the two modes of deformation. A shear wall weakened by a row of openings may tend to act as a frame by deflecting in a shear mode. Therefore, the combined action depends on the relative rigidities of the elements used in this system [5].

Anas M. Fares is MSc. lecturer of the Structural Engineering, with the Building Engineering Department, Palestine Technical University - Kadoorie, Tulkarm, Palestine (e-mail: anas_fares76@yahoo.com).

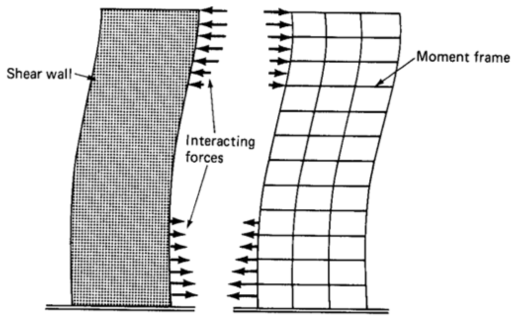

Fig. 1 Shear Wall-Frame interaction [6]

II. Lateral Displacement

Lateral displacements may be one of the most decisive factors in designing of the structures. In cases where maximum displacements must be limited, because of adjacent buildings orserviceability issues, the biggest challenge is to reduce the displacements to allowable amounts. Hook's law relates applied forces to displacements using the concept of stiffness. In buildings, this law also applies using the equation:

$$F = K\,d \tag{1}$$

where F is the applied force, d the displacement, and K the stiffness which established the relation between the two.

Equation (1) clearly shows the inverse relationship between stiffness of a structure and produced lateral displacements. As a result, displacements are highly influenced by stiffness of a structure and therefore, it is very important to acknowledge how changes in stiffness can impact the behavior of structure in terms of maximum lateral displacements, which is part of the study in this paper.

III. Seismic Force

The variations in stiffness can affect seismic forces, as an example of a common lateral loads, that the building will experience. The change in the stiffness can lead to the change in the fundamental period of the structure and thus impact the design accelerations which may lead to different seismic forces as shown in the response spectrum curve according to ASCE7-16 code as shown in Fig. 2. Therefore, it is seen that a change in stiffness of the structure can also impact applied forces in seismic analysis.

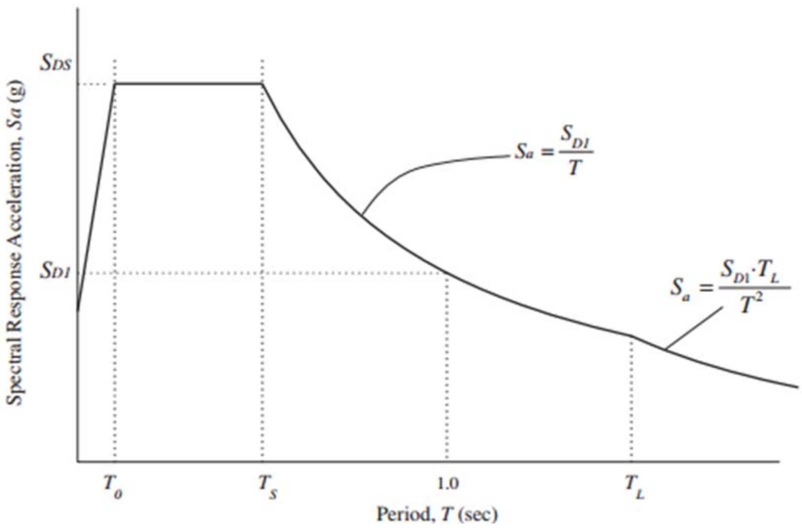

Fig. 2 The acceleration response spectrum [7]

IV. Cracks Effect

There is a famous adage about concrete which says: "There are two guarantees about concrete. One, it will get hard and two, it will crack!". Cracking is an inevitable issue in concrete structures which is a result of different factors such as applied loads, shrinkage, thermal loads and settlements in the structure. When concrete is in tension, if tensile stress of a particular element grows beyond rupture stress, cracking will occur and that element will not have the same stiffness as it used to have prior to cracking. It would be ideal that member stiffness's reflect the degree of cracking caused by applied loads to each member. However in reality, some of the complexities in assigning different stiffness's make the analysis inefficient. ASCE 7-16 [7] states that the models that are created to analyze the forces and displacements in a structure must consider the effects of cracked sections on stiffness properties of concrete and masonry elements. The reason is that the lateral deflection which a structure sustains under factored lateral loads might be substantially different from what is obtained using linear analysis [8]. This is due to the fact that members show in elastic responses and a decrease in effective stiffness is inevitable. ACI code [9] describes a simple way to calculate the nonlinear lateral deflection by using linear analysis and this may be estimated by reducing the stiffness of concrete members using stiffness modifiers. ACI provision states that lateral deflections of reinforced concrete building systems resulting from factored lateral loads shall be computed by linear analysis with member stiffness's defined as Table I [9].

TABLE I
CRACKED STIFFNESS MODIFIERS

Structural Element	Moment of inertia
Columns	0.70Ig
Walls-Un cracked	0.70Ig
Walls-cracked	0.35Ig
Beams	0.35Ig
Flat Plate slabs	0.25Ig

ACI explains that "if the factored moments and shears from an analysis based on the moment of inertia of a wall, taken equal to 0.70Ig, indicate that the wall will crack in flexure, based on the modulus of rupture, the analysis should be repeated with I = 0.35Ig in those stories where cracking is predicted using factored loads" [9]. These stiffness reduction factors will result into larger lateral displacements and the overall stiffness of structure will drop. At the same time, lower stiffness of an element (due to cracking) means less force will be attracted by that element and the rest will be passed to adjacent members that are not cracked and have a higher stiffness [8]. In this paper, the main focus is on investigating the effects of cracking on stiffness and lateral displacement of shear walls using ACI provisions explained above. The attempt is to implement a more precise method in identifying elements that will crack under applied loads and study how these cracked elements, influence the behavior of shear walls.

V. Model Description and Methodology

When the wall is subjected to lateral loads, it bends about the neutral axis. As a result, tension and compression stresses are formed in the two halves of the section. At the same time, walls resist shear and axial loads as well. Therefore, a small element in the wall undergoes stresses from axial loads, shear forces and bending. By transforming the stresses, principal stresses can be found. In this study, the shear wall is analyzed by using ETABS v.16.2.0 [10], and thus, the principal stresses can be obtained for all elements in shear walls. Based on ACI code [9], the modulus of rupture, f_r, is calculated using (2):

$$f_r = 0.62\sqrt{f_c'} \qquad (2)$$

where f_c' is the concrete compressive strength in MPa.

If the stress obtained from the analysis is larger than stress obtained from (2), it can be assumed that the element will crack under applied loads. Since in this study the compressive strength used in the models is 24 MPa, the modulus of rupture will be

$$f_r = 0.62\sqrt{24} \approx 3.037MPa$$

Based on the approach, it can be said that any element has a tensile stress of more than 3.037 MPa in the wall will crack and stiffness modifiers for cracked wall must be applied to that element. In contrast, if the tensile stress in element is less than 3.037 MPa, that element can be assumed as un-cracked and the stiffness modifier applied to that section is 0.70Ig. These modifiers will adjust the results and produce a more realistic value for displacements and element forces by considering the effects of cracking. To be able to recognize which elements of the wall will crack and need stiffness multipliers, a fine mesh is applied. By meshing the walls into smaller segments, data are obtained for each of the elements individually and modifiers can be applied to that particular section. Otherwise, if the wall is not properly meshed, data are generated for bigger elements which will not lead to a precise analysis. There is a down side to this approach however. Since there are hundreds of new elements created due to meshing, ETABS generates massive amount of data which require strong computers in order to process all of the output. Therefore, it can take a long time for regular computers to analyze even medium sized structures. To overcome these obstacles, a simple model is required which is able to represent certain conditions and a mesh of 0.50 x 0.50 m will be used in this model [8].

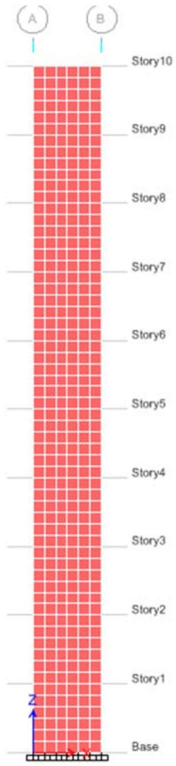

Fig. 3 The model of 2D shear wall on ETABS

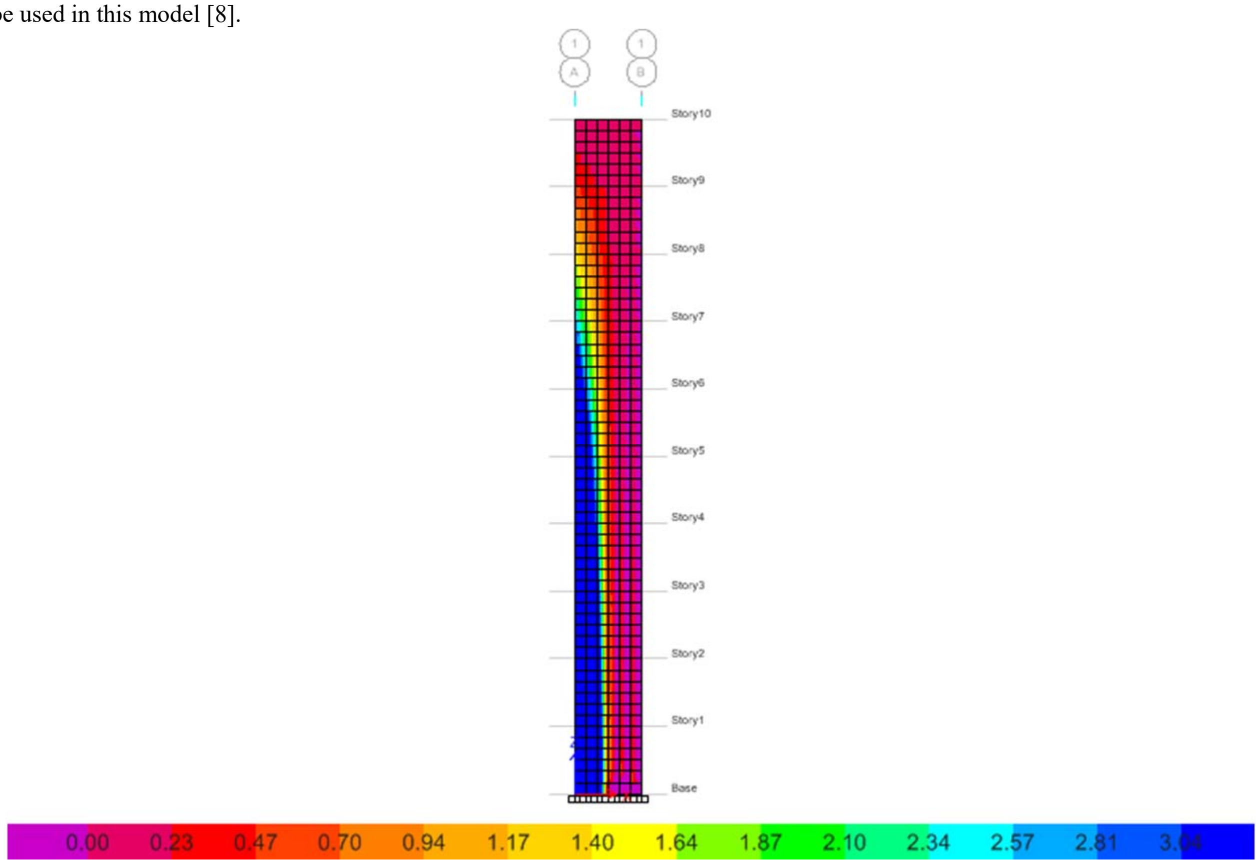

Fig. 4 The maximum tensile stresses in elements due to lateral load for the first step analysis in MPa

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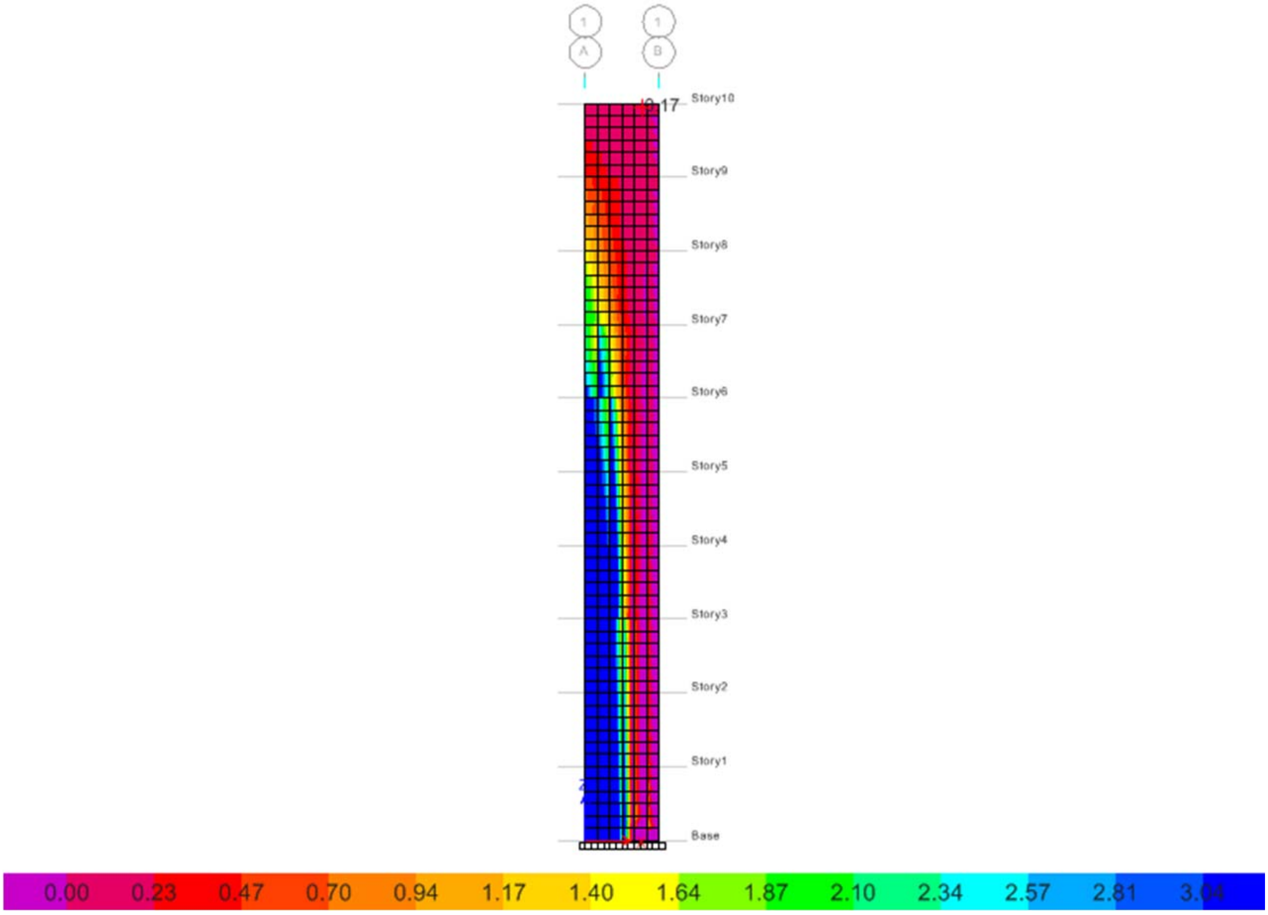

Fig. 5 The maximum tensile stresses in elements due to lateral load for the second step analysis in MPa

A shell thin cantilevered shear wall is considered for this paper. The geometric dimensions of the model are thickness equal 0.20 m, and length of 3 m with 3 m floor height, with 10 floors the total height of the walls will be 30 m. A lateral load of non-uniform triangle shape 50 kN load is distributed as shown in Table II on the model on Fig. 3.

TABLE II
LATERAL LOAD DISTRIBUTION ON FLOORS

Floor number	Load value (kN)
1	5
2	10
3	15
4	20
5	25
6	30
7	35
8	40
9	45
10	50

VI. RESULTS OF THE NUMERICAL MODEL

The multi-step analysis is used in analyzing this model until results converge and no new cracked element appears in analysis.

At first step which represents no cracks in wall, the stiffness multiplier modifier should be 0.7Ig for all of elements. Table III shows the results of lateral displacements for all floors in first analysis.

TABLE III
LATERAL DISPLACEMENT FOR FIRST STEP

Floor number	Load displacement (mm)
1	3.73
2	13.47
3	28.35
4	47.39
5	69.69
6	94.40
7	120.78
8	148.20
9	176.15
10	204.29

Now, if the S_{max} in the elements on ETABS exceeds the modulus of rupture, which it is calculated in (2), then the element can be considered cracked due high tensile stresses. Fig. 4 shows the contour range from 0 to 3.037 MPa and it can be noticed that blue color represents elements that cracked because the tensile stresses on each exceeded the rapture. Thus, the model shall be re-analyzed with new modifiers for the cracked elements only and with value equal to 0.35Ig.

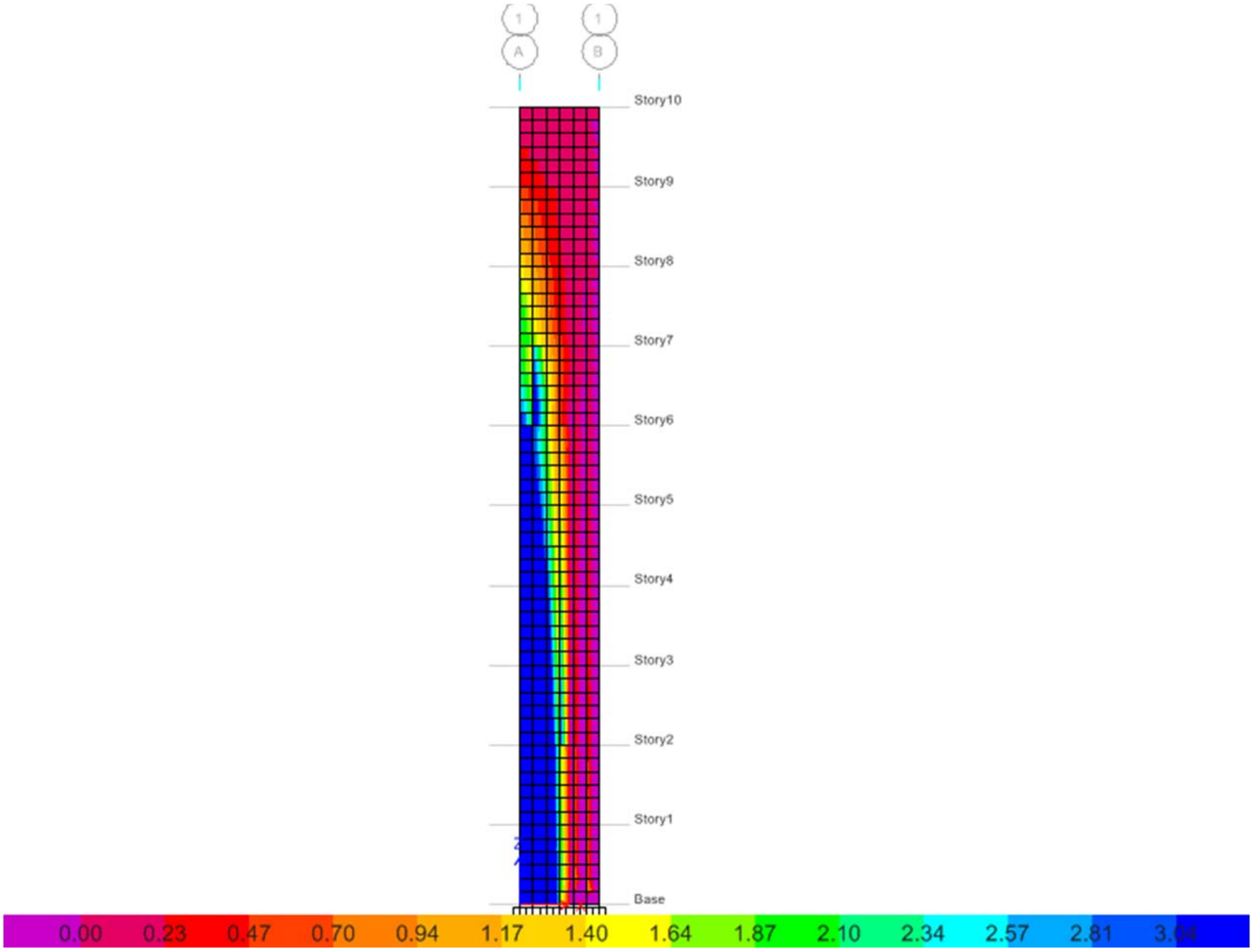

Fig. 6 The maximum tensile stresses in elements due to lateral load for the third step analysis in MPa

At second step, Table IV shows the results of lateral displacements for all floors.

TABLE IV
LATERAL DISPLACEMENT FOR SECOND STEP

Floor number	Load displacement (mm)
1	5.49
2	19.63
3	41.25
4	68.77
5	100.85
6	136.31
7	173.98
8	212.85
9	252.26
10	291.86

Fig. 5 illustrates the contour range from 0 to 3.037 MPa and as it can be seen, more elements have blue color which means that these elements have cracked.

For the third step the modification is applied to the stiffness modifiers to fulfill the condition of the cracked. Table V shows the results of lateral displacements for all floors.

TABLE V
LATERAL DISPLACEMENT FOR THIRD STEP

Floor number	Load displacement (mm)
1	5.57
2	19.83
3	41.52
4	69.26
5	101.73
6	137.70
7	175.90
8	215.31
9	255.25
10	295.38

Fig. 6 describes the contour range from 0 to 3.037 MPa and as it can be that the change in the contour range distribution from Fig. 5 is small enough to say that this is the final step.

VII. Discussion of the Results

Fig. 7 shows the lateral displacement results for all floors in all analysis steps.

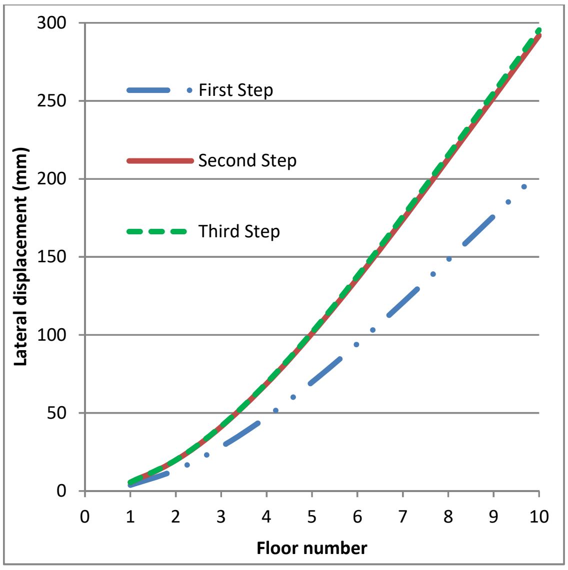

Fig. 7 Comparison of lateral displacement for all analysis steps

As it can be seen from Fig. 7, the cracked elements will affect the value of the lateral displacement of the shear wall and the lateral stiffness too, and this effect will appear obviously in the top floors where the difference in the value between each analysis step becoming too high. Also, after first analysis step, the difference can be hardly noticed in Fig. 7.

VIII. Conclusions

Based on this study, the following conclusions are drawn:

1. Cracks on shear walls affect lateral displacement and lateral stiffness of building and this will affect fundamental period of buildings and seismic force.
2. The effect of cracks in shear walls will appear obviously in top floors lateral displacement, where the difference between the analysis steps in top floors is higher than bottom floors.
3. Finite element method can be used to predict the propagation of the cracks in members and thus to modify the stiffness modifiers to make the results more accurate and realistic.

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