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Improving Total Moment Concept Equations for RC Coupled Shear Walls by Considering Coupling Beams Axial Load

Masoud Amin Safaei Ardakani [1], Mohammad Gholami [2], Sohrab Shoja [1*]

[1*] *M. Sc. Structural Eng., Department of Civil Eng., School of Engineering, Yasouj University, Yasouj, Iran*

(s_shoja@outlook.com)

[2] *Assistant Professor, Department of Civil Eng., School of Engineering, Yasouj University, Yasouj, Iran*

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ABSTRACT

Shear walls are widely used in steel and reinforced concrete buildings and have great importance among structural parts in medium and tall buildings as lateral loads are endured by shear walls. Coupled shear walls are being widely used in recent decades due to architectural and structural necessities. Most studies performed in this area, are addressing load transfer mechanisms, equilibrium equations of wall parts, fracture mechanisms, behavior of coupling beams and also system behavior against cyclic loads. However, effect of axial load in coupling beams has been neglected in these researches. Although many researchers considered this parameter as a negligible term in their works, a simple fact that if there is no axial load in coupling beams, there is no shear loads in the walls, proves inaccuracy of this assumption. The aim of this research is to use equilibrium equations and load transfer mechanisms for rearranging Total Moment Concept (TMC) equations and investigating coupled shear walls response against lateral loads. After improving TMC equations, a set of 3D finite element models are built to verify the results of this equations and compare the new equations to the original TMC equations. Afterwards, the required parameters for calculating TMC and Improved Total Moment Concept (ITMC) are extracted from these 3D models. It is shown that the improved equations are representing coupled shear walls behavior with more accuracy compared to the previous TMC equations. Finally, after comparing these two sets of results, some suggestions are given to improve the design process of coupled shear walls.

Keywords:

Coupled Shear Wall, Total Moment Concept, Finite Element Analysis, Pushover Analysis, Concrete Damage Plasticity.

1. Introduction

In concrete and steel structures, when buildings are taller than a certain amount (which depends on structural system and many other factors), lateral stiffness of the building is increased to control lateral displacements of the building against earthquakes and lateral loads. One of the most common ways to do this, is to use shear walls [1]. Shear walls position in building plan can affect lateral and torsional stiffness of the building. Choosing a suitable place for shear walls faces some difficulties due to architectural considerations. After the Second World War, the application of shear walls became common in France. Some engineers and architectures used door and window openings in shear walls. Afterwards, the new system called coupled shear wall was introduced [2]. Soon this new system -coupled shear wall- has been known for engineers and architectures all over the world and since then many researchers have investigated the behavior of this system. Some advantages of using coupled shear walls are as follows: walls lateral stiffness increases because there is more space to add more length to the wall, walls base moment which decreases the foundation stability is more granted because overturning moment is more nullified by the axial loads in two walls and energy damping mechanism is more effective because elastic and plastic deflections are scattered across a wider region [3, 4]. Most studies and researches on coupled shear walls are addressing force transition mechanisms in wall parts, equilibrium equations, equilibrium in wall parts, failure and fracture mechanisms and walls behavior against cyclic loading. These studies suggest a better performance for coupled shear walls in comparison with the traditional one parted shear walls. Zhang et al. [5] investigated effect of different beam aspect ratio, reinforcement layout and coupling beam boundary condition on behavior of the coupled wall. Talledo and Tesser [6] have used 2D membrane models to investigated the effect of simplifying assumption on the behavior of reinforced concrete structures and coupled shear walls. Their results shows that their model is fairly accurate when compared to experimental investigations. Liu et al. [7] investigated load transfer mechanisms and seismic performance of Hybrid Coupled Wall with steel coupling beams and replaceable fuse. Salameh et al. [8] proposed and innovative steel and concrete hybrid coupling shear wall and performed incremental dynamic analysis to understand performance base of the proposed system. Effect of several parameters were investigated using a parametric analysis and story number and uniformity number is introduced as the most influential parameters. They found out that the current q behavior factor is almost suitable for short building but it should be reevaluated for medium and tall buildings. Wang et al. [9] have investigated drift ratio, damage and bending and shear deformation ratio along the height of RC coupled shear walls using finite element method and proposed a new dual control damage index of deformation and energy. There are some shortcomings in these researches, specifically those performed on coupling index (or degree of coupling [10]) determination and load transition paths in wall parts. Subedi [4] performed an investigation on final lateral loading capacity of coupled shear walls but coupling beams axial load was not considered. In another research Subedi et al. [11] developed their studies on these systems and used TMC to predict failure mechanisms of the wall and coupling beams. However, based on these researches, effect of axial load has not been considered yet again. It is a common presumption that each wall axial load is at its cross-section's centroid, but due to the existence of moment and non-rectangular stress distribution, this is not a very realistic assumption. El-Tawil et al. [12] have investigated the effect of increasing load on steel coupling beams in shear walls. Effect of beams axial load was not considered and each walls axial load was assumed to be at its cross-

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section's centroid. El-Tawil and Harries [13] have presented a recommendation for analysis and design of coupled shear walls and again did not consider beams axial load in deriving the equations. Brena and Ihtiyar [14] have investigated concrete coupling beams under cyclic load. Xiaodong Ji et al. [15] have investigated reinforced concrete coupled shear walls tension-shear behavior. They examined tensions effect on shear walls capacity. However, effect of tension on transferring the forces to the compressed wall through coupling beam has not been investigated. In their research, effect of coupling beams axial load has not been investigated or at best, its consideration was not mentioned in the manuscript. Not considering axial load in beams, which is common in majority of the literature, means there is no shear force in the wall and this is not realistic. Also, axial load in beams changes bending capacity of beams and this can cause serious problems in beams performance during earthquakes. Due to lack of investigations in this area, effect of coupling beams axial load on coupled shear walls behavior is not known. Thus, this research is performed to cover this shortcoming by means of equilibrium equations and FE models. First, TMC equations are derived and then improved by applying the effect of beams axial load in equations. Then results of these two sets of equations are compared to those obtained from FE analysis. Failure mechanisms and cracking pattern of different parts of walls are investigated as a result of performing a pushover analysis. Based on the results of these analysis, some suggestions are given for making coupled shear walls design more reliable and realistic.

2. Improved Total Moment Concept (ITMC) Equations

As it is shown in literature, effect of beams axial load on coupled shear walls behavior is not considered and not considering this factor means there is no shear in the walls. For covering this shortcoming in the past researches, derivation of TMC equations and correcting them is in order. Thus, a typical coupled shear wall which is shown in figure 1 is considered. An opening is considered for each story. In figure 1, n is the story number, P is total load applied at roof top, H is total height, W1 is the wall under tension and W2 is the wall under compression, hi is height of ith story, d1 and d2 are lengths of the walls, O1 and O2 are centroids of the walls, a is length of coupled shear walls, L1 and L2 are distances between walls centroids to the middle of the coupling beams and L is the distance of walls centroid.

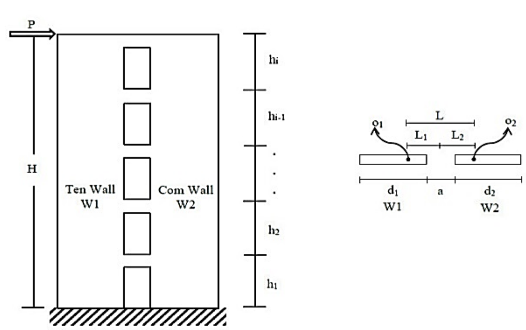

Figure 1. Coupling shear wall schematics and parameters

A typical coupled shear wall internal forces are demonstrated in figure 2. Degree of coupling is determined using equation 1. Since walls shear stiffness is equal (same cross section), shear is distributed between the walls equally (Equation 2).

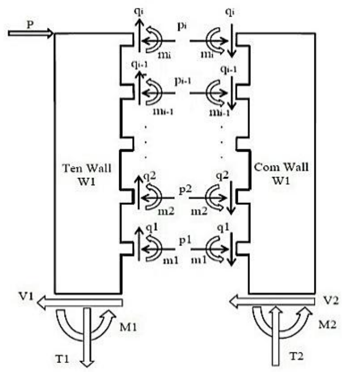

Figure 2. Coupling shear wall internal forces
(Under P load at the top)

$$DoC = TL/(TL + M1 + M2) \tag{1}$$
$$V1 = V2 = P/2 \tag{2}$$
$$T1 = T2 = T \tag{3}$$
$$M1 + M2 + TL = PH \tag{4}$$

Equations 1 to 4 are derived based on the assumption that two walls cross sections are identical. All parameters are demonstrated in figure 2. In case of equal story height, equilibrium for tensioned wall gives out:

$$\sum F_Y = 0 \rightarrow \sum q_i = T \tag{5}$$
$$\sum F_X = 0 \rightarrow \sum p_i = P/2 \tag{6}$$
$$\sum M_{o1} = 0 \rightarrow \sum m_i + M_1 + h \sum iP_i + TL_1 = PH \tag{7}$$

In equation 7, M1 is resisting bending moment of the wall, and other parameters are the results of resisting bending moment of the beams. Figure 3 is demonstrating moment-axial load interaction graph in a concrete cross section. After pure moment situation, introducing compression results in increasing the bending capacity, but contrariwise, introducing tension to the section, reduces bending capacity of the tensioned wall. The damages inflicted on W1 by tension is causing cracks and micro separations and as a result, reduces shear and bending capacity of the wall and makes M1 negligible. Considering these assumptions, it is given:

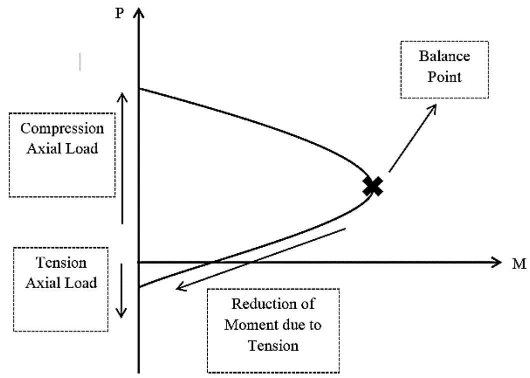

Figure 3. Moment-axial load interaction graph for concrete cross section

$$M_2 + TL = PH \quad (8)$$

$$\sum p_i = P \quad (9)$$

$$\sum m_i + h \sum i\, p_i + TL_i = PH \quad (10)$$

3. Modeling and Verification

In order to confirm correctness of the Improved Total Moment Concept equations, FE models are built and three categories of results are extracted. Parameters for calculating TMC equations and ITMC equations are extracted and then the results of these two sets of equations are compared to those of FE analysis. Simulating the walls is performed using ABAQUS package. Since 1952 definition of concrete behavior is commonly done using Drucker-Prager model. However, based on some recent researches, this model cannot match the concrete behavior quite perfectly [16]. In ABAQUS package, Concrete Damage Plasticity (CDP) is introduced as a new and reliable model. This model is an improved version of Drucker-Prager which is mostly suggested by Lubliner et al. [17]. In this method, in each moment, concrete behavior is investigated considering the damage caused by compression and tension in cross sections. In a common research on concrete walls, tension capacity of concrete section is neglected. However, this parameter which CDP considers, can have a significant effect on the results of the research so CDP is adapted for FE analysis in this research. Concrete and steel general mechanical characteristics are presented in table 1. However, based on the nature of CDP, plastic characteristics (strain-stress graphs) of steel rebars and concrete are needed to be used as FE analysis input (figure 4 and 5). For steel rebars a three linear behavior presented in figure 5 is adapted. After careful consideration, 8 models are built. These models are different in coupling beams height and steel rebar combination. General parameters of coupling beams are shown in figure 6 and steel rebar combinations are presented in table 2 and 3.

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Table 1. General characteristics of concrete and steel rebars.

Material	Parameter	Value
Concrete	Mass Density	2400 kg/m3
	Young Modulus	26.48 GPa
	Poisson Ratio	0.167
	Dilation Angle	35 Degree
	Eccentricity	0.1
	fbo/fco	1.16
	K	0.667
	Viscosity Parameter	0
Rebar S400	Mass Density	7850 kg/m3
	Young's Modulus	200 GPa
	Poisson's Ratio	0.3

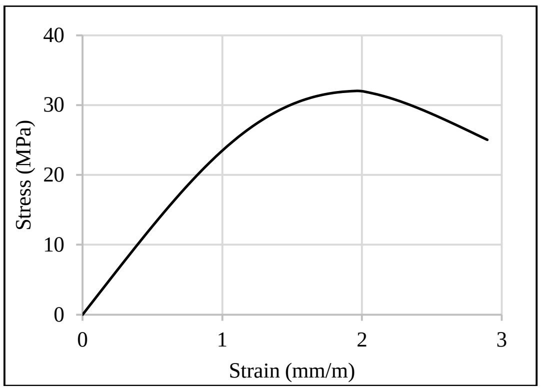

Figure 4. Concrete strain-stress graph.

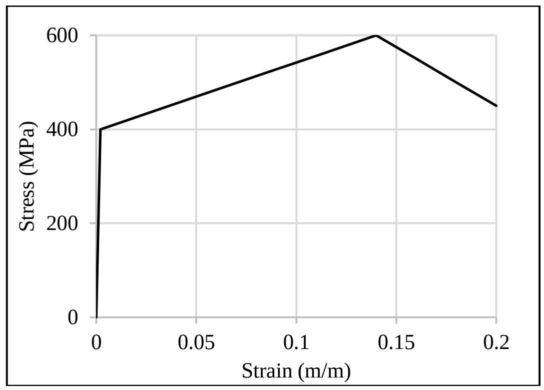

Figure 5. S400 rebar tri-linear strain-stress graph.

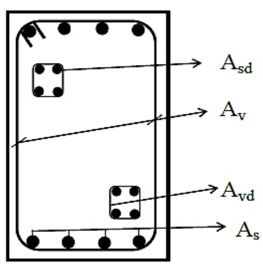

Figure 6. Coupling beams cross section and reinforcement parameters.

Table 2. Walls general characteristics.

Wall length	3 m
Wall thickness	0.2 m
Story height	3 m
Vertical rebar combination	18Φ10 mm @ 17 cm (2 Layer)
Horizontal rebar combination	16Φ10 mm @ 19 cm (Closed Stirrup)
Coupling beam length	1 m

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Table 3. Coupling beams rebar combination.

Model name	Coupling Beams height (cm)	As	Av	Asd	Avd
SWb50a	50	4Φ20 mm	Φ10 mm@10 cm	-	-
SWb50b	50	4Φ20 mm	Φ10 mm@20 cm	-	-
SWb50c	50	6Φ20 mm	Φ10 mm@20 cm	-	-
SWb50d	50	8Φ20 mm	Φ10 mm@20 cm	-	-
SWb100a	100	4Φ20 mm	Φ10 mm@10 cm	-	-
SWb100b	100	4Φ20 mm	Φ10 mm@5 cm	-	-
SWb100c	100	4Φ20 mm	Φ20 mm@5 cm	-	-
SWb100d	100	4Φ20 mm	Φ20 mm@5 cm	4Φ20 mm	Φ10 mm@15 cm

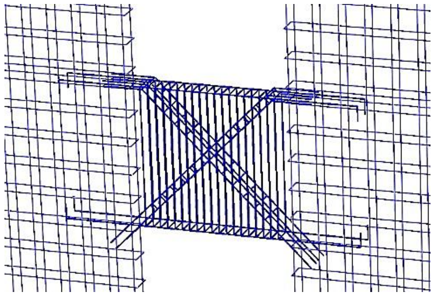

Figure 7. Wall and coupling beams connection schematics (general shape)

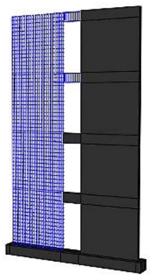

Figure 8. Complete coupled shear wall schematic (general shape)

4. Results and Discussion

The introduced models are analyzed under a large displacement on the roof top to investigate load transition mechanisms and cracking patterns in different parts of the wall and its condition to the point of collapse. Pushover analysis results are presented in figure 9 and 10. As shown in figure 9, in cases with beams height of 50 cm, SWb50a energy is damped more than other models and in cases with beams height of 100 cm, SWb100a energy is damped more than other cases. However, in some cases with beam height of 100 cm failure occurs in much smaller displacement in comparison with the others. This is mainly because this wall lack harmony in designing the different parts, meaning when all parts of the wall do not act in balance, some parts will fail sooner than expected and the walls behavior undergoes drastic changes. With the same reasoning, SWb100c, SWb100d and Swb50d cases, which have stronger coupling beams compared to the other models, cannot withstand up to 100mm displacement. In these three models, coupling beams or wall- foundation connection engages in local failure before reaching final displacement and the wall cannot reach its full capacity. The ups and downs in pushover graphs (figure 9 and 10) are the result of cracking in concrete beams and walls and as a result, transition of loads to steel rebars. As shown in figure 11, SWb100a model damps more energy than SWb50a. However, SWb100a final top displacement is 20 mm less than SWb50a.

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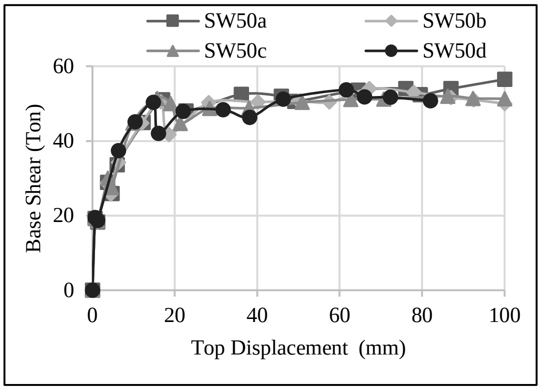

Figure 9. Pushover results for SWb50 models

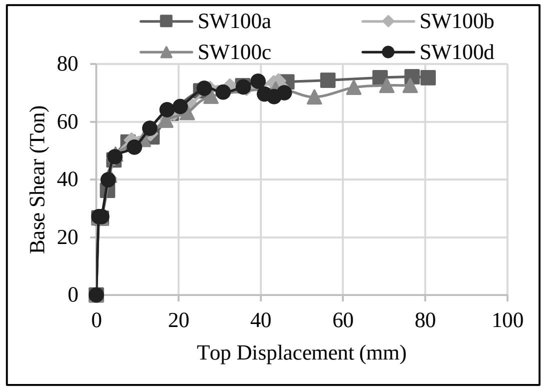

Figure 10. Pushover results for SWb100 models

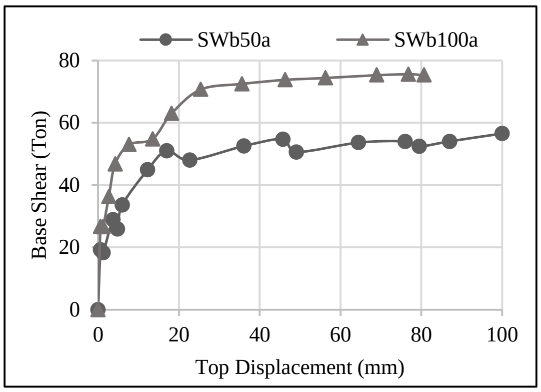

Figure 11. Comparison of pushover results for SWb50a and SWb100a

Comparison of TMC and ITMC for SWb50a models is presented in figure 12 and 13. Total base moment is calculated by multiplying the concentrated load to the total height of the wall and TMC and ITMC graphs are calculated using the extracted parameters from the FE models. As shown in figure 12, neglecting coupling beams axial load in calculations, gives out unrealistic or even incorrect answers (about 80% differences). At the same time ITMC results are very close to the base moment obtained from FE analysis (under 5% differences). The little difference in PH and ITMC results is caused by neglecting the inertia effect in static analysis (calculating the base moment by PH). In figure 13 and 14, compressed and tensioned walls share in base shear and moment are demonstrated. It is clear that the tensioned walls share is much less than compressed wall. In normal procedure for designing the coupled shear walls, each wall is designed for its share of shear and moment and its share is directly related to its stiffness. This means if the two walls have similar stiffness (which is almost always the assumption) their shares would be half of shear and half of moment. However, based on what is shown in figure 13 and 14 and what is said about the differences of tensioned and compressed walls capacity, in any given time, the compressed wall is enduring approximately 80 percent of the base shear and moment. So, designing the walls for their share of shear and moment based on their stiffness, can cause unwanted and unforeseen bending fractures and buckling of longitudinal steel rebars in areas near foundation during earthquake.

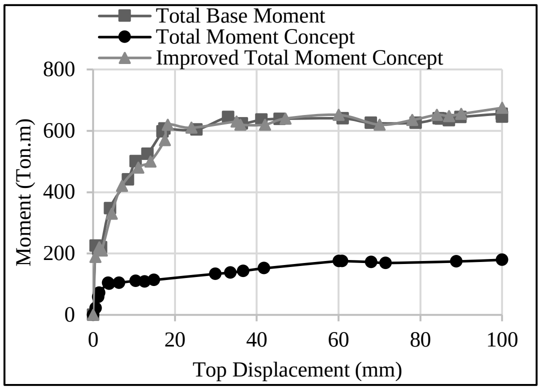

Figure 12. TMC and ITMC comparison for SWb50a model in respect to base moment

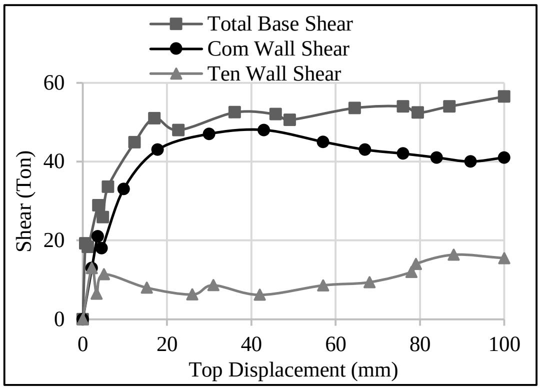

Figure 13. TMC and ITMC comparison for SWb50a model in respect to base shear

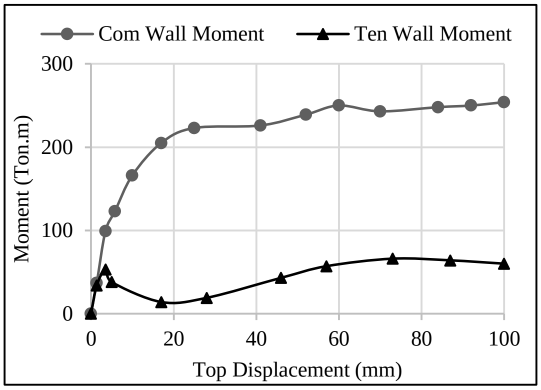

Figure 14. Comparison of bending moments share in compressed and tensioned walls for SWb50a

Walls cracking patterns are presented in figure 15 and 16. The diagonal cracking and fractures in the compressed wall (the right wall) shows magnitude of shear stresses in compressed walls. In all cases, tensioned wall is cracking much sooner and more than compressed wall. This shows that compressed wall is playing the main role in enduring the lateral loads. As it is shown in TMC and ITMC equations, coupled shear wall resistance is composed of walls and beams resistance. In order to reach the optimal wall resistance and top displacement these two parts must be in harmony. If beams are designed too strong (SWb100a case) the cracking and failure is bound to happen in wall foundation connection region and final failure is caused by yielding of vertical rebars. However, if the beams are weak (SWb50a), beams bending failure causes separation of the walls and consequently total failure before reaching the desired displacement will be inevitable. Thus, the most important lesson to be learned is the importance of reaching a proper degree of balance in the designing process.

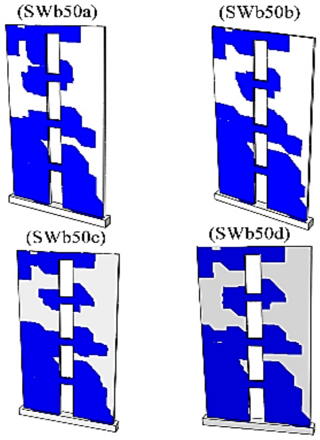

Figure 15. SWb50 models cracking patterns

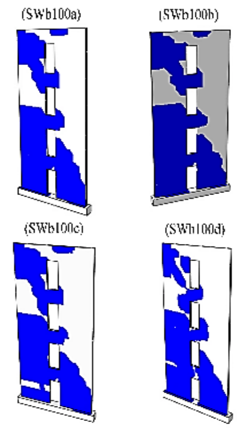

Figure 16. SWb100 models cracking patterns

5. Conclusions

TMC equations are derived using equilibrium. Afterwards, these equations are improved by considering the effect of coupling beams axial load. For verifying the new equations and comparison of the two sets of equations (ITMC and TMC), FE models are developed. Needed parameters are extracted from FE models and TMC and ITMC results are compared to each other and those of static analysis results. Neglecting the coupling beams axial load is proven to be the source of a considerable error in TMC results. It is shown that this error can be corrected by considering beams axial load (as in ITMC). The tensioned wall is not enduring much shear and a very high percentage of shear (about 80 %) is transferred to the compressed wall. As a result, designing the walls for their share of shear based on their stiffness is proven to be futile and can cause local and total failure under lateral loads. A pushover analysis is performed on the models. Walls cracking pattern and failure modes are investigated using the FE models results. All of the shear causes compressed wall to undergo serious diagonal shear cracking because it is not designed for this amount of shear. Same reasoning can be applied to moment. It is strongly suggested to design each wall for a reasonable and calculated percent of the applied shear and moment. Design of coupling beam reinforcement is significantly affected by its axial load and exact calculations can help in reaching a more efficient and reliable design. Also, coupling beams axial load causes the beams bending capacity to decrease significantly. When axial load is not considered, beams failure occurs much sooner than expected. When beams fail, two walls act separately and capacity of the whole system decreases drastically. Beams stiffness can affect energy damping process in the whole wall. In walls with suitable beams, cracking is distributed in coupling beams, wall-beam connections and wall-foundation connection and after damping the energy to maximum capacity, failure must occur in an order which does not disrupt the structural integrity of the building unexpectedly. However, in walls with stronger coupling beams, cracking and failure are more focused in wall-foundation connection areas, which cause the collapse to occur suddenly. Thus, it is strongly suggested that a performance investigation (including nonlinear analysis) would be carried out after reaching a final design, so that structural designer can understand buildings behavior thoroughly.

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