

## Non-Linear Analysis Of Thin RC Walls With Openings Subjected Axial Load With An Eccentricity

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**Abstract:** - Thin reinforced concrete wall behavior subjected axially loading with an eccentricity can be accurately predicted using non-linear analysis application program FEA modeling based on the experimental test. A numerical study was undertaken to verify the effectiveness of the Finite Element Analysis (FEA) in predicting the failure characteristics of thin reinforced concrete walls with openings. The existing experimental RC wall test results which were compression strength 47.0 and 99.3 MPa, height to thickness ratio 40, sectional area 25% opening at the center, and restrained top and bottom sides only were adopted to model numerically. The numerical model was constructed by the nonlinear analysis application program FEA produced by MIDAS-IT. The three-dimensional solid analysis considering concrete and reinforcement properties simultaneously using solid brick element defined the total strain crack model with elastic modulus in compression and brittle in tension is applicable. The ultimate loads, load-deflection responses up to failure, lateral displacements and crack propagations predicted by the FEA were compared at 7 concrete compressive strengths by 24, 35, 47, 60, 70, 80, 90 MPa taken account with linear and non-linear analysis.

The comparative study also confirmed that the FEA is a reliable and effective numerical modeling technique for determining ultimate load capacity of high strength concrete walls with high height to thickness ratio and opening. Especially the maximum lateral displacements of wall around opening are investigated at the linear and non-linear mode and compared the test observations.

**Keywords:** - Axial loaded with an eccentricity, Crack propagation, Finite element analysis, Lateral displacement, Thin reinforced concrete walls.

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### I. INTRODUCTION

There are two useful simplified design equations for axially loaded wall panels given in the Australian Standard AS3600 [1] which was originated from British Standard BS3600 [2] and American Concrete Institute Code ACI-318 (2014) which led to Korean Concrete Standard KCI. The Codes are restraints to walls with height to thickness ratio of less than 25, and are not intended to be acceptable the concrete strength should be less than 65 MPa. The code derived from limited researches [5][6][7]. From the recent research [8][9][10][11][12][13][14], the thin concrete wall with more than the height to thickness ratio 25 is verified that has structural performance. However, the use of thin concrete walls for tall building with high strength concrete is increasing resulted in needing to provide the reasonable code. It is evident that more investigations are required of the thin walls with higher concrete strength over 65 MPa and height to thickness ratio over 25. It is well known that the concrete characteristic is stronger enough for the compressive strength rather than the tensile strength. There is a need to study how much are influenced about the thin reinforced concrete walls axially loaded with an eccentricity depending on the compressive strength. An experimental test focused on this was carried out by Lee [15]. The thin concrete wall behaviors subjected axially loading with an eccentricity can be accurately predicted to be modeled by the finite element method according to the experimental test procedure.

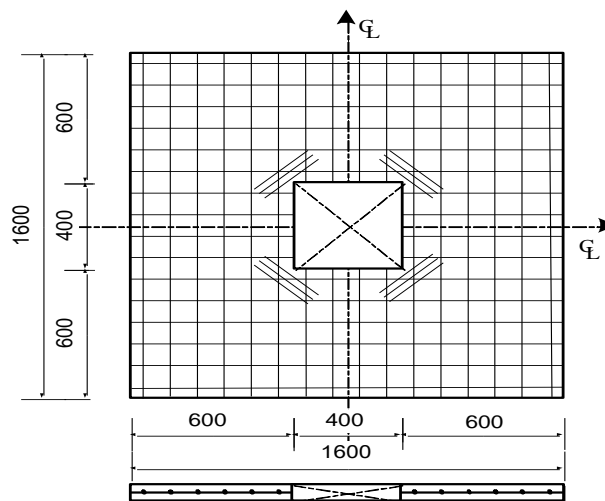
### II. METHODOLOGY

The existing experimental test results which the applied compression strengths were 47 MPa and 99.3 MPa, reinforced concrete thin walls; height to thickness ratio 40 with 25% opening located at the center, and restrained top and bottom sides are adopted to model numerically. The numerical model was constructed by the nonlinear analysis application program FEA produced by MIDAS-IT. The three-dimensional solid analysis method of FEA considering the material properties of concrete and reinforcement simultaneously is used a solid brick element defined the total strain crack model in compression and the brittle model in tension. The ultimate load at failure, load-deflection responses up to failure, lateral displacements and crack propagations predicted by

the FEA were compared with 10 types of concrete compressive strength by 24, 35, 47, 60, 70, 80, 90, 100, 120, 150 MPa between linear and non-linear analysis. The comparison of maximum lateral displacement and crack propagation between by FEA and experimental result shows the effectiveness of the use of the non-linear mode in numerical analysis of the thin concrete walls[16][17].

**2.1 EXPERIMENT SPECIMEN**

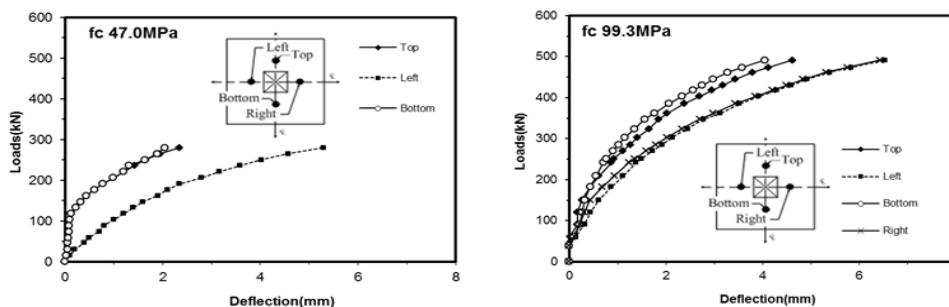
A wall panel with openings was tested by Lee (2008), which is detailed in Fig. 1. The wall panel produced was square type. The lengths and heights of the panels was 1600mm with a thickness of 40 mm. The wall was restrained top and bottom edges; height to thickness ratio was 40, and had one opening located at the center. The opening sectional area ratio was 25% and the opening configuration was based on practical dimensions in common building window situations. The tested wall panel was subjected a uniformly distributed axial load with an eccentricity of thickness over 6 resulting the whole section loaded in compression. The F41 mesh (yield strength of 450 MPa and the minimum tensile strength of 500 MPa) was embedded. The reinforcement ratio was 0.0031 satisfying the minimum requirement in Australian Standard and ACI code. The test specimen material property and load-displacement test result show in Table 1 and Fig. 2 respectively.



**Figure 1** Test specimen detail (units: mm)

**Table 1** Test specimen material property

	Elastic modulus (MPa)	Shear modulus (MPa)	Concrete strength (MPa)	Tensile strength (MPa)	Ultimate load (kN)	Maximum deflection (mm)
Test1	29725	12385	47.0	2.5	294.3	5.3
Test2	29725	12385	99.3	5.0	503.3	6.5

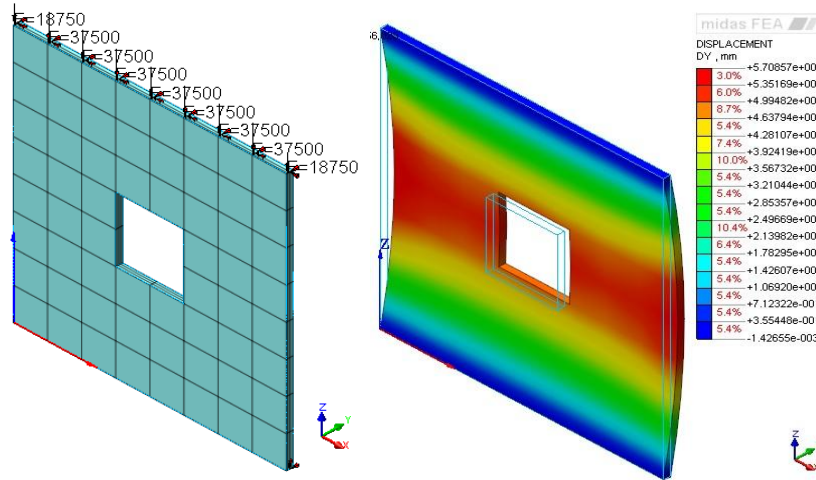


**Figure 2** Load-deflection response of test result

**2.2 NUMERICAL MODELING**

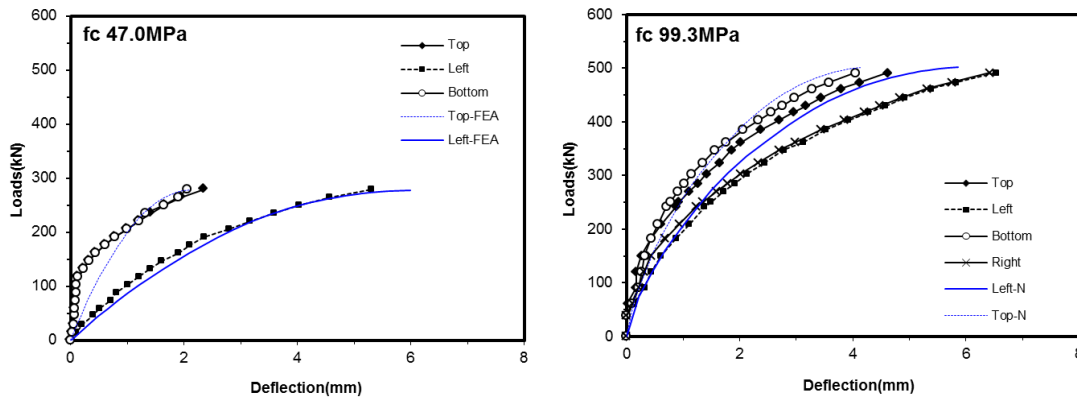
A Finite Element Analysis (FEA) is applied to investigate structural behavior of concrete wall with opening. The concrete wall with opening tested by Lee is modeled numerically. Using the MIDAS FEA Version 3.4.0, a numerical model modeled to a wall of 1600 x1600 x40 mm with one opening of 400 x400 mm and

typical lateral deflection contour at failure show in Fig. 3 respectively. The elastic modulus of 29725 MPa, the Poisson’s ratio of 0.2 and compressive strength of 47.0 MPa and 99.3 MPa were identical with material properties of tested walls are adopted. The restraint condition is hinged supporting on the top and bottom edges. The lumped (non-consistent) load approach is used to convert a set of nodal loads on the top edge to simulate a uniformly distributed load at an eccentricity within the sectional core. It usually employs a lumping method in dividing the amount of element load. The total element load is simply divided up and applied as a series of point loads to the nodes that the element is connected.



**Figure 2** Numerical model and analyzed displacement

load-deflection responses analyzed by FEA are presented in Fig. 4. The effectiveness of the FEA is demonstrated through a comparison with the test results and observations in terms of the deformed shapes and the load-deflection response as well as the ultimate loads. The successful agreements of the comparisons are satisfied to endure the applicable numerical model of the concrete slender walls. Although more discrepancies exist between the test and FEA due to the limitations of experimental testing, the comparisons further confirm that the numerical model is the appropriate in terms of accuracy. Based on the convergence study, the numerical model is used to conduct comparative studies in the following section.



**Figure 3** Load-deflection response by test and linear FEA results

**III. RESULTS**

In this chapter, the comparative study confirmed that the FEA is a reliable and effective numerical modeling technique for determining ultimate load capacity of between normal and high strength concrete walls with high height to thickness ratio and opening. Especially the maximum lateral displacements of wall around opening are investigated at the linear and non-linear mode and compared with the test observations.

**3.1 LINEAR MODE ANALYSIS**

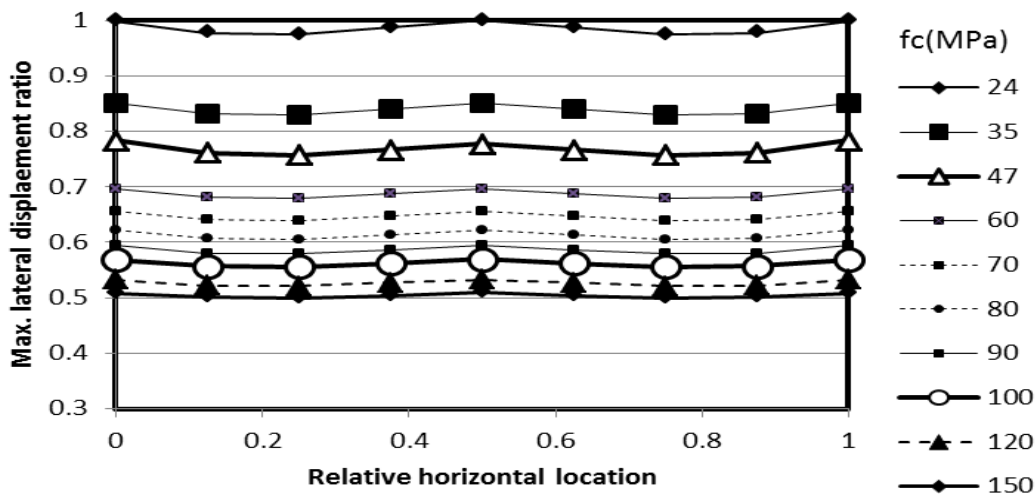
The maximum lateral displacements are predicted by the linear mode of FEA. Based on 10 types of compressive strength, the maximum lateral displacements on the horizontal location upon the top of the opening were changed according to increase or decrease of compressive strength from normal strength to high strength

indicated in Table 2 as well as the ultimate loads at failure. The maximum lateral deflection occurs at the mid-height of wall panels as a single curvature-deform shape led to the horizontal cracks at the center of walls. Although the maximum lateral displacements occur at the center of opening, the data is recorded at the 1000mm of height to figure out the deflected shape of wall panel horizontally.

**Table 2** Linear analysis results; lateral deflection (mm)

Compressive Strength, $f'_c$ (MPa)	24	35	47	60	70	80	90	100	120	150	
Ultimate Loads, $P$ (kN)	150	250	300	350	400	450	500	550	650	800	
Location (mm)	$L_1$ (0)	3.391	4.815	<b>5.318</b>	5.516	5.938	6.347	6.719	<b>7.084</b>	7.834	9.214
	$L_2$ (200)	3.317	4.71	<b>5.169</b>	5.396	5.809	6.193	6.573	<b>6.938</b>	7.688	9.068
	$L_3$ (400)	3.308	4.696	<b>5.139</b>	5.381	5.792	6.168	6.554	<b>6.919</b>	7.669	9.049
	$L_4$ (600)	3.352	4.759	<b>5.208</b>	5.452	5.869	6.25	6.641	<b>7.006</b>	7.756	9.136
	$L_5$ (800)	3.395	4.820	<b>5.278</b>	5.522	5.945	6.332	6.726	<b>7.091</b>	7.841	9.221
	$L_6$ (1000)	3.352	4.759	<b>5.207</b>	5.452	5.869	6.25	6.641	<b>7.006</b>	7.756	9.136
	$L_7$ (1200)	3.308	4.696	<b>5.139</b>	5.381	5.792	6.168	6.554	<b>6.919</b>	7.669	9.049
	$L_8$ (1400)	3.317	4.710	<b>5.169</b>	5.396	5.809	6.193	6.573	<b>6.938</b>	7.688	9.068
	$L_9$ (1600)	3.391	4.815	<b>5.318</b>	5.516	5.938	6.347	6.719	<b>7.084</b>	7.834	9.214

The displacements between two test results and FEA are reasonably identical. Analyzed wall edge over center deformed ratio  $L_1/L_5$  and mid over center deformed ratio  $L_2/L_5$  are calculated of the average are 100.01% and 97.89% respectively. It means that at the edge of wall  $L_1, L_9$  and center  $L_5$  a crack occurs to start and propagates heading toward mid points  $L_3$  and  $L_7$ . To figure out horizontal deformed shape in terms of varying concrete strength, the maximum lateral displacement ratio (displacement over ultimate load based on the displacement ratio at the center of wall with concrete strength 24 MPa) is presented in Fig. 5. It is obviously different with test observations.



**Figure 4** Lateral displacement ratio at the wall center analyzed by linear mode

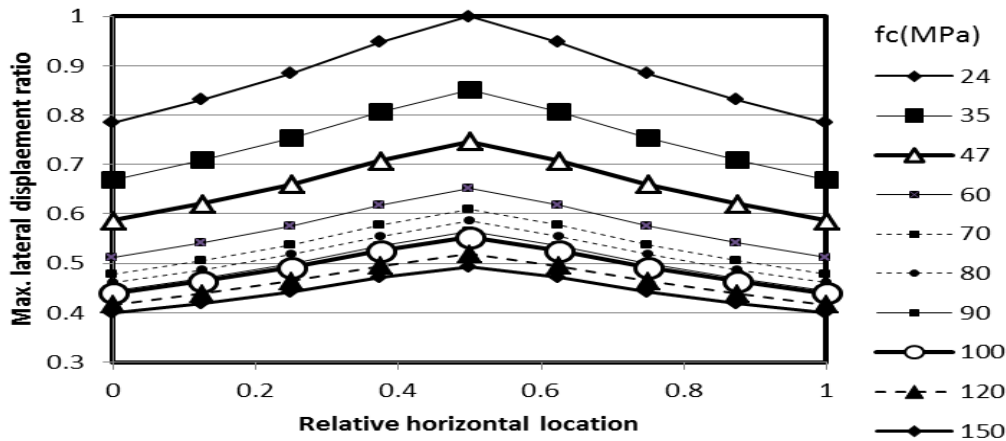
### 3.2 Non-Linear mode analysis

In the non-linear mode using Newton-Raphson method it is applied to 0.1 of the initial load factor, 0.001 of the minimum load factor and 0.001 of the displacement norm in convergence criteria. The analyzed results are presented in table 3. On the average, the analyses in 73.18% of given loads is stopped due to the limit of allowed displacements. Considering the safety factor, it is reasonable ultimate loads calculated by using the non-linear method.

**Table 3** Linear analysis results; lateral deflection (mm)

Compressive Strength, $f_c$ (MPa)	24	35	47	60	70	80	90	100	120	150	
Ultimate Loads, $P$ (kN)	104.9	153.1	<b>218.6</b>	281	330.3	375.1	414.1	<b>444.5</b>	490.7	531.5	
Location (mm)	$L_1$ (0)	2.129	2.647	<b>3.314</b>	3.72	4.081	4.465	4.754	<b>5.054</b>	5.284	5.484
	$L_2$ (200)	2.255	2.804	<b>3.510</b>	3.94	4.323	4.727	5.035	<b>5.335</b>	5.565	5.765
	$L_3$ (400)	2.397	2.98	<b>3.730</b>	4.188	4.594	5.022	5.352	<b>5.652</b>	5.882	6.082
	$L_4$ (600)	2.57	3.195	<b>4.000</b>	4.491	4.926	5.384	5.739	<b>6.039</b>	6.269	6.469
	$L_5$ (800)	2.712	3.372	<b>4.221</b>	4.739	5.199	5.684	6.056	<b>6.356</b>	6.586	6.786
	$L_6$ (1000)	2.57	3.195	<b>4.000</b>	4.491	4.926	5.384	5.739	<b>6.039</b>	6.269	6.469
	$L_7$ (1200)	2.397	2.98	<b>3.731</b>	4.188	4.594	5.022	5.352	<b>5.652</b>	5.882	6.082
	$L_8$ (1400)	2.255	2.804	<b>3.510</b>	3.941	4.323	4.727	5.036	<b>5.336</b>	5.566	5.766
	$L_9$ (1600)	2.129	2.647	<b>3.314</b>	3.72	4.081	4.465	4.754	<b>5.054</b>	5.284	5.484

The deformed shapes between two test results and FEA at the non-linear mode are identical. Analyzed wall edge over center deformed ratio  $L_1 / L_5$  and mid over center deformed ratio  $L_2 / L_5$  are calculated of the average are 79.16% and 83.66% respectively. It means that a crack occurs to start at the center of wall panel and propagates significantly heading to the edges both side horizontally. It is obviously identical with test observations. The displacement ratios of concrete strength are presented in Fig. 6. The slope of the displacement ratio shows steep about 20~10% and decreases depending on the concrete strength increase as well as steeper around the opening.



**Figure 5** Lateral displacement ratio at the wall center analyzed by non-linear mode

### 3.3 Comparison between linear and non-linear mode analysis

Maximum displacement ratios at the identical load in which are maximum and minimum among the nodes lined at the wall center horizontally in linear and non-linear mode are presented in Fig. 7. Maximum deflection on the nodes occurs at the center of the wall and minimum one occurs at the end of the wall in non-linear mode, on the other hand maximum one occurs at the center and end of the wall and minimum one occurs at the mid-point between the center and the end of the wall in linear mode. In linear mode analysis, the gap between maximum and minimum displacements is a little and the maximum points are three on the horizontal line of the wall. Those are constant despite the concrete strength increase up to 150 MPa. In non-linear mode analysis, the gaps are decreasing from 21.5% to 9.5% correspond to the concrete strength from 24 MPa to 150 MPa. In the concrete strength of 60 MPa, the gap of 14% means that the crack mode is changing from bending crack in tension side to crushing in compression side. The gap between center and end of walls leads that cracks occur at the center of wall and propagate to the end side of the wall horizontally. The displacement ratio is smoothly decreasing in terms of the concrete strength increasing at the identical load.

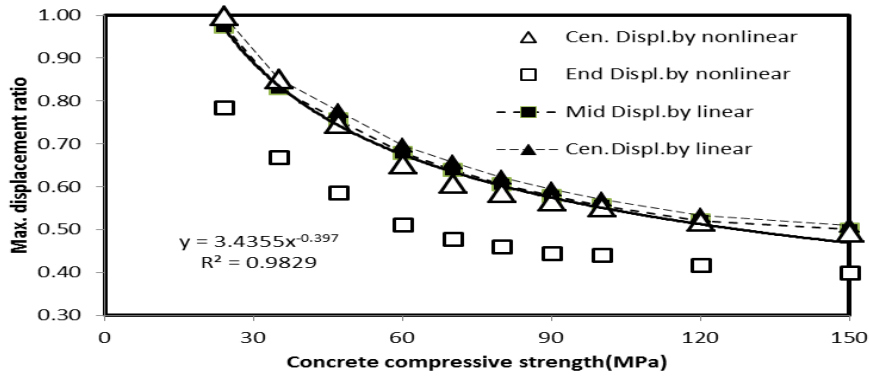


Figure 6 Maximum displacements of the wall with respect to concrete strength

The ultimate load analyzed in linear and non-linear mode between normal concrete strength and high strength is illustrated in Fig. 8. The ultimate loads analyzed in non-linear mode are reasonable and safe even though the ultimate load analyzed in linear mode are closer to test results but a little bit overestimate.

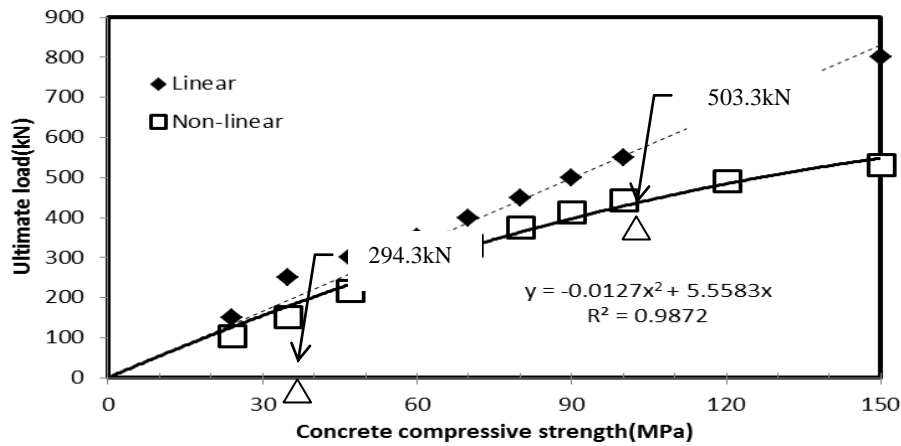
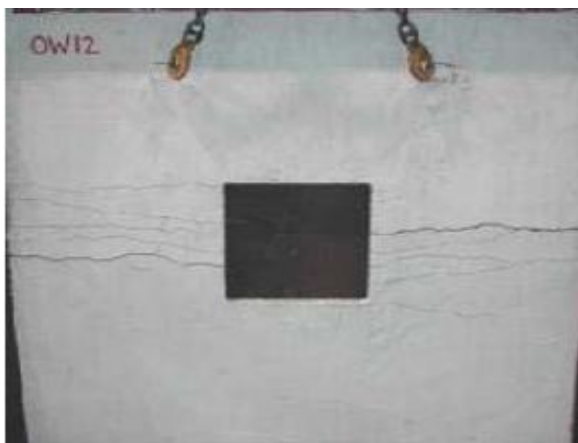


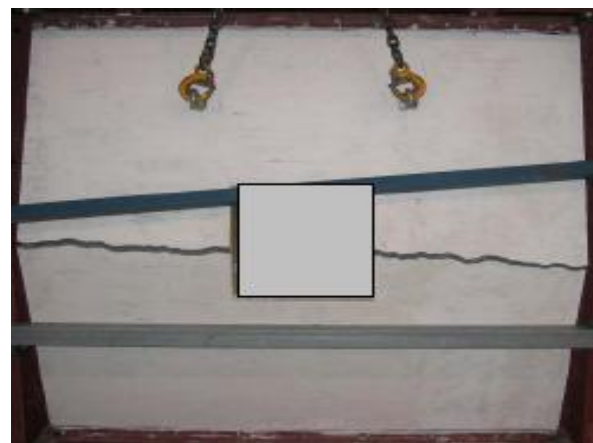
Figure 7 Ultimate load of the wall with respect to concrete strength

### 3.4 Comparison between experimental results and non-linear mode analysis

In the experimental results at failure indicated in Fig. 10 shows that the cracks start at the mid height of opening and reach to the both end edges. The clear single crack at high concrete strength wall panel indicates to occur the crushing crack in compression side otherwise the several fine cracks in normal strength wall panel represents the bending crack in tension side.



Compressive strength: 47.0 MPa



Compressive strength: 99.3 MPa

Figure 8 Experimental results tested by Lee



The displacement ratios graphs between Fig. 6 and 7 shows

- 1) the deformed shape slope in non-linear analysis is clear to occur crack,
- 2) the slope decreases smoothly from around 60 MPa; means changing fracture mode from the bending crack to the crushing crack,
- 3) the slope around mid-height of opening is steeper indicates the cracks start the point otherwise the slope analyzed in linear mode indicates not match with test observation. Therefore, in this study it proposes to use non-linear mode in numerical model of concrete necessary

#### IV. CONCLUSION

The structural behaviors of thin reinforced concrete walls axially loaded with an eccentricity, such as ultimate loads, load-deflection response and crack propagation, are non-linear analyzed by the FEA package program. The analyzed result in non-linear mode is identical with existing test observations indicated the model and procedure are appropriated.

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