Modeling and Validation of Experimental Test Results on Infilled Frame With Eccentric Reinforced Opening

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Abstract. This research was conducted to find out how to model and validate experimental test results of the single-story infilled frame structure with eccentric and reinforced wall opening. Modeling method derived from this study further could be applied on complex model of full-scale building structures. Validation were being done on type 3/II and 4/II specimens from Sigmund and Penava (2012) experiment results. Specimen with full infill wall was also included as reference model. Stress-strain parametric relation curve of concrete by Mander et al. (1984) and infill wall masonry by Kaushik et al. (2007) were constructed and approached correspondingly by multiple straight lines to obtain elasticity modulus changes and lateral load stages. Number of stages of lateral load and modulus of elasticity changes then were applied to analytical models of each specimen to generate force-displacement curve. Curve of validation results from analytical model are visually alike to the experiment. There are five load stages applied to specimen 3/II and 2/III, while six load stages on specimen 4/II. Average deviation of displacement values for model 3/II, 4/II, and 2/III are about 36%, 5%, and 11%, respectively.

Keywords. Infilled frame, eccentric opening, reinforced opening, curve-fitting, validation model

INTRODUCTION

Contribution of infill walls to frame structures has been widely researched and has proven that it can increase the strength and stiffness of the building structure (Asteris, et al., 2012). Even though the wall has openings for doors, windows, or both, it still has contribution to increase the rigidity of structure. This is evident from the results of laboratory tests by Kakaletsis and Karayannis (2009). In designing an infilled frame with opening, it must be reinforced with beams and columns around the opening. The presence of reinforcement around the opening can reduce stress and damage of infill walls around it (Sigmund & Penava, 2012).

Infill walls are usually modeled using the shell element and diagonal strut. The shell element method can describe behavior of structures such as stresses that occur in walls. Meanwhile, the diagonal strut method is simpler in its modeling because it is considered as a diagonal bar. Many studies have been conducted to find the equation of diagonal strut width, such as Mainstone (1971), Paulay and Priestley (1992), and FEMA 356. However, this equation was only representing infilled frame without opening. Asteris (2012), Sigmund and Penava (2013) conducted a study on infill walls with openings and proposed a reduction factor for stiffness to calculate equation of strut width. However, the proposed equations were only for unreinforced openings infilled frame.

For this reason, it is necessary to conduct further research to obtain a diagonal strut width equation of infilled frame with eccentric opening and reinforcement around it that corresponds to the results of experimental tests. At initial, it is required to study on how to model and validate experiment results. Modeling and validating process is done by doing curve-fitting on specimen experimental results of type 3/II, 4/II, and 2/III from Sigmund and Penava (2012).

LITERATURE REVIEW

Behavior of concrete and infill wall material is determined based on elasticity modulus and stress-strain parameters. Elasticity modulus of concrete (E_c) is calculated depends on its weight (w_c) and compressive strength (f'_c) as shown in equation (1) from SNI 2847:2019. While elasticity modulus of infill wall masonry (E_m) is derived from FEMA 356 as shown in equation (2).

$$E_c = w_c^{1,5} 0{,}043 \sqrt{f'_c} \tag{1}$$

$$E_m = 550 f'_m \tag{2}$$

with f'_m is compressive strength of infill wall masonry.

Mander et al. (1984) proposed concrete stress-strain parametric relation consists of two regions i.e., curve region and linear region. Stress-strain parametric relation for infill wall masonry is proposed by Kaushik et al. (2007) have similar regions with concrete but have different form of curve. Both curves are shown in figure below.

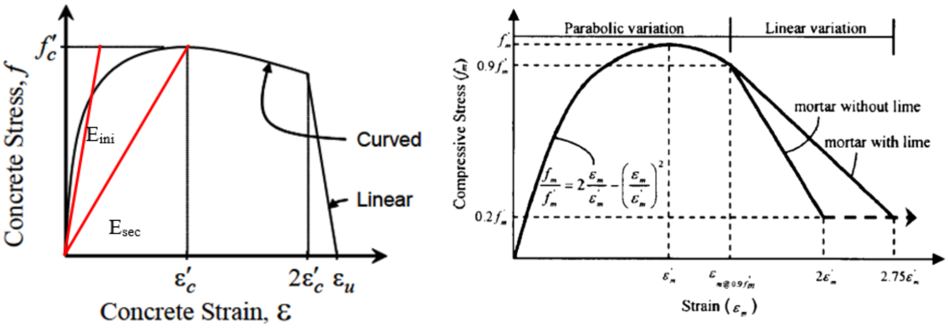


FIGURE 1. Stress-strain parametric relation of concrete and infill wall masonry

For concrete, equation that forming curve and linear regions are shown in equation (3) and (4).

$$f_c = \frac{f'_c xr}{r - 1 + x^2} \tag{3}$$

$$f_c = \left(\frac{2 f'c^r}{r - 1 + 2^r}\right)\left(\frac{\varepsilon_u - \varepsilon_c}{\varepsilon_u - 2\varepsilon'_u}\right) \tag{4}$$

with,

$$x = \frac{\varepsilon_c}{\varepsilon'_c} \tag{5}$$

$$r = \frac{E_C}{E_C - \left(\frac{f'_c}{\varepsilon'_c}\right)} \tag{6}$$

While equation forming curve and linear without lime regions for infill wall masonry are shown in equation (5) and (6).

$$\frac{f_m}{f'_m} = 2\frac{\varepsilon_m}{\varepsilon'_m} - \left(\frac{\varepsilon_m}{\varepsilon'_m}\right)^2 \tag{7}$$

$$\frac{f_m - 0{,}9 f'_m}{0{,}2 f'_m - 0{,}9 f'_m} = \frac{\varepsilon_m - \varepsilon_{m@0{,}9f'm}}{0{,}2\varepsilon_m - \varepsilon_{m@0{,}9f'm}} \tag{8}$$

Modeling infilled frame can be done with considering infill wall as shell element. Dorji and Thambiratnam (2009) proposed that there is link element connect shell elements to frame elements as a gap. Gap elements have stiffness (K_g) which calculated with equation (3).

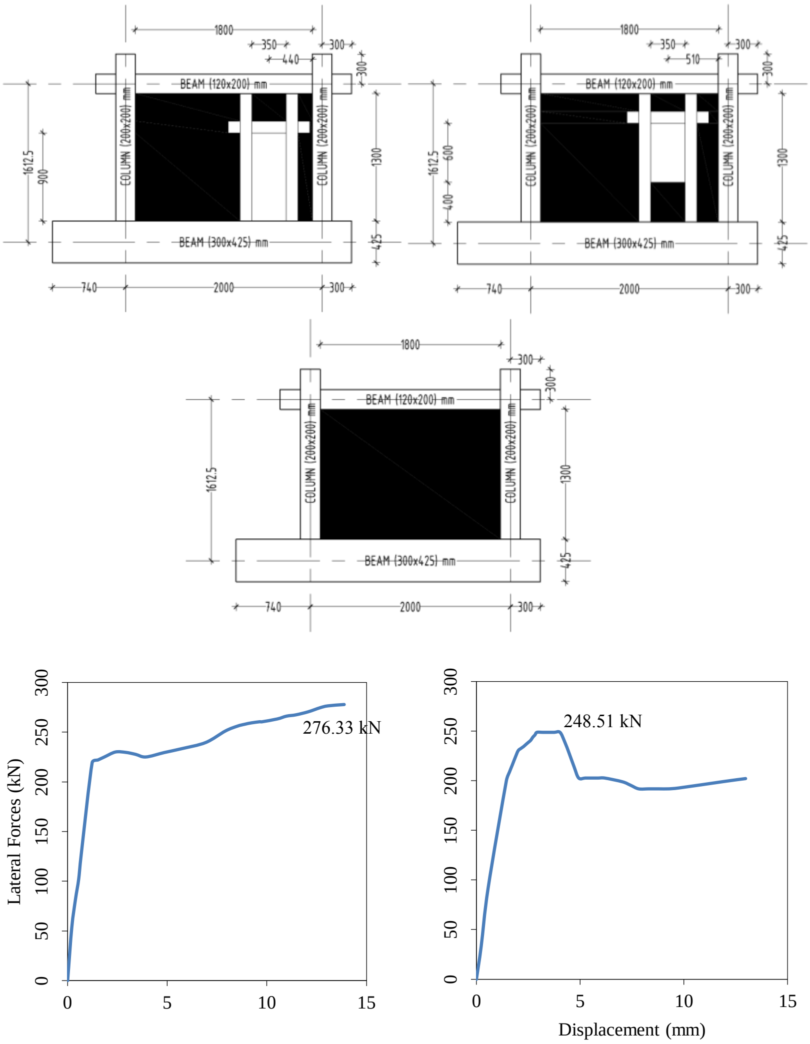
$$K_g = 0{,}0378K_i + 347 \tag{9}$$

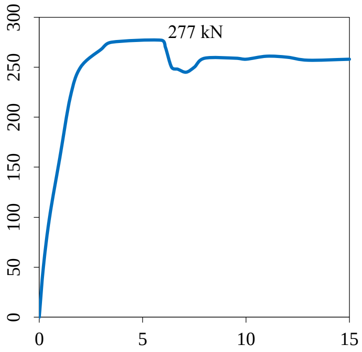
$$K_i = E_i t \tag{10}$$

where K_i, E_i, and t are stiffness, elasticity modulus, and thickness of infill wall.

METHODS

Sigmund and Penava (2012) tested ten specimens that were classified based on presence of opening and its position. Three specimens are used in this study which are type 3/II, 4/II, and 2/III. Type 3/II and 4/II are infilled frame with reinforced eccentric opening of door and window. While type 2/III are infilled frame without opening that will be used as reference model. Figure 2 shows the specimens and its experimental result below.





(a) (b) (c)

FIGURE 2. Specimens of reinforced concrete frames with infill wall, experiment results, and peak loads. (a) Type 3/II, (b) Type 4/II, and (c) Type 2/III

Validating process is started by considering effect of nonlinear material. Stress-strain parametric relation curve of concrete and infill wall masonry are approached by multiple straight lines corresponding to load stages until peak load is reached. Peak loads for each result were 276,33 kN, 248,51 kN, and 277 kN as can be seen on Figure 2. Stress-strain curve of concrete material is constructed by using equation and model proposed by Mander et al. (1984) with assumption maximum stress occurred at peak load. Whereas stress-strain curve of infill wall masonry is calculated using equation and model referred to Kaushik et al. (2007). Elasticity modulus changes is started to occur based on assumption when concrete frame is crack. Crack section of beam and column is modeled by reducing moment of inertia values according to SNI 2847:2019 (BSN, 2019).

After load stages and elasticity modulus changes are derived, modeling infilled frame of the specimens is done by using SAP2000 which are shown in Figure 3. To apply number of load stages, these analytical models need to be replicated with its elasticity modulus values are modified according to curve-fitting results. Because the load is static, displacements of each stage are recorded as points to form the curve.

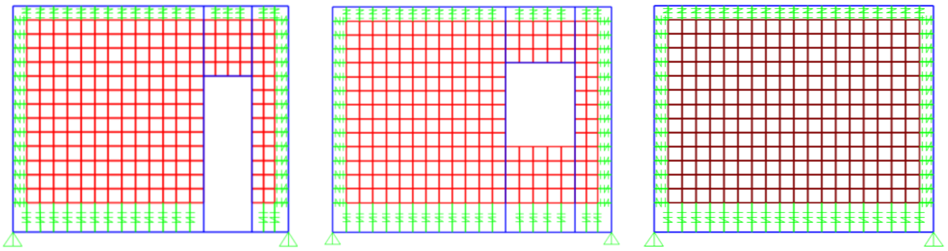


FIGURE 3. Analytical models of specimen type 3/II, 4/II, and 2/III using SAP2000

Analytical model consists of main reinforced concrete frame, infill wall shell elements, and gap between main frame to infill wall. Reinforced concrete of lintel columns and beams as reinforcement around opening are also modeled for infill wall with opening only. The gap elements are modeled as link element with its stiffness calculated refer to Dorji & Thambiratnam (2009). Distance of gap is measured from frame centerline to edge of infill wall. Gap between infill wall and lintels are not considered with assumption lintels are part of infill wall and are not structural component.

RESULT AND DISCUSSION

Stress-Strain Curve-Fitting

Curve-fitting process on constituent materials of all specimens has been done and results can be seen in Figure 4-6. Curve on the left is for concrete material and the right is for infill wall. For concrete material, peak point of stress is the compressive strength valued 58 MPa. While for infill wall material, its compressive strength is 2,7 MPa.

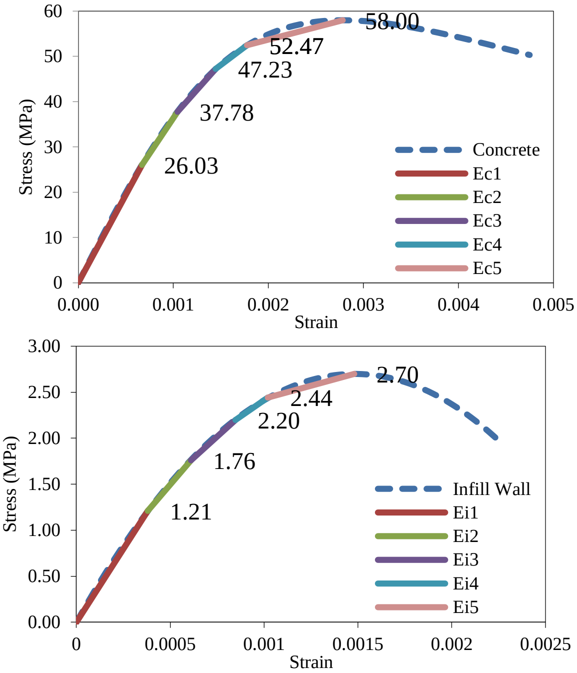


FIGURE 4. Curve-fitting results on concrete and infill wall masonry stress-strain curves of type 3/II

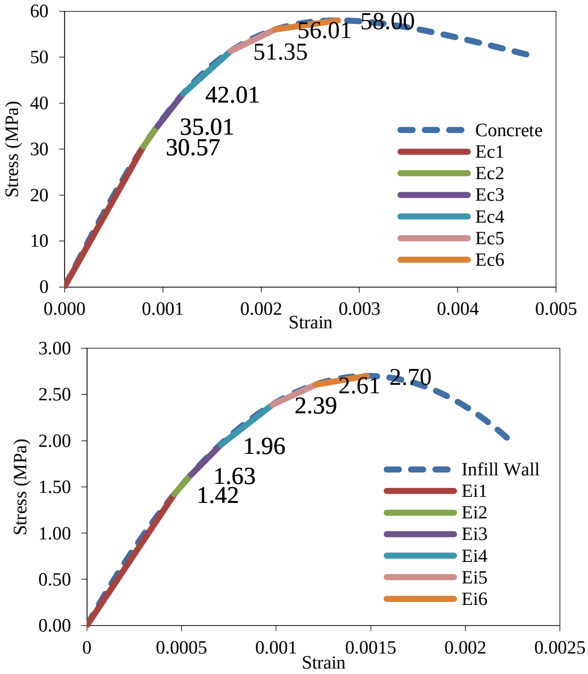


FIGURE 5. Curve-fitting results on concrete and infill wall masonry stress-strain curves of type 4/II

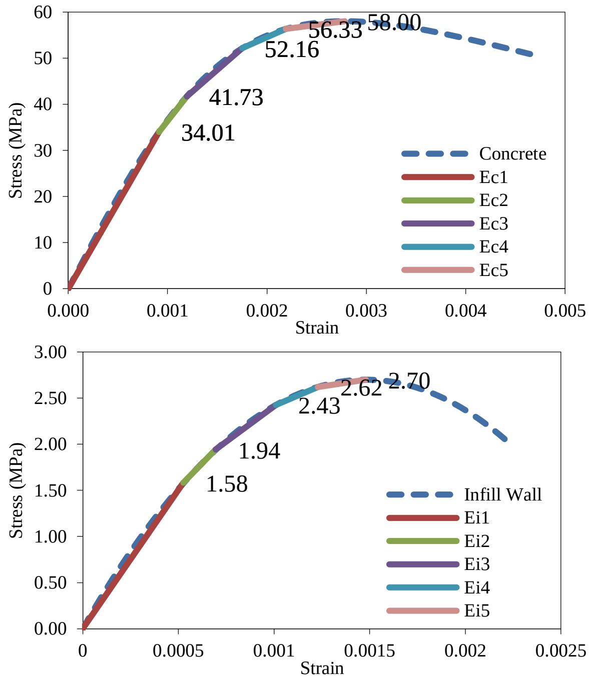


FIGURE 6. Curve-fitting results on concrete and infill wall masonry stress-strain curves of type 2/III

From curve-fitting results can be obtained that there are five to six approaching straight lines that indicates number of elasticity modulus changes and load stages. Load values are calculated from proportion of stress for each stage compared to peak stress. Therefore, percentage of stress achieved on both curve-fitting have to be same. Stage of loads, stresses, strains, and elasticity modulus changes for all models are recapitulated in Table 1-3.

TABLE 1. Curve-fitting values on concrete and infill wall masonry of type 3/II

Stages of Load	**%**	***P* (kN)**	**Concrete**			**Infill Wall**		
			σ (MPa)	**ε ($\times10^{-4}$)**	***E* (MPa)**	**σ (MPa)**	**ε ($\times10^{-4}$)**	***E* (MPa)**
1	45	124,00	26,03	6,70	41000,00	1,21	3,80	3900,00
2	65	180,00	37,78	10,43	36240,68	1,76	6,10	2883,22
3	81	225,00	47,23	14,46	32659,85	2,20	8,47	2595,58
4	90	250,00	52,47	17,77	29537,57	2,44	10,20	2394,83
5	100	276,33	58,00	27,83	20840,82	2,70	14,80	1824,32

TABLE 2. Curve-fitting values on concrete and infill wall masonry of type 4/II

Stages of Load	**%**	***P* (kN)**	**Concrete**			**Infill Wall**		
			σ (MPa)	**ε ($\times10^{-4}$)**	***E* (MPa)**	**σ (MPa)**	**ε ($\times10^{-4}$)**	***E* (MPa)**
1	53	131,00	30,57	8,03	41000,00	1,42	4,62	3900,00
2	60	150,00	35,01	9,46	37007,03	1,63	5,50	2963,11
3	72	180,00	42,01	12,05	34857,60	1,96	7,07	2766,13
4	89	220,00	51,35	16,94	30319,47	2,39	8,00	2439,03
5	97	240,00	56,01	21,42	26150,25	2,61	12,10	2154,99
6	100	248,51	58,00	27,83	20840,82	2,70	14,80	1824,32

TABLE 3. Curve-fitting values on concrete and infill wall masonry of type 2/III

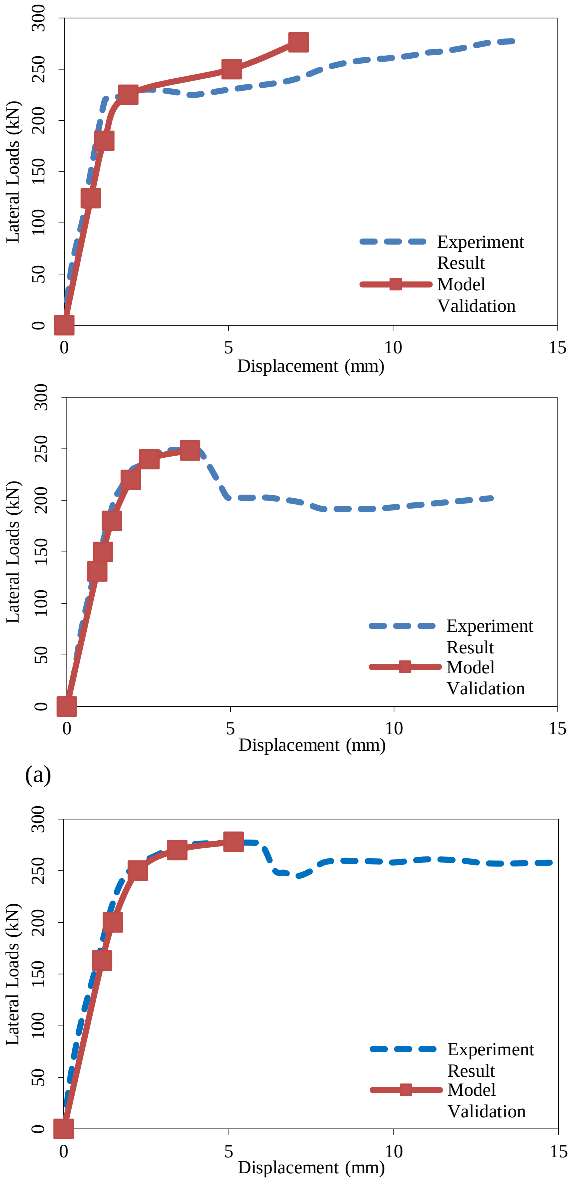
Stages of Load	**%**	***P* (kN)**	**Concrete**			**Infill Wall**		
			σ (MPa)	**ε ($\times10^{-4}$)**	***E* (MPa)**	**σ (MPa)**	**ε ($\times10^{-4}$)**	***E* (MPa)**

1	59	163	34,01	9,13	41000,00	1,58	5,26	3900,00
2	72	200	41,73	11,94	34947,00	1,94	6,95	2794,89
3	90	250	52,16	17,53	29762,00	2,43	10,10	2404,02
4	97	270	56,33	21,90	25722,00	2,62	12,30	2131,95
5	100	277	58,00	27,83	20840,00	2,70	14,80	1824,32

As load stages, load values, and material properties changes are derived and applied to analytical models, validation results is discussed by comparing experimental results to analytical force-displacement curve.

Validation Results

Analytical results from SAP2000 model analysis in form of force-displacement relation curve has been plotted and is compared to experimental results as shown on Figure 7.



(a)

(b)

(c)

FIGURE 7. Force-displacement curve comparison between experimental and analytical results.
(a) Type 3/II, (b) Type 4/II, and (c) Type 2/III

All analytical load-displacement curves are visually lookalike to the experimental especially type 4/II and type 2/III. On type 3/II, three first points of curve are tight to the experiment, but last two points have relatively large deviation. Detail comparison values of displacement between analytical and experimental results are shown in Table 4-6.

TABLE 4. Displacement comparison between experimental and analytical result of type 3/II

Stage	*P* (kN)	*δ* (mm)		Difference (mm)	% Difference (Relative to Analytical)
		Experimental	Analytical		
1	124,00	0,81	0,67	0,14	17,28
2	180,00	1,22	1,00	0,22	18,03
3	225,00	1,95	1,80	0,15	7,69
4	250,00	5,10	7,83	2,73	53,53
5	276,33	7,13	13,06	5,93	83,17

Average difference = 1,83 mm (35,94%)

From Table 4 can be seen that at stage 4 and 5 have the largest difference values of displacement which are 2,73 mm and 5,93 mm which are 53,53% and 83,17% in percentage relative to analytical. There is no clear provision to clarify whether the result is valid or not. However, infill wall masonry material has very high nonlinearity to be modeled accurately.

TABLE 5. Displacement comparison between experimental and analytical result of type 4/II

Stage	*P* (kN)	*δ* (mm)		Differences (mm)	% Difference (Relative to Analytical)
		Experimental	Analytical		
1	131,00	0,93	0,88	0,05	5,38
2	150,00	1,11	1,04	0,07	6,31
3	180,00	1,38	1,28	0,10	7,25
4	220,00	1,96	1,81	0,15	7,65
5	240,00	2,53	2,62	0,09	3,70
6	248,51	3,77	3,75	0,02	0,53

Average difference = 0,08 mm (5,14%)

TABLE 6. Displacement comparison between experimental and analytical result of type 2/III

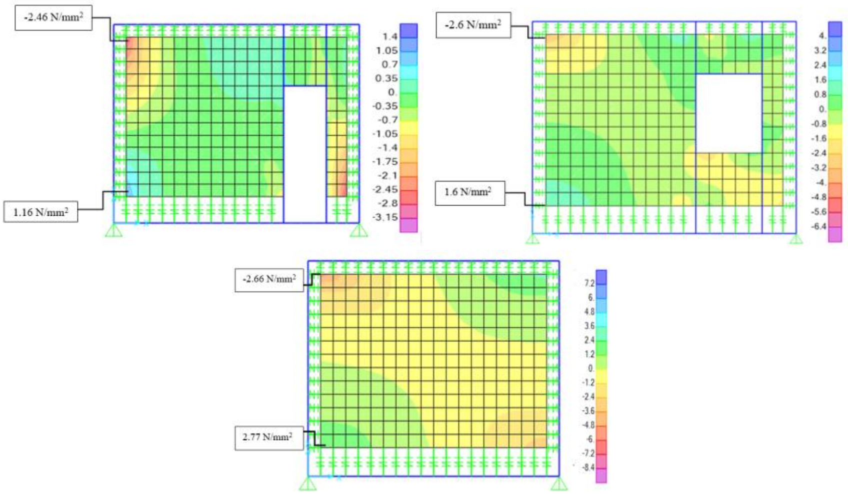
Stage	*P* (kN)	*δ* (mm)		Differences (mm)	% Difference (Relative to Analytical)
		Experimental	Analytical		
1	163	1,16	1,03	0,13	11,21
2	200	1,49	1,33	0,16	10,74
3	250	2,25	2,00	0,25	11,11
4	270	3,44	3,14	0,30	8,72
5	277	5,15	5,90	0,75	14,56

Average difference = 0,32 mm (11,27%)

Model of type 3/II has the largest average difference which is 1,83 mm. While the other two models only have average difference 0,08 mm and 0,32 mm.

Stress Distribution

From analytical results can be observed how stress is distributed around the shell element of infill wall which can be seen in Figure 8.



(a) (b) (c)

FIGURE 8. Stress distribution on shell element. (a) Type 3/II, (b) Type 4/II, and (c) Type 2/III

Stress contour of full infill wall model, which is used as reference model in this study, is at lateral load of 163 kN has compressive stress 2,66 MPa located on the top left corner where lateral load is applied. Compressive stress, indicated by yellow to orange regions, develops diagonally against lateral load direction forming a diagonal strut mechanism. While green regions are tensile stress with maximum value 2,77 MPa. The two other models which have reinforced opening on the infill wall develop same diagonal strut mechanism. This means besides using shell element, analysis using diagonal strut can be done on infill frame with hole. However, need to be studied further on how opening condition affect the stiffness of strut.

CONCLUSION AND SUGGESTION

Study on modeling and validation of experimental test results on infilled frame with eccentric reinforced opening has been done and can be concluded that:

1. Infill wall masonry materials have high nonlinearity that make it very hard to mimic experimental curve result accurately.
2. Achieved as accurate as possible, analytical curve result of type 3/II has the largest deviation at stage 4-5. This stage is in the post linear region of force-displacement curve.
3. No matter there is hole or not, diagonal strut mechanism is still formed. This phenomenon can be used to calculate diagonal strut stiffness in order to do research of infill frame with reinforced eccentric opening using strut analysis or pushover analysis even further.

It can be suggested that need to do more accurate curve-fitting process with increasing number of approaching straight lines. Validation of force-displacement curve need to be done and compared with strut and pushover analysis.

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