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ANALYSIS STUDY OF REINFORCED CONCRETE FRAME STRUCTURES WITH INFILL WALLS DUE TO LATERAL LOADS USING THE EQUIVALENT DIAGONAL STRUT AND FINITE ELEMENT METHOD

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The analysis study of reinforced concrete frame structures with infill walls due to lateral loads using the equivalent diagonal strut (EDS) method proposed by Saneinejad & Hobbs (1995) aims to determine the accuracy in the analysis. This study began by evaluating reinforced concrete frame structures with infill walls as a result of the experiments of Mehrabi et al. (1994) using the finite element method (FEM). Then FEM analysis was carried out on the reinforced concrete frame structure by varying the h_{inf}/l_{inf} of the infill walls with a ratio of 0.50, 0.67, 1.00 and 1.50. Next, the FEM analysis results will be evaluated using the EDS method. The analysis results show that the EDS method can predict the maximum lateral load close to the experimental results and FEM analysis. In the analysis using the EDS method, the friction coefficient (μ) and basic shear stress (v) parameters greatly influence the strength of the infill wall.

Keywords: *infill wall, frame structure, reinforced concrete, equivalent diagonal strut, finite elements*

1 INTRODUCTION

In building structural planning, often in structural analysis the presence of infill walls is ignored and simplified by eliminating infill walls. Structures that do not include infill walls will behave differently from structures that include infill walls when responding to lateral loads, namely earthquake and wind loads. This can be seen from several studies that examine the influence of the behavior of structures that with infill walls and without infill walls, where structures that with infill walls better reflect the behavior of the actual structure [1]-[5]. The presence of infill walls will change the lateral load distribution system on the structure, what was originally a load distribution system on a frame structure became a truss system. This system change is due to the tensile and compressive behavior that occurs along the diagonal of the infill wall [1], [3], [6]-[9]. Changes in this distribution system affect the stiffness of the structure, where the structure becomes stiffer, and there is an increase in the axial load capacity of the column but will reduce its bending and shear capacity. On Reinforced concrete structures can cause a soft story phenomenon, short and torsion columns [1], [3], [10]. Understanding of behavioral changes and the negative impacts of infill walls has long been understood. However, in planning practice, structures are still analyzed without including infill walls, because it is difficult to model the non-linear behavior of infill walls in ordinary elastic analysis.

Research on the behavior of structures that with infill walls began to be intensively carried out when Rathbun (1938) reported that infill walls contributed to the structural stiffness of the Empire State Building in New York in resisting lateral loads due to wind [11], [12]. After this incident, a lot of research was carried out both experimentally and analytically based on elastic, plastic theory and finite element methods to find empirical equations for modeling infill walls. Research was carried out, among others, by Polyakov (1960), Holmes (1961), Smith (1966), Smith & Carter (1969), Mainstone, (1971), Liauw & Kwan (1983), Saneinejad & Hobbs (1995), El-Dakhakhni (2002) and El-Dakhakhni et al. (2003), in general, the researchers concluded that under lateral loads a full infill wall (without openings) will behave as a diagonal strut at both corners [6], [11], [13]-[19], as shown in Figure 1 therefore, and for analysis, the infill wall can be modeled as an equivalent diagonal strut (EDS).

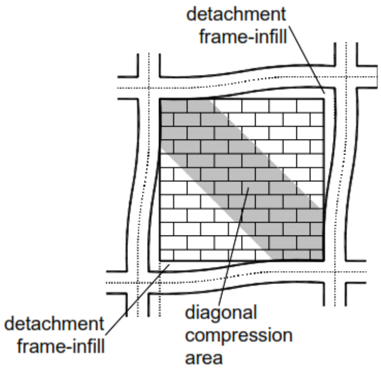


Fig. 1. EDS on infill walls, Source: [10]

The EDS equations proposed by the researchers above are different from each other [20]-[22]. Asteris et al. (2011) conducted a study of various EDS equations, concluding that each equation has advantages and disadvantages and is still open to study [21]. Likewise, research conducted by Crisafulli et al. (2000) stated that the EDS model is simple and efficient where the equation formulation is based on a physical representation of the behavior of frame structures with infill walls [22]. Amalia & Iranata (2017) conducted research comparing various EDS equations and found that the equation proposed by Saneinejad & Hobbs (1995) was one of the equations whose analysis results lie between structures without infill walls and those with infill walls [19], [20]. This equation uses an inelastic analysis method which takes into account the elastic and plastic behavior of infill wall frame structures and the analysis results provide predictions that are close to experimental results and finite element analysis results compared to other EDS methods [1].

The Indonesian region is prone to earthquakes, a good understanding of planning earthquake-resistant structures is very necessary [23, 24, 25]. One solution for planning earthquake-resistant building structures is to understand the EDS method in planning reinforced concrete frame structures with infill walls. This research discusses the EDS method proposed by Saneinejad & Hobbs (1995) [19] which is used to evaluate reinforced concrete frame structures with infill walls which are analyzed using the FEM. The reinforced concrete frame structure with infill walls used as a reference is the result of experiments carried out by Mehrabi et al. (1994) [26].

2 EQUATION BY SANEINEJAD & HOBBS (1995)

The EDS method assumes a frame structure with infill walls as a braced frame with infill walls that are only strong against compressive forces. If the mechanical properties of the EDS are known then the structure can be analyzed as an open frame structure. The mechanical properties of EDS are determined based on the strength of the filler wall in resisting lateral loads. The failure of infill walls to withstand lateral loads is determined by three failure methods, namely, corner crushing (CC) where the corner is destroyed, at least at one of the diagonal ends, diagonal compression (DC) where the infill wall is destroyed in the middle of the diagonal and Shear slip (SS), namely horizontal shear failure in the grout connection of the infill wall [10], [19], as shown in figure 2.

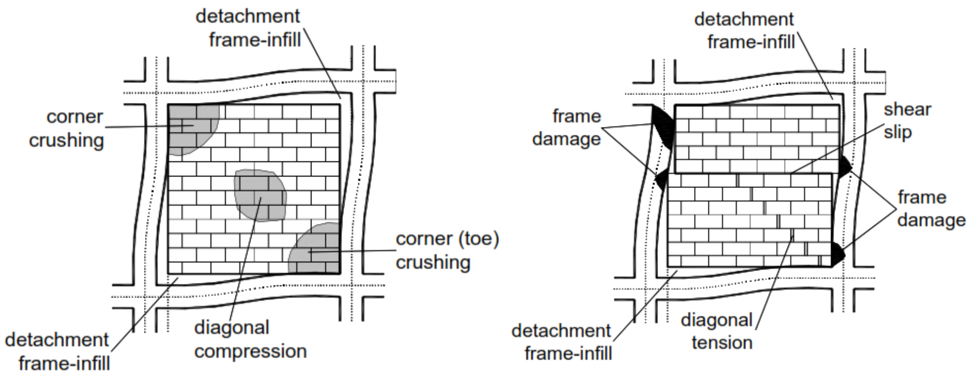


Fig. 2. Infill wall failure model, Source: [10]

The steps for EDS equation analysis according to Saneinejad & Hobbs (1995) [19] are as follows.

1. Specifying values for parameters:
   a. coefficient of friction (μ) and basic shear stress (v) of infill walls based on standards or research results
   b. $r = \frac{h\ (height)}{l\ (width)}$.
   c. θ = *arctan* r
   d. effective compressive stress of the infill wall.

$$f_a = 0.6\phi f_m \tag{2.1}$$

   With: $\phi = 0.65$, θ = angle from the ratio of the height and width of the infill wall and f_m = compressive strength of masonry
2. Determine the bearing capacity of the frame structure with infill walls based on the failure conditions of the infill walls. CC, DC and SS with the following equation.
   a. CC failure,

$$\mathrm{R} = \mathrm{R_{cc}} = \frac{(1-\alpha_c)\alpha_c th\sigma_c + \alpha_b tl\tau_b}{\cos\theta} \tag{2.2}$$

   With: R = R_{CC} = load (N), α_c = percentage of column contact area length, t = wall thickness (mm), h = frame height (mm), σ_c = normal contact stress (MPa), α_b = percentage of beam contact area length, l = frame width (mm) and τ_b = shear contact stress (MPa).
   b. DC failure,

$$\mathrm{R} = \mathrm{R_{Dc}} = \frac{0.5.h\prime.t.f_a}{\cos\theta} \tag{2.3}$$

With: R = R_{DC} = load (N), h' = clear height of the frame (mm), t = wall thickness (mm), f_a = actual compressive strength of the infill wall (MPa), and θ = compression diagonal angle (degrees).

c. SS failure

$$R = R_{ss} = \frac{\gamma.v.t.l'}{(1-0.45\tan\theta')\cos\theta} < \frac{0.83\gamma.t.l'}{\cos\theta} \quad (2.4)$$

With: R = R_{ss} = load (N), γ = load factor, v = basic shear stress (MPa), t = wall thickness (mm). l' = net width of the portal (mm), and θ = compression diagonal angle (degrees).

3. Determine the horizontal force that causes cracks in the infill wall (H)

$$H = R\cos\theta + \frac{2M_{pj}}{h} \quad (2.5)$$

With: H = horizontal force (N), θ = compression diagonal angle (degrees), and M_{pj} = plastic moment resistance (N.mm).

4. Determining Lateral Deformation (Δh)

$$\Delta h = 5.8.\varepsilon_c.h.\cos(\alpha_c^2 + \alpha_b^2)^{0.333} \quad (2.6)$$

With: Δh = lateral deformation (mm), $\boldsymbol{\varepsilon_c}$ = strain in concrete, h = frame height (mm), α_c = percentage of column contact area length (mm), and α_b = percentage of beam contact area length (mm).

5. Determine the area parameters (A_d) and initial elastic modulus (E_{do}) of the EDS

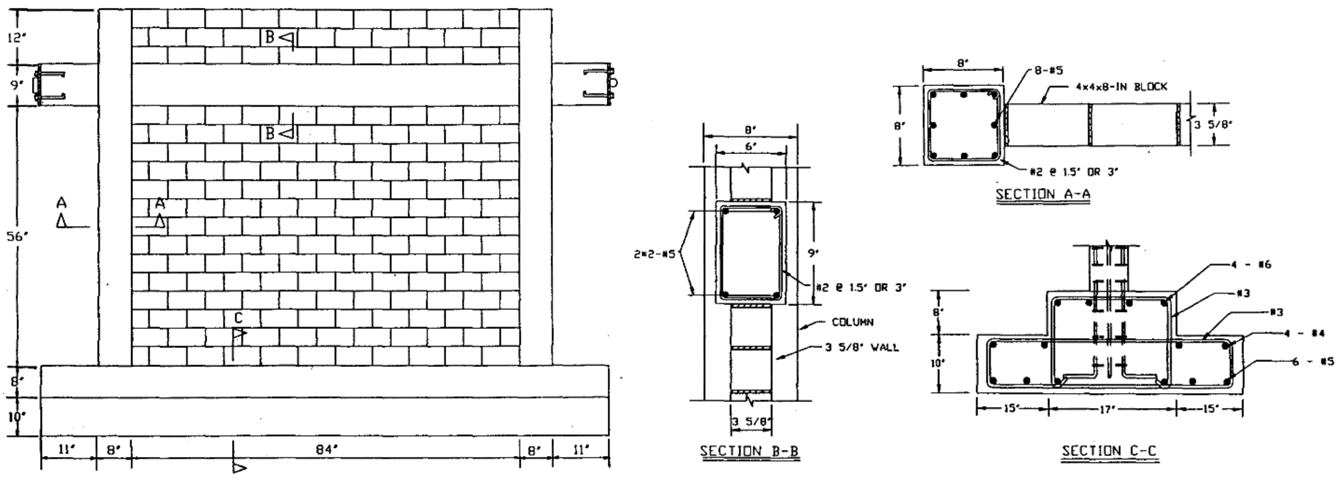
$$A_d = \frac{R}{f_a} \quad (2.7)$$

$$E_{d0} = \frac{2hf_c}{\Delta_h\cos^2\theta} \quad (2.8)$$

With: A_d = EDS area (mm2), R = load (N), f_a = effective compressive stress of the infill wall (MPa), E_{do} = initial modulus of elasticity (MPa), and θ = compression diagonal angle (degrees).

3 RESEARCH METHODS

The research was carried out analytically, the EDS method was used to evaluate the results of the finite element method analysis of frame structures with infill walls. The infill wall frame structure used is the result of experiments carried out by Mehrabi et al. (1994) [26]. Experimental data is presented in Figure 3 and Table 1 below.



Source: [26]

Fig. 3. Experimental model of frame structure with infill walls

Table 1. Infill wall frame structure

Frame and infill wall parameters					
Frame parameters	Value	Unit	Infill wall parameters	Value	Unit
H	1573	mm	H_{inf}	1422	mm
L	2312	mm	L_{inf}	2134	mm
b_c	178	mm	b_{inf}	184	mm
h_c	178	mm	t_{inf}	92	mm
b_b	153	mm	E_{inf}	9515	MPa
h_b	229	mm	f_m	15.09	MPa
			v_m	0.41	MPa

<table>
<tr><th colspan="8">Frame and infill wall parameters</th></tr>
<tr><th>Frame parameters</th><th>Value</th><th>Unit</th><th colspan="3">Infil wall parameters</th><th>Value</th><th>Unit</th></tr>
<tr><td rowspan="2">h_b</td><td rowspan="2">229</td><td rowspan="2">mm</td><td colspan="3">ε_m</td><td>0.0029</td><td></td></tr>
<tr><td colspan="3">μ_m</td><td>0.45</td><td></td></tr>
<tr><td colspan="2"></td><td colspan="3">Concrete</td><td colspan="3"></td></tr>
<tr><td colspan="2">Tensile Stress (MPa)</td><td colspan="3">Strain at max tension ε_{cu}</td><td colspan="3">Secant modulus (MPa)</td></tr>
<tr><td colspan="2">3.289</td><td colspan="3">0.0018</td><td colspan="3">21925.334</td></tr>
<tr><td colspan="8">Steel</td></tr>
<tr><td>Diameter (mm)</td><td colspan="3">Yield stress (MPa)</td><td colspan="2">Ultimate stress (MPa)</td><td colspan="2">Elasticity (MPa)</td></tr>
<tr><td>6.35</td><td colspan="3">367.49</td><td colspan="2">449.54</td><td colspan="2">200000</td></tr>
<tr><td>12.70</td><td colspan="3">420.58</td><td colspan="2">661.90</td><td colspan="2">200000</td></tr>
<tr><td>15.88</td><td colspan="3">413.69</td><td colspan="2">661.90</td><td colspan="2">200000</td></tr>
</table>

Source: [26]

FEM analysis uses the Lusas finite element analysis (Lusas FEA) program, where the frame structure with infill walls is modeled as 2D plane elements and concrete reinforcement as bar elements. The lateral load is modeled as a monotonic load with a maximum load increase of 5 kN until the program stops iterating if the limit strain of one of the materials is exceeded. A static vertical load of 294 kN was applied to both columns to simulate the load from the top floor [26]. In order to ensure the reliability and accuracy of the analysis, the Lusas FEA program is first calibrated. Calibration was carried out by evaluating the frame structure with infill walls from the experimental tests of Mehrabi et al. (1994) [26]. Modeling of the frame structure with infill walls results as shown in Figure 4.

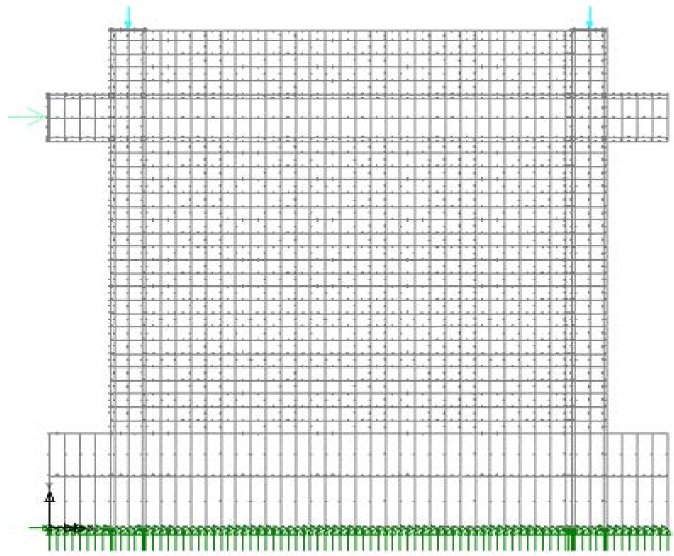


Fig. 4. FEM model for frame structure with infill walls, Source: Prepared by the authors (2024)

Model calibration input data that produces loads and lateral deformations that are close to experimental results is used in subsequent analysis, namely by varying the ratio of height (h_{inf}) and width (l_{inf}) of the infill wall, as shown in table 2.

Table 2. Variations in h_{inf}/l_{inf} comparison

h_{inf}/l_{inf}	h_{inf} (mm)	l_{inf} (mm)
0.50	1000	2000
0.67*	1422	2134
1.00	2000	2000
1.50	3000	2000

*infill wall Mehrabi et al. (1994)

Source: Prepared by the authors (2024)

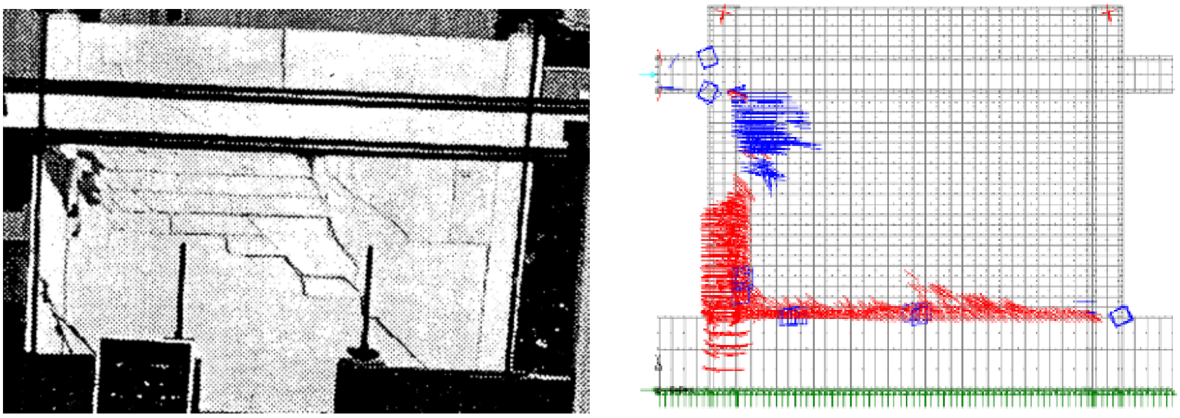
3.1 Model Calibration

The analysis results obtained by comparing the maximum lateral loads and displacements that occur in frame structures with infill walls are presented in table 3 below.

Table 3. Comparison of analysis results of frame structures with infill walls

Analysis	Load	Deformation
	P_U (KN)	Δ_u (mm)
Experiment	277.57 (100%)	3.30 (100%)
FEM	278.91 (100,48%)	2.61 (79.09%)

Source: Prepared by the authors (2024)



Source:[26]
a. Experiment

Source: Prepared by the authors (2024)
b. FEM

Fig. 5. Crack pattern at maximum load

From the analysis results it can be concluded that the maximum lateral load from the FEM analysis is close to the experimental results with a comparison difference of 0.48%. The crack pattern of the infill wall at maximum load from the experimental results as shown in Figure 5, shows the same crack pattern as the FEM analysis results, where failure occurs due to shear (SS), corner failure (CC) and diagonal failure (DC). Thus, the model settings and data input in the Lusas FEA program are appropriate and can be used for further analysis.

4 RESULTS AND DISCUSSION

The results of the analysis of maximum lateral loads on frame structures with infill walls based on the EDS and FEM methods are presented in table 4 and figure 5.

Table 4. Analysis results of EDS and FEM methods

h_{inf}/l_{inf}	Load (kN)		Deformation (mm)		Stiffness (kN/mm)	
	EDS	FEM	EDS	FEM	EDS	FEM
0.50	203.43 (58.84%) SS	345.71 (100%) SS, CC	6.24	2.24	32.60	154.33
0.67	215.49 (77.26%) SS	278.91 (100%) SS, CC	6.83	2.61	31.55	106.86
1.00	256.34 (104.95%) SS	244.25 (100%) SS, CC	7.42	3.78	34.55	64.62
1.50	216.76 (122.48%) CC	176.98 (100%) SS, CC	8.10	5.15	26.76	34.37

Source: Prepared by the authors (2024)

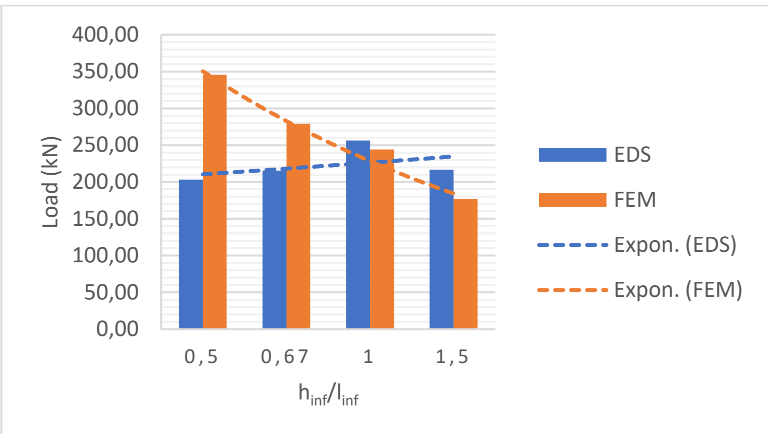


Fig. 5. Maximum lateral load EDS and FEM methods, Source: Prepared by the authors (2024)

From table 4 it can be seen that only h_{inf}/l_{inf} = 1.00 provides predictions of lateral load capacity close to experimental results with a difference of 4.95%, while variations of 0.50, 0.67 and 1.50 each have a difference of -41%. .16%, -37.67% and 22.48%. From Figure 5 it can also be seen that the trend line on the FEM analysis results graph has decreased, in contrast to EDS which has increased. This can also be seen from the structural stiffness value, in FEM analysis, the greater the h_{inf}/l_{inf} ratio or the slimmer the structure, the stiffness of the structure will be degraded or reduced, but in EDS analysis it is different. This difference is caused by the EDS parameters taken, namely the friction coefficient (μ) and basic shear strength (v) based on the relevant regulations, in this analysis they are taken based on the provisions of ACI318-88 [19]. According to Choon & Ingham (2003) and Dautaj et al. (2019) stated that the friction coefficient and base shear stress parameters are closely related to the compressive strength of the infill walls, where the greater the μ and v values, the greater the compressive strength of the infill walls, with a non-linear increase.

The influence of lateral loading on the strength of infill wall materials has been widely studied, in general there are two parameters that are often studied, namely behavior and resistance factors. The resistance of infill walls is related to shear resistance, shear modulus and tensile strength, where shear resistance depends on geometry, μ and v [28-30]. The μ value proposed by Paulay & Priestly (1992) is 0.3-1.2, Lourenço et al. (2004) of 0.7-1.2, Abdou (2006) of 0.88 for solid and 0.89 for hollow bricks, and Vermeltfoort (2010) of 0.66-0.91. The v value according to Saneinejad & Hobbs, (1995) is 0.25-0.41 MPa, and Lavado & Gallardo (2019) is 0.39-0.51 Mpa [19, 28-32].

Based on the description and research results above, a re-analysis was carried out for the EDS method using a μ value of 1.2 and v of 0.51. The results of the analysis are shown in table 5 and figure 6 below.

Table 5. Analysis results of EDS (reanalysis) and FEM method

h_{inf}/l_{inf}	Load (kN)		Deformation		Stiffness (kN/mm)	
	EDS	MEH	EDS	MEH	EDS	MEH
0.50	237.39 (68.67%) SS	345.71 (100%) SS, CC	6.24	2.24	34.656	154.33
0.67	253.48 (90.88%) SS	278.91 (100%) SS, CC	6.83	2.61	32.415	106.86
1.00	282.53 (115.67%) SS	244.25 (100%) SS, CC	7.42	3.78	31.219	64.62
1.50	175.34 (99.07%) CC	176.98 (100%) SS, CC	8.10	5.15	17.073	34.37

Source: Prepared by the authors (2024)

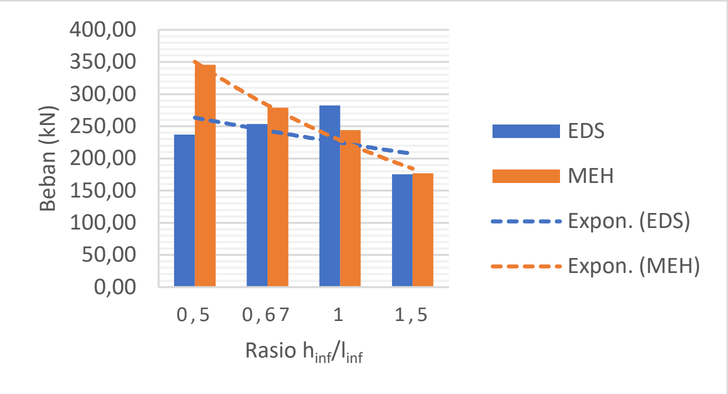


Fig. 6. Maximum lateral load EDS (reanalysis) and FEM methods, Source: Prepared by the authors (2024)

From table 5 it can be seen that after adjusting the μ value of 1.2 and v of 0.51, the EDS analysis results are closer to the FEM results, as well as the stiffness of the structure and the graph in figure 6 shows the same trend where the greater the h_{inf}/l_{inf} ratio or the slimmer the structure, the stiffness of the structure will decrease. Collapse at the maximum load from the FEM analysis results was caused by CC and SS failure, while the EDS analysis results at the h_{inf}/l_{inf} ratio, namely 0.50, 0.67 and 1.00, SS failure occurred and 1.50 occurred CC failure.

The results of the EDS method analysis show that the parameters μ and v have a significant effect on the resistance of the infill wall under the influence of lateral loading, where the greater the value of μ will increase the resistance of the infill wall to the risk of failure due to CC, DC and SS while the parameter v only has an effect on increasing the resistance of the infill wall at the collapse of the SS. Using parameter values μ = 1.2 and v = 0.51 in the EDS method provides maximum lateral load predictions close to the experimental results of Mehrabi et al. (1994), where the EDS result was 253.48 kN (91.32%) and the experimental results of Mehrabi et al. (1994) of 277.57 kN (100%), with a difference of -8.68%. Evaluation of the analysis results of the FEM method, at a h_{inf}/l_{inf} ratio of 0.50, the EDS method gives conservative prediction results of 68.67% or a difference of -31.33%, while at ratios of 0.67, 1.00 and 1.50 it gives good prediction, with differences respectively of -9.12%, 15.67% and -0.93% to FEM results.

5 CONCLUSIONS

The analysis of reinforced concrete frame structures with infill walls requires an accurate approach to predict the behavior and capacity of the structure under lateral loading. Various methods have been developed to enhance the precision of the analysis, one of which is the use of the Equivalent Diagonal Strut (EDS) method. Based on the results of an analysis study of the use of the EDS and FEM methods in reinforced concrete frame structures with infill walls, which has been carried out can be concluded as follows:

1. FEM analysis using the Lusas FEA program and the EDS method with parameters μ of 1.2 and v of 0.51 provides predictions of maximum load capacity close to the experimental results of Mehrabi et al. (1994) with a respective difference of 0.48% for FEM analysis and -8.68% for EDS.
2. The parameters μ and v analysis in EDS greatly influence the resistance of infill walls due to lateral loading, where the μ value influences the risk of failure due to CC, DC and SS and the μ value only influences SS collapse, so the greater the value, the greater it is resistance of infill walls due to lateral loads.
3. The h_{inf}/l_{inf} ratio influences the stiffness of the structure, where the greater the h_{inf}/l_{inf} ratio, the smaller the structural stiffness.

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