ANALYTICAL REVIEW ON THE VARIATION OF EQUIVALENT DIAGONAL STRUT WHILE MODELING THE MASONRY INFILL'S

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Abstract

Since long Masonry Infills (MI) are being used to fill the voids between the horizontal and the vertical structural elements such as beams and columns. They are treated as non-structural elements and they are not considered during the analysis and design of the structure. But, when Laterally loaded, the MI tends to interact with the RC frame, changing the structural behavior. Here, in this study, an attempt is being made to incorporate the MI in the form an Equivalent Diagonal Strut (EDS), whose width is calculated using the various relations proposed by the researchers. A general review of the relations proposed by the Researchers in calculating the width of the EDS is being made and compared. The paper also focuses to study the variation in the Deflection and the Stiffness in the frame by modeling the MI as EDS and performing the linear analysis. The software being used for the analysis is ANSYS.

Keywords: *Masonry Infill (MI), Infilled frames (IF), Equivalent Diagonal Strut (EDS), Deflection, Stiffness.*

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1. INTRODUCTION

Masonry infill are commonly used in buildings for functional and architectural purposes. They are often used to protect the inside of the building from the external environment (wind, rain, snow etc.) or used as partitions - to divide the spaces within. The MI will add on to the Base shear of the structure and these gravity loads does not pose much of a problem. It is assumed that the MI do not contribute in resisting any kind of loads either axial or lateral and hence their structural contributions are usually neglected in the design process. However, masonry infill tends to interact with the surrounding RC frame when the structure is subjected to lateral loads. It has been recognized that RC frames with masonry infill have more strength and rigidity in comparison to that of the bare frames and the ignorance of masonry infill has become the cause of failure of many multi-storey buildings. The main reason for failure being the stiffening effect of the masonry IF frame that changes the basic behavior of buildings when laterally loaded and creating a new failure mechanism.

2. LOAD TRANSFER MECHANISM

Masonry infill panels, confined by reinforced concrete frames on all four sides, play a vital role in resisting the lateral seismic loads on buildings. It has been shown experimentally that masonry infill panels have a very high initial lateral stiffness and low deformability. Thus introduction of infill panels in RC frames changes the lateral-load transfer mechanism of the structure from predominant frame action as represented in fig.1.a, to predominant truss action as represented in fig.1.b and both truss and frame action as represented in fig.1.c.

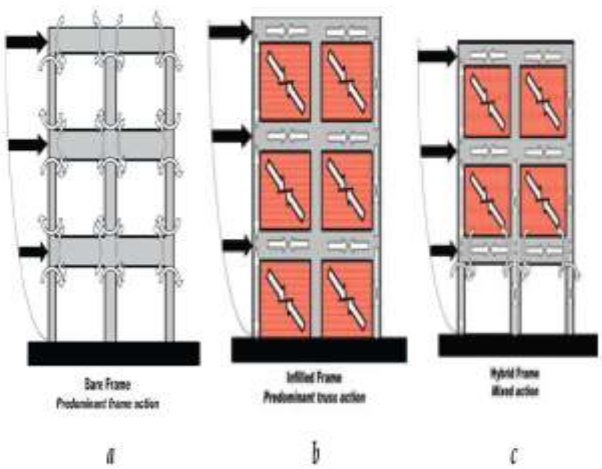

Fig 1: Load Transfer Mechanism [3].

2.1 Failure Mechanism with Infills

MI also contribute to the failure of the reinforced concrete frame when subjected to seismic loading. As the structure is laterally loaded, the frame will displace as depicted in fig.2. Once this situation arises, the masonry infill starts to act on the column and beam. The infill causes plastic hinges in the frame at the contact points which will lead to a multitude of failure modes (Paulay and Priestley, 1992)[8].

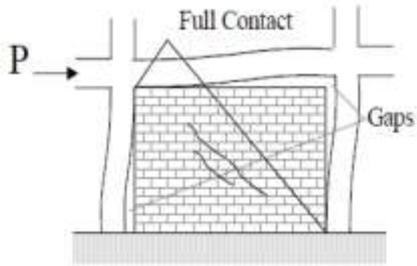

Fig 2: Displacement of frame under Lateral loads [8].

When laterally loaded, the MI are compressed at the loaded corner and the MI are elongated (stretched) at the Unloaded corner-where the MI gets separated out from the frame as depicted above in fig.2.

3. EFFECTS OF MASONRY INFILLS

- Unequal distribution of lateral forces.
- Vertical irregularities in strength and stiffness.
- Horizontal irregularities.
- Inducing the effect of short column or captive column in IF frame.
- Failure of masonry IF - out of plane and in plane failure.

4. MODELING OF MASONRY INFILLS

The study of interaction of MI with RC frames has been attempted by using analysis like finite element analysis (FEA) or theory of elasticity. An approximate method of analysis was acceptable because of the uncertainty that was involved in defining the interface conditions between the masonry IF with the RC frames. Several methods for analysis of IF frames had been proposed by various investigators. These methods could be divided into two groups depending on the degree of refinement used to model the structure. The first group consists of the **macro models** to which the simplified models belong which are based on physical understanding of the structure (Equivalent Diagonal Strut). The second group involves the **micro models** including the finite element formulations where local effects in detail are taken into account.

Macro Models

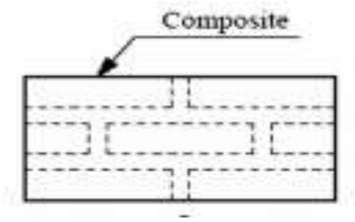

Fig 3: Macro modeling [10].

According to this procedure, no distinction between the individual masonry units and joints was made, and masonry was considered as homogeneous, isotropic or anisotropic continuum as shown above in fig.3. While this procedure would be preferred for the analysis of large masonry structures, it was not suitable for a detailed stress analysis of a small panel. It was due to the fact that it was difficult to capture all its failure mechanisms. The influence of mortar joints acting as planes of weakness could not be accounted for.

The macro-model of an IF frame structure included the stiffness effects of the infill as a pair of diagonals in the bays of the frame. The diagonals were considered as resisting only compression axial loads. Their lines of action intersected the beam-column joints. In the current study macro modeling of MI is being adopted.

Micro Models

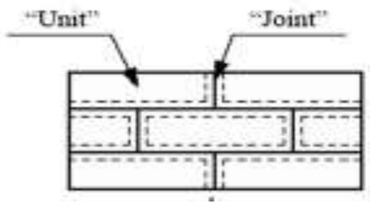

Fig 4: micro modeling [10].

The development of finite element methods offered some relief to the shortcomings pointed out in the previous methods. According to this procedure, the masonry units, the mortar, and the unit-mortar interface were modeled separately as depicted in fig.4. While this led to more accurate results, the level of refinement meant that any analysis would be computationally intensive, and hence its application would be limited to small laboratory specimens and structural details.

5. CALCULATION OF THE WIDTH OF EQUIVALENT DIAGONAL STRUT

Many researchers have worked and made contributions in the field of analyzing an RC frame by considering the MI. Some of the researchers who contributed towards this were, Holmes, Smith and Carter, Mainstone, Mainstone and Weeks, Liaw & Kwan, Decanini & Fantin, Paulay & Priestley, Durrani & Luo and Hendry. Equivalent Diagonal Strut Method is used for modeling the infill wall. In this method the infill wall is idealized as diagonal strut and the frame is modeled as beam or truss element. Frame analysis techniques are used for the elastic analysis.

The width of the equivalent diagonal strut (*w*) can be found out by using a number of expressions [2], [4], given below by different researchers represented in the Equations Eq1.0 to Eq.10.

1) According to Holmes:

$$w = \frac{d_z}{3}$$ Eq.1

2) According to Mainstone and Weeks:

$$w = 0.175 d_z (\lambda_h H')^{-0.4}$$ Eq.2

3) According to Liaw and Kwan:

$$w = \frac{0.95 H \cos\theta}{\sqrt{\lambda_h H'}}$$ Eq.3

4) According to Decanini and Fantin:

(For uncracked masonry) -

$$w = \left(\frac{0.748}{\lambda_h} + 0.085\right) d_z$$ --------------Eq.4

5) According to Decanini and Fantin:

(For cracked masonry) -

$$w = \left(\frac{0.707}{\lambda_h} + 0.01\right) d_z$$ -----------Eq.5

6) According to Paulay and Priestly:

$$w = \frac{d_z}{4}$$ --------------Eq.6

7) According to Durrani and luo:

$$w = \gamma \sqrt{L'^2 + H'^2} \sin 2\theta$$ --------------Eq.7

where,

$$m = 6\left[1 + \frac{6E_b I_g H'}{\pi E_b I_c L'}\right]$$ ----------- EQ.7.1

$$\gamma = 0.32\sqrt{\sin 2\theta}\left[\frac{H'^4 E_i t}{m E_b I_s H}\right]^{-0.1}$$ ---------- Eq.7.2

8) According to P100/1 - 2006:

$$w = \frac{d_z}{10}$$ ----------- Eq.8.0

9) According to Mainstone:

$$w = 0.16 d_{inf} (\lambda_h H_{inf})^{-0.3}$$ -----------Eq.9.0

10) According to Hendry:

$$w = 0.5\sqrt{\alpha_h^2 + \alpha_L^2}$$ ----------Eq.10.0

$$\alpha_h = \frac{\pi}{2}\left[\frac{4E_c I_c H_{inf}}{E_{inf} t \sin 2\theta}\right]^{1/4}$$ ------------Eq.10.1

6. PRESENT STUDY

In the study here, an effort was being made to study and review the formulae given by various researchers in calculating the Equivalent width of the Diagonal strut. With this, the variation in the width of the EDS calculated was being observed.

The study was being undertaken with reference to the frame considered by Diana [5], wherein a single bay, single storey-RC frame (Frame-1), with suitable dimensions was being considered as shown below (fig.5) and the software SAP-2000 was being used for analysis. This frame was again being analyzed using the software package ANSYS 10.0 and appropriate conclusions were drawn with the help of graphs, in terms of deflection and stiffness. The study proposed a comparison of the results and indicated the most suitable relation to be used in practical design.

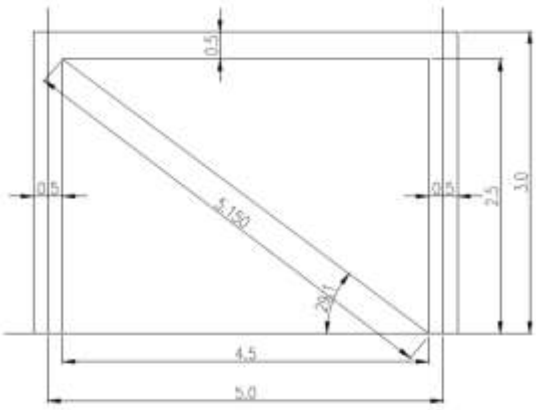

Fig 5: Dimensions of the frame (Frame–1).

The geometrical properties and the material properties considered for the Frame-1 were as tabulated in table 1 and table 2.

Table 1 - Geometrical parameters:

Frame Element	**Sectional Dimensions (mm)**	**M.I of the section (mm^4)**
Beam	250 x 500	$I_g = 2.6 \times 10^9$
Column	500 x 500	$I_s = 5.21 \times 10^9$

Table 2 - Material properties:

Materials	**Mod. of Elasticity (N/mm^2)**	**Poisson Ratio**
Concrete (f_{ck} = 25)	$E_b = 25 \times 10^3$	0.2
Masonry	$E_z = 4.5 \times 10^3$	0.19

Note: The thickness of the infill wall was being considered as 250 mm and the angle of inclination of the equivalent diagonal strut with the horizontal was being calculated - as θ = 29.1°.

The Width of the EDS were being calculated using the relations predicted by various researchers i.e. Equations no. 1 to 10 discussed earlier. The various parameters accounted for in calculating the width of the EDS by the researchers were as tabulated in Table 3.0. The calculated widths using the relations were tabulated below in Table 4.0.

Table 3 - Parameters considered by the Researchers in calculating the EDS:

Researcher	Ei	Ef	L	L'	h	h'	Ic	θ	d'
Holmes	N	N	N	N	N	N	N	N	Y
Smith & Carter	Y	Y	Y	Y	Y	Y	Y	Y	Y
Mainstone	Y	Y	Y	Y	Y	Y	Y	Y	Y
Mainstone & Weeks	Y	Y	Y	Y	Y	Y	Y	Y	Y
Liaw & Kwan	Y	Y	Y	Y	Y	Y	Y	Y	Y
Decanini & Fantin 1	Y	Y	Y	Y	Y	Y	Y	Y	Y
Decanini & Fantin 2	Y	Y	Y	Y	Y	Y	Y	Y	Y
Paulay & Priestley	N	N	N	N	N	N	N	N	Y
Durrani & Luo	Y	Y	Y	Y	Y	Y	Y	Y	N
P100/1 - 2006	N	N	N	N	N	N	N	N	Y
Hendry	Y	Y	Y	Y	Y	Y	Y	Y	N

Y - considered.
N - Not considered.

where,
E_i - Modulus of Infill.
E_f - Modulus of frame.
L - Length of beam b/w centre line of columns.
L' - Length of Infill wall.
h - Column height.
h' - Height of Infill.
I_c - M.I of columns
θ - Angle of inclination of the diagonal strut.
d' - Length of the diagonal strut.

From the above Table 3.0, it has been observed that,
a) Researchers Holmes, Paulay and Priestly and p100/1 - 2006 had derived the width of the EDS which solely depended on the *Length of the Diagonal strut (d')*. No others parameters were considered in deriving the relation for the width of the EDS.

b) Researchers Smith & Carter, Mainstone, Mainstone & Weeks, Liaw & Kwan, Decanini & Fantin had *included all the parameters* in deriving the relation for calculating the width of the EDS.

c) Researchers Durrani & Luo and Hendry had included all the parameters except for the Length of the Diagonal strut in deriving the relation for calculating the width of the EDS.

Table 4 - Width of equivalent diagonal strut using various formulae:

SL. NO.	RESEARCHERS	WIDTH OF EDS (mm)
1	HOLMES	1720
2	SMITH & CARTER	4630
3	MAINSTONE	604.5
4	MAINSTONE & WEEKS	590
5	LIAW & KWAN	1200
6	DECANINI & FANTIN 1	4600
7	DECANINI & FANTIN 2	4000
8	PAULAY & PRIESTLEY	1290
9	DURRANI & LUO	1006
10	P100/1 - 2006	520
11	HENDRY	1340

From the above Table 4.0, it has been observed that, for the same Frame-1,
a) Relations proposed by smith & Carter, Decanini & Fantin 1 and Decanini & Fantin 2, had generated very high values for the width of the EDS between 4000 to 4630 mm.
b) Whereas relations proposed by Liaw & Kwan, Paulau & Priestly and Hendry had generated values between 1200 to 1340 mm for the width of the EDS.
c) Mainstone, Mainstone & Weeks and P100/1-2006 relations had generated values between 520 to 600 mm for the width of the EDS.

The graph of the width of the EDS v/s Researchers plotted was as shown below in fig.6.

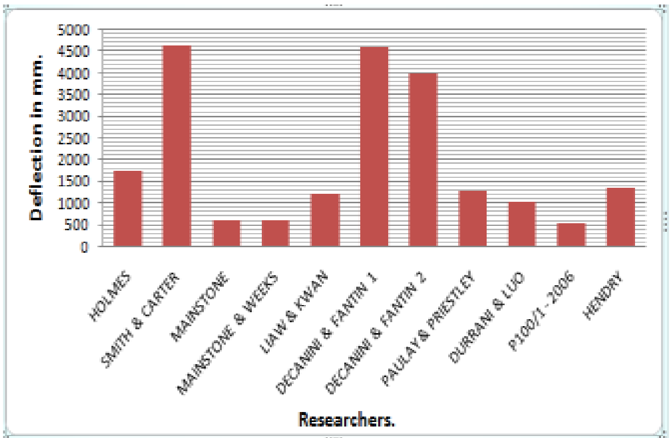

Fig 6: Bar graph representing the variation in the width of the EDS.

Discussion*:* With reference to the graph (fig.6), a large variation in the width of the EDS calculated was being observed.
a) A few relations had generated very large values while a few had generated moderate and less values.
b) Smith & Carter, Decanini & Fantin 1 and Decanini & Fantin 2 relations generated very high values of the Diagonal strut width although it accounted for all the parameters. On the contrary, P100/1 - 2006 relation generated the least value of the Diagonal strut width wherein it didn't account for all

the parameters. It only depended on the Length of the Diagonal strut.

c) The widths of the Diagonal strut calculated using Holmes and Paulay & Priestly relations didn't account for all the parameters. The widths depended solely on the Length of the Diagonal strut.

d) Mainstone, Mainstone & Week's relations generated values very close to each other and they also accounted for all the parameters in their relations.

7. LINEAR ANALYSIS ON THE FRAME

In the Linear analysis of the frame, the parameters deflection and stiffness was found to be depending on the width of the diagonal strut. To study this, the Frame-1 was modeled and Linear analysis was being performed on the frame. All the width of the Diagonal struts calculated using the various relations given by the researchers was being adopted one by one and the Frame-1 was being analyzed. The analysis results were studied, compared and the conclusions were drawn in terms of *Deflection and Stiffness*.

The loads on the frame and the method of analysis is being discussed below

Loads considered on the structure:

- **Dead Loads:** The self weights of the structural elements (beams, columns & slab).
- **Live Loads:** A live load of 3.0 Kn/m^2 was being considered.

Method of Modeling and Analysis

Linear analysis was being adopted here for the analysis. The Frame-1 was being analyzed in ANSYS wherein the ***2D - beam elements*** were being used to model the Columns and the beams (fig.7). An ***Aspect ratio of 1:1*** was being adopted for modeling (meshing). The frame was being subjected to a Lateral load [5].

A typical model of Frame-1 was as shown in the below fig.7.

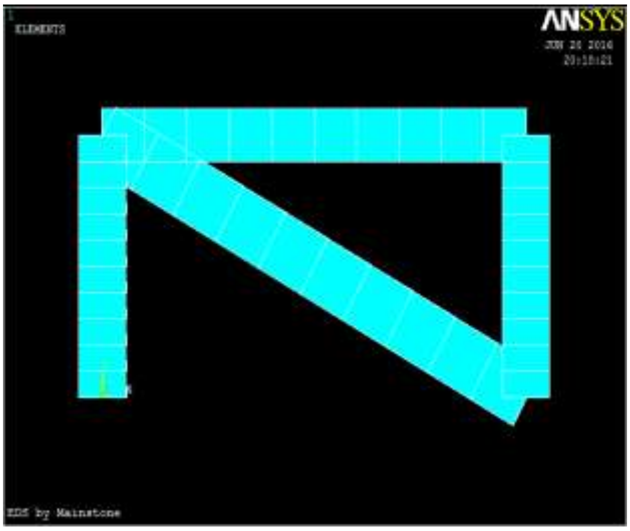

Fig 7: Typical model of Frame-1.

The Deflection and the stiffness in the Frame-1, analyzed adopting the width of the EDS calculated using the various relations given by the Researchers were as tabulated in the below Table 5.0.

Table 5 - Variation in the Deflection and Stiffness in the Frame-1

Researchers	*Width of EDS (mm)*	*Deflection (mm)*	*Stiffness (N/mm)*
Holmes	1720	0.618	265372.1683
Smith & Carter	463	0.534	307116.1049
Mainstone	604.5	0.937	175026.6809
Mainstone & Weeks	590	0.947	173178.4583
Liaw & Kwan	1200	0.703	233285.9175
Decanini & Fantin 1	4600	0.534	307116.1049
Decanini & Fantin 2	4000	0.52	315384.6154
Paulay & Priestly	1290	0.684	239766.0819
Durrani & Luo	1006	0.752	218085.1064
P100/1 - 2006	520	0.998	164328.6573
Hendry	1340	0.674	243323.4421

The graph showing the variation of the Deflection and Stiffness in the Frame-1 was as depicted below in fig.8 and fig.9. The stiffness is being calculated using the relation $P = k.\Delta$.

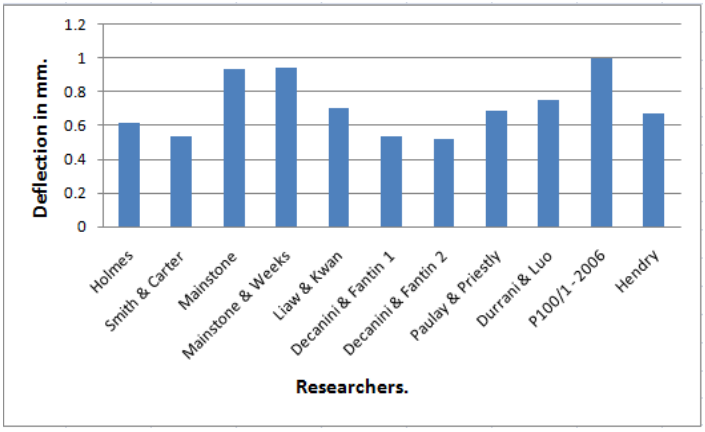

Fig 8: Bar graph showing the variation in the Deflection of Frame -1.

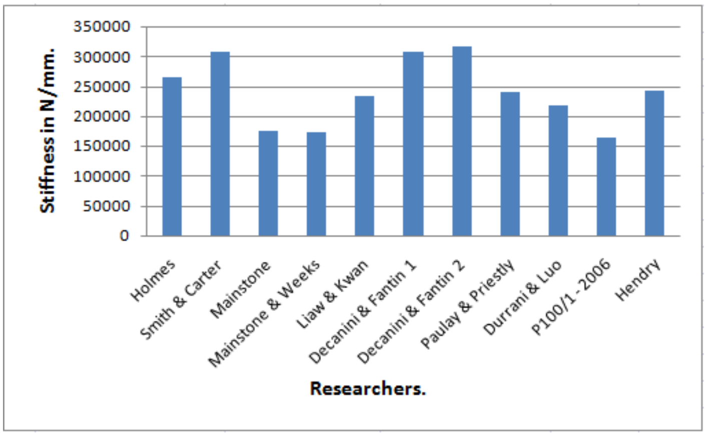

Fig 9: Bar graph showing the variation in the Stiffness of Frame-1.

With respect to the table 5.0 and also observing the variations in the Deflection and Stiffness in the Frame-1 (fig.8 and fig.9), it has been observed that,

a) There was a large variation in the values of the deflection and stiffness obtained from the analysis using the width of the EDS given by the Researchers.

b) The deflections were large where the widths of the EDS were less as calculated by the researchers Mainstone, Mainstone & Weeks and P100/1-2006. This was because with lesser width of the diagonal strut the stiffness in the frame reduced.

c) The deflections were small where the widths of the EDS were large as calculated by the researchers Smith & Carter, Decanini & Fantin 1 and Decanini & Fantin 2. This was because with larger width of the diagonal strut the stiffness in the frame increased.

8. CONCLUSION

1) It was observed that MI contributed in enhancing the strength and stiffness of the structure. Hence, the MI should be considered for the design and analysis of the structure.

2) The deflections in the frame were observed to be less due to increased stiffness in the frame because of width of the EDS.

3) The relative study of the various relations for calculating the width of the EDS, discloses that Mainstone relation was the most appropriate choice.

4) With reference to various literature reviews, Mainstone's relation was widely used for most of the experimental and analytical works, as it predicted the value of the width of the Diagonal strut which was very near/close to the Romanian code and it was commonly adopted because of its simplicity.

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