Finite Element Analysis of 2D Masonry Infilled RC Frames Validated with Modal Assurance Criterion

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Abstract: *Contribution of infill walls to in-plane structural response of reinforced concrete (RC) frame is an important aspect which many researchers have studied using experimental and numerical methods. This paper presents modelling of 2D RC unreinforced masonry (URM) infill frames using multiple nodes to one node constraint (MTOCO) with independent node at centre of gravity of infill with mass and inertial properties of infill. This method of modelling is then compared with other macro and micro modelling methods. Macro model with diagonal strut using 1D element and micro model with 8-noded brick elements with interface between infill and RC frame modelled using node to surface tied interface and small sliding contact. All these four models are solved using Virtual Performance Solution (VPS) implicit FE solver. Natural frequencies of the structure from these four numerical solutions are then compared with available experimental shake table [6] results. To assess the degree of consistency between the four numerical methods, Modal Assurance Criterion (MAC) [9] is used. The Modal Assurance Criterion is a statistical indicator that is most sensitive to large differences and relatively insensitive to small differences in the mode shapes. This yields a good statistical indicator and a degree of consistency between mode shapes.*

Keywords:**Modal assurance criterion, Multi to one nodal constraint, Diagonal strut, Unreinforced masonry, Virtual Performance Solution**

1. INTRODUCTION

In reinforced concrete (RC) frame construction, large quantity of unreinforced masonry is used as infills. This type of construction is one of the most utilized type of construction in many parts of the world. In gravity loads design, these infills are considered as non-structural elements which is justifiable. But, from earthquake point of view, that the interaction of infill with RC frame has a role to play, is evident from many earlier studies. The interaction of infill with RC frame could lead to either favorable or unfavorable modification of global structural response. Hence, computation of natural frequencies of structure with infills assumes importance under dynamic loading. Micro modelling is time consuming. Hence, simplified modelling using diagonal strut assumes importance. In this study a multiple node to one node constraint (MTOCO) with independent node at center of gravity of infill with mass and inertial properties of infill is used. The state-of-the-art VPS Implicit FE solver is used for modelling infill as micro and macro models. Micro model with 8-noded brick elements with interface between infill and RC frame is modelled using node to surface tied interface and small sliding contact. Macro model is made of 1D elements to represent diagonal strut and the width of the diagonal strut is computed using IS 1893 (Part 1): 2016 [11]. The analytical results from VPS Implicit FE solver is then compared with the available shake table [6] experimental results.

To assess the degree of consistency between the four numerical methods, Modal Assurance Criterion (MAC) [9] is used. This gives a good statistical indicator and a degree of consistency between mode shapes of numerical approaches adopted.

2. Experimental background

Shake table [6] is a testing facility platform excited by hydraulic actuators to simulate artificial earthquakes and dynamic testing signals. In 2009, Chethan K, as a part of his PhD conducted experiments of 2D and 3D RC frames with and without infills. In this paper, natural frequencies of different configurations of 2D RC frames with infill from these experimental results are taken as the base to compare with the numerical results [6]. Experimental results are available for six 2D RC frames of one bay, two bays of one storey, two storeys and three storeys. Actual experimental specimens placed on shake table are shown in Figure 1. Natural frequencies for these experimental specimens are as shown in Table 2.

Figure 1. Specimens on shake table [6]

3. Finite Element Modelling

Table 1. Material properties and model dimensions

Property / Dimension	Value
Width of Beam / Column, b	0.075 m
Depth of Beam / Column, d	0.1 m
Slab Thickness	0.05m
Thickness of masonry infill, t	0.075mm
Height of masonry infill, h	0.8 m
Length of masonry infill, l	1.1 m
Diagonal length of masonry infill, L_{ds}	1.36 m
Height of column, hcol	0.9 m
Moment of Inertia of Beam / Column, I_c	$6.25\ x\ 10^{-6} 10m^2$
Modulus of elasticity of concrete, E_c	$2.5\ x\ 10^7 kN/m^2$
Modulus of elasticity of masonry infill, E_m	$1.4\ x\ 10^7 kN/m^2$
Slope of the infill diagonal to the horizontal, θ	0.6288 radians

3.1 Using diagonal strut proposed by IS 1893, Part 1, 2016 (Diagonal-Strut)

Width of the diagonal strut w_{ds} is as shown in Figure 2. Macro model using 1D element to represent the diagonal strut is as shown in Figure 3.

$$w_{ds} = 0.175\alpha_h^{-0.4}\,L_{ds} \qquad (1)$$

$$\lambda_h = h\left(\sqrt[4]{\frac{E_m t \sin 2\theta}{4E_c I_c h}}\right) \qquad (2)$$

Width of diagonal strut w_{ds}= 0.1217m

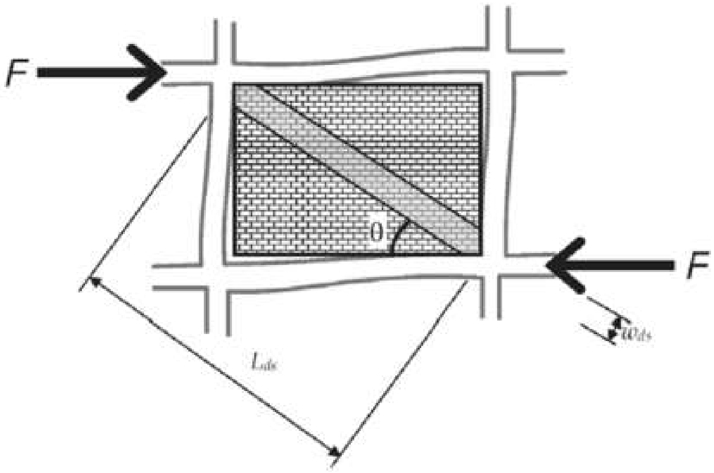


Figure 2. Equivalent diagonal strut [11]

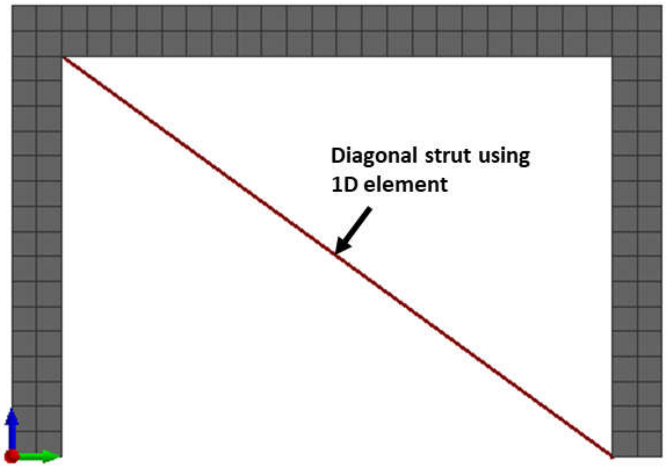


Figure 3. Equivalent diagonal strut using 1D element

3.2 Using node to surface tied interface to represent interaction between RC frame and infill (TIED)

Micro model using 8-noded solid elements with a minimum of two elements along the width and thickness of beams, columns and infill is used as shown in Figure 4. The interface between RC frame and infill is modelled using tied interface with infill as slave and RC frame as master.

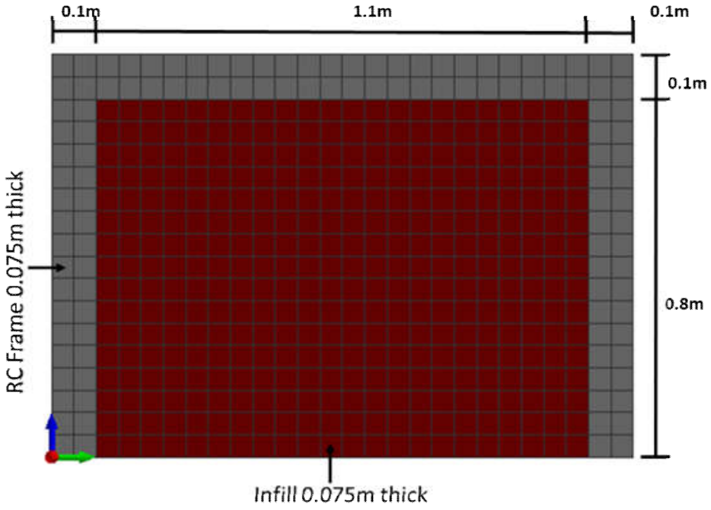


Figure 4. Typical 1B1SF dimension

3.3 Using small sliding contact to represent interaction between RC frame and infill (CNCT)

Micro model using 8-noded solid elements with a minimum of two elements along the width and thickness of beams, columns and infill is used. The interface between RC frame and infill is modelled using contact with infill as slave and RC frame as master.

3.4 Using mass element with inertial properties and multiple node to one node constraint (MTOCO)

Macro model using mass element with inertial properties and MTOCO to represent the infill is used. The mass element is of single node, created at the centre of gravity of the infill. Moment of inertia of the infill is computed and applied to the mass element as shown in Figure 5.

Method of modelling using MTOCO:

- Compute mass of the infill
- Compute geometrical centre of gravity of infill
- Compute first, second and third principal moment of inertia of infill section
- Create a mass element with inertial properties at the independent node which is located at the centre of gravity of the infill
- 50% of surface nodes (RC frame nodes – Beams and Columns) at the contact points are considered

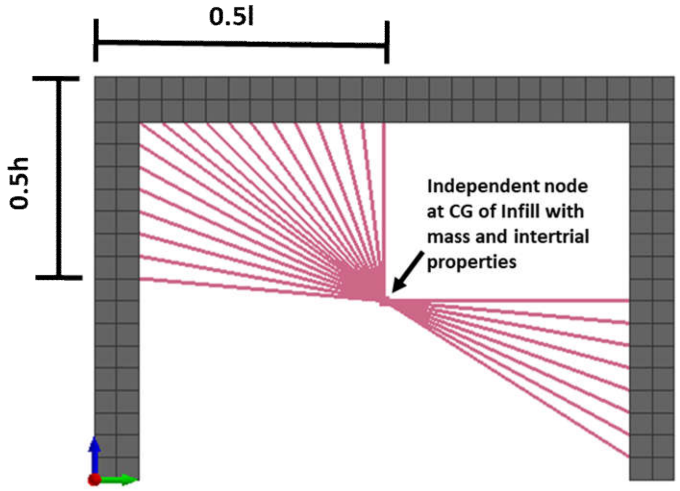


Figure 5. Modelling infill using MTOCO

3.4 Models considered for this study

Six 2D RC frames of one bay, two bays of one storey, two storeys and three storeys are considered. All configurations used in this study are shown in Figure 6. A typical model 2B3SF with diagonal strut, TIED and MTOCO configuration is shown in Figure 7. The natural frequencies of all the configurations are shown in Table 2.

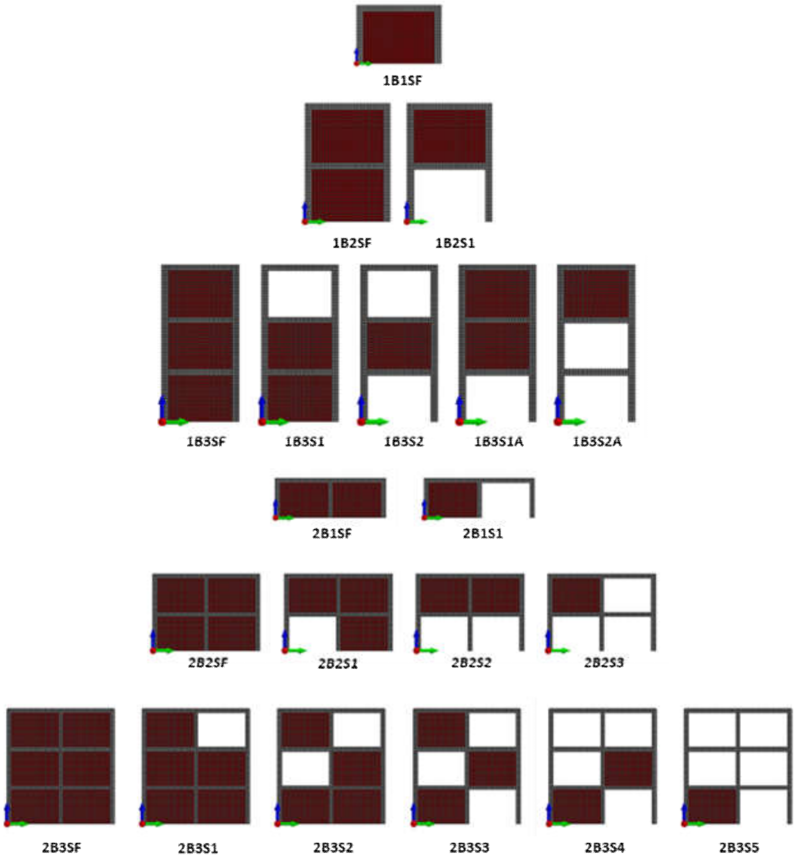


Figure 6. Models used in this study

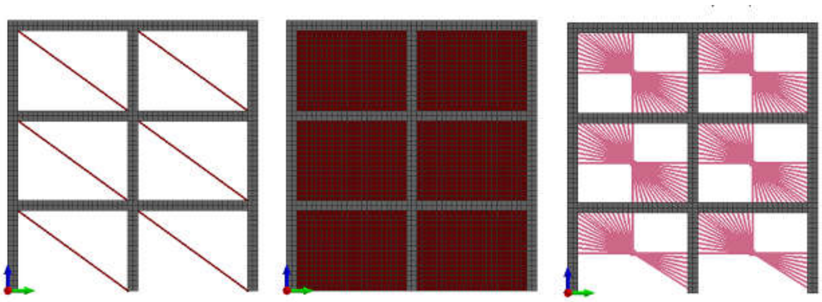


Figure 7. Typical Equivalent Diagonal Strut, TIED and MTOCO configuration

4. Modal assurance criterion (MAC)

The Modal Assurance Criterion [9] is a statistical indicator that is most sensitive to large differences and relatively insensitive to small differences in the mode shapes. This yields a good statistical indicator and a degree of consistency between mode shapes.

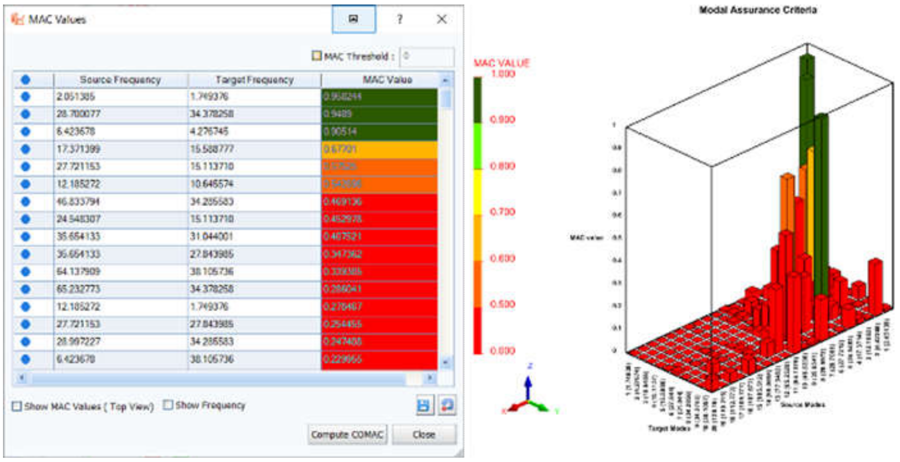
The MAC considers only modal shapes which mean that a separate frequency comparison must be used in conjunction with the MAC values to determine the correlated mode pairs.

The MAC is often to use to pair modes shapes derived from analytical models with those obtained experimentally. It is easy to apply and does not require an estimate of the system matrices. It is bounded between 0 and 1, with 1 indicating fully consistent mode shapes. It can only indicate consistency and does not indicate validity or orthogonality. A value near 0 indicates that the modes are not consistent.

In the current study the tool “MAC Computation” of VPS is used to compare the mode shapes of models between different types of modelling as shown in Figure 8.

- Macro model equivalent diagonal strut Vs Micro model with brick elements (TIED)
- Macro model equivalent diagonal strut Vs Micro model with brick elements (CNCT)
- Macro model equivalent diagonal strut Vs Macro VPS MTOCO model
- Micro model with brick elements (TIED) Vs Macro VPS MTOCO model
- Micro model with brick elements (CNCT) Vs Macro VPS MTOCO model

The MAC values of all the above comparisons are as shown in Table 3.



☐ MAC Threshold : 0

●	Source Frequency	Target Frequency	MAC Value
●	2.051385	1.749376	0.958244
●	28.700077	34.378258	0.9489
●	6.423678	4.276745	0.90514
●	17.371399	15.588777	0.67701
●	27.721153	15.113710	0.57525
●	12.185272	10.646574	0.542556
●	46.833794	34.285583	0.469136
●	24.548307	15.113710	0.452978
●	35.654133	31.044001	0.407521
●	35.654133	27.843985	0.347362
●	64.137909	38.105736	0.339385
●	65.232773	34.378258	0.286041
●	12.185272	1.749376	0.278467
●	27.721153	27.843985	0.254455
●	28.997227	34.285583	0.247408
●	6.423678	38.105736	0.229955

☐ Show MAC Values (Top View) ☐ Show Frequency

Figure 8. MAC comparison between macro model equivalent diagonal strut Vs micro model with brick elements (TIED), 2B3SF configuration, MAC Value = 0.94

5. Results and discussions

Table 2. Result Comparison (Experimental and Numerical) – Natural Frequency in Hz

Type	Models	Existing Shake Table Results	Simulated using VPS Implicit			
			Micro		Macro - Diagonal Strut IS-1893	MTOCO
			TIED	CNCT		
2B3S	2B3SF	29.50	34.38	34.37	28.70	31.83
	2B3S1	36.00	37.57	37.53	27.49	35.30
	2B3S2	30.00	31.55	31.55	26.26	30.48
	2B3S3	26.25	25.64	25.64	20.82	23.28
	2B3S4	25.75	27.77	27.77	19.80	25.56
	2B3S5	19.25	18.77	18.77	16.95	18.37
	2B3S	14.00	13.76			
2B2S	2B2SF	60.56	60.56	60.56	33.44	53.83
	2B2S1	35.00	39.97	39.97	22.62	41.65
	2B2S2	15.00	15.05	15.05	14.24	14.80
	2B2S3	15.50	16.56	16.56	15.54	16.34
	2B2S	19.25	21.16			
2B1S	2B1SF	**	138.07	138.07	94.39	100.54
	2B1S1	**	103.76	103.77	91.00	87.70
	2B1S	39.75	39.74			
1B3S	1B3SF	29.00	23.49	23.48	22.26	21.68
	1B3S1	34.00	28.15	28.15	32.53	25.90
	1B3S2	20.75	15.72	15.72	14.15	15.31
	1B3S1A	12.75	12.77	13.04	12.70	12.66
	1B3S2A	11.25	11.62	11.62	10.94	11.56
	1B3S	14.00	13.51			
1B2S	1B2SF	42.75	45.93	45.92	37.11	40.99
	1B2S1	16.50	17.57	16.42	15.37	17.09
	1B2S	20.00	21.04			
1B3S	1B1SF	**	121.92	121.91	58.63	93.45
	1B1S	41.25	41.58			

Table 3. MAC Comparison between different numerical methods

Type	Models	MAC Computation

		Diagonal Strut Vs TIED	**Diagonal Strut Vs CNCT**	**Diagonal Strut Vs MTOCO**	**MTOCO Vs TIED**	**MTOCO Vs CNCT**
2B3S	2B3SF	0.94	0.94	0.89	0.96	0.96
	2B3S1	0.95	0.95	0.90	0.95	0.95
	2B3S2	0.93	0.93	0.88	0.97	0.97
	2B3S3	0.93	0.93	0.95	0.95	0.95
	2B3S4	0.90	0.90	0.95	0.97	0.97
	2B3S5	0.98	0.98	0.98	0.99	0.99
2B2S	2B2SF	0.93	0.93	0.79	0.90	0.90
	2B2S1	0.91	0.91	0.79	0.94	0.94
	2B2S2	0.99	0.99	0.99	0.99	0.99
	2B2S3	0.99	0.99	0.99	0.99	0.99
2B1S	2B1SF	0.90	0.90	0.61	0.76	0.76
	2B1S1	0.85	0.85	0.78	0.89	0.89
1B3S	1B3SF	0.95	0.95	0.93	0.99	0.99
	1B3S1	0.98	0.98	0.96	0.99	0.99
	1B3S2	0.99	0.99	0.99	0.99	0.99
	1B3S1A	0.99	0.99	0.99	0.99	0.99
	1B3S2A	0.99	0.99	0.99	0.99	0.99
1B2S	1B2SF	0.85	0.85	0.78	0.96	0.96
	1B2S1	0.99	0.99	0.99	0.99	0.99
1B1S	1B1SF	0.91	0.91	0.76	0.82	0.82

- Using VPS Implicit solver, four types of models are modelled - two micro models and two macro models.
  - Diagonal Strut – 1D element with cross sectional area A which is product of Diagonal Strut width using IS 1893, Part 1, 2016 method and Infill thickness = 0.1217 x 0.075 = 0.0091275 m^2.
  - TIED – Node to surface tied interface definition. This is to model the interface between RC Frame and Masonry Infill. Search distance used is 0.001m.
  - CNCT – Small sliding contact definition. This is to model the interface between RC Frame and Masonry Infill. Contact thickness used is 0.001m.
  - MTOCO – Multi to one nodal constraint method. Mass and inertial properties of Infill are computed and applied on to the independent node created at the centre of gravity of the infill. Dependent nodes are selected on the RC Frame.
- 2D frames natural frequencies are compared in the in-plane mode, which is along Y-Axis of the model.
- As we see from the Table 2, most of the results are comparable within the limits.
- Modes are compared between different modelling techniques and Modal Assurance Criterion (MAC) method is used. Here comparison is made between:
  - Macro model equivalent diagonal strut Vs Micro model with brick elements (TIED)
  - Macro model equivalent diagonal strut Vs Micro model with brick elements (CNCT)

  - Macro model equivalent diagonal strut Vs Macro VPS MTOCO model
  - Micro model with brick elements (TIED) Vs Macro VPS MTOCO model
  - Micro model with brick elements (CNCT) Vs Macro VPS MTOCO model
- MAC numbers are comparable between all the models. Most of the variations match above 90%.
- From the results, it is evident that MTOCO method can be adopted to estimate natural frequencies.
- Major advantage of MTOCO method is that it is flexible and can be adopted even to Infill with openings, partial filling, etc.,

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