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SEISMIC DESIGN OF MASONRY-INFILLED FRAMES: A REVIEW OF CODIFIED APPROACHES

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This paper reviews the approach of eleven national codes on the analysis and design of masonry-infilled frames. It is shown that, in general, codes can be divided into two groups. The first group isolates the masonry and frame members by providing gaps to minimize the interaction between them. This method ensures that the complexities involved in analyzing the structure is avoided. However, the width of the gaps recommended is different for each of the codes. The second group takes advantage of the presence of high stiffness and strength masonry infill. In this technique, an equivalent-strut modeling strategy is mostly recommended. It is shown that the strut model suggested in each of the codes is different. An attempt to obtain a generic model for masonry-infilled frame failed largely due to the existence of many behavior-influencing parameters. Finally, it is suggested to have a paradigm shift in the modeling strategy where the masonry-infilled frames are classified into different categories and a model is suggested for each of them.

Keywords: National standards, Masonry, Equivalent-strut, FE modeling.

1 INTRODUCTION

Masonry-infilled frame (MIF) is a structural system consisting of moment-resisting frames infilled with masonry panel. These types of structure have been in use for almost a century (NZSEE 2017). While the benefit of incorporating masonry infill as a structural element includes the enhancement of the strength and stiffness of the structure, its interaction with the frame members results into a complex phenomenon. This complexity makes the research to continue despite the study having begun as early as the 1930s (Mohyeddin *et al.* 2017). In general, the two methods used in the modeling of MIF are macro- and micro- modelings. The former method of analysis considers the masonry to be equivalent to a diagonal strut (Figure 1), while the latter techique models each of the brick, mortar, and interface elements separately. Micro-modeling is often more accurate but is limited by the requirement of cost, time, and complexity of computer algorithms. Extensive research on developing a generic strut that is suitable for all types of MIFs has been proposed. Most of the studies estimated the strut width, w, using a relative stiffness ration of the masonry and the frame, $\lambda_h h$, and contact length, z, proposed by Stafford-Smith (1962) as seen in Eqs (1) and (2):

$$\lambda_h h = \sqrt[4]{\frac{E_m t \sin 2\theta}{4 E_f I_c h_I}}\, h \tag{1}$$

$$z = \frac{\pi}{2(\lambda_h h)} h \tag{2}$$

where *h* is the height of the column, from the base/foundation to the centerline of the beam is E_m, *t* is the modulus of elasticity and thickness of the masonry, θ is the angle formed between the diagonal of the infill and the horizontal line, E_f is the modulus of elasticity of the frame material, I_c is the moment of inertia of the column, and h_I is the height of the infill panel. However, the attempt has failed largely due to the presence of many parameters that influence the behavior of MIF and highly nonlinear response exhibited during FE modeling.

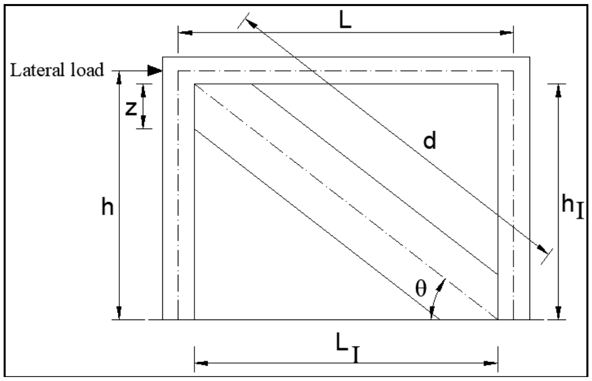

Figure 1. Equivalent-strut.

Although Kaushik *et al*. (2006), Dorji (2009), and Wang (2015) have undertaken a review of the national codes in the analysis and design of MIF, they have become outdated since most codes have been updated following the recent seismic events after their publication. Of the eleven codes studied in this research, two each belong to America, Australia, and Nepal and one each to Canada, China, Europe, India, and New Zealand. Thus, the codes belong to the regions, which have experienced highly destructive earthquakes in the past or are influential codes that are followed by other countries. Australian standards have been added because it is of the interest of the authors to conduct extensive investigations of the Australian buildings in the future.

2 CONNECTION REQUIREMENT

Table 1 represents a summary of the approach of the national codes on MIF. Both American codes and NZSEE (2017) provide options to either isolate or construct the infill in full contact with the frame; however, the ASCE/SEI 41 (2017) suggests the gap width to be a minimum of the expected lateral deflection, while the TMS 402/602-16 (2017) provides an absolute value of 9.5 mm. NZSEE (2017) does not provide any information on the width of the gap. The Canadian, Chinese, and European codes state that the MIF components need to be in full contact to achieve composite action. The Eurocode 8 (2004) recommends having no connection between them so that the masonry infill does not contribute to resisting the lateral load, which is contradictory to its suggestion of maintaining full contact between the materials. No information on the connection detailing is available in the Australian, Indian, and Nepalese codes.

Table 1. Summary of design codes approach to MIFs.

Standard	Connection of masonry and frame	Connection detailing requirements	Effect of masonry in period	Strut model	Effect of opening in strut equation
America ASCE/SEI 41 (2017)	Full contact or with gaps	Gaps shall be wider than maximum lateral deflection	Yes	Yes	Yes
America TMS 402/602-16 (2017)	Full contact or with gaps	Gaps must be at least 9.5 mm wide	NG	Yes	NG
Australia AS 1170.4 (2007), AS 3700 (2018)	NG	NG	Yes	NG	NG
Canada CSA S304-14 (2019)	Full contact	Masonry panel shall be tied to the frame members to enable composite action	NG	Yes	NG
China GB 50011-2010 (2016)	Full contact	2- 6 mm dia reinforcing bars with 4 mm dia tie bars to be provided every 500 mm along the wall height	NG	NG	NG
Europe Eurocode 8 (2004)	Full contact	No structural connection between them. Considered as non-structural element	Yes	NG	NG
India IS 1893 (2016)	NG	NG	Yes	Yes	No
Nepal NBC 105 (1994), NBC 201 (1994)	NG	NG	NG	NG	Yes
New Zealand NZSEE (2017)	Full contact or with gaps	NG	Yes	Yes	Yes

*NG = Not Given

3 PERIOD ESTIMATION AND MODELING

3.1 Period Estimation

The presence of masonry infill makes a major significance is in allocating the appropriate value of C_t in predicting the fundamental period of a building using Eq. (3)

$$T = C_t H^{\beta} \tag{3}$$

where H is the height of the building. While both C_t and β depend on the type of moment-resisting structure, C_t is further reliant on the presence of masonry infill. Barring Eurocode 8 (2004) and IS 1893 (2016), most standards do not clearly mention the effect of masonry infill and for lack of this information, design engineers are forced to use the C_t value assigned as "other" structures for MIF, which vary according to different standards (Table 2). Eurocode 8 (2004) and IS 1893 (2016) consider the effect of masonry where the value of C_t in both standards is equal to $0.075/\sqrt{A_m}$; A_m being the area of the masonry in the first story of the building.

3.2 Equivalent-Strut Modeling

In terms of evaluating the strut width, IS 1893 (2016) recommends the use of the expression suggested by Mainstone (1971) that depend on the relative stiffness ratio. NZSEE (2017) also proposes the strut width based on stiffness ratio but developed by Turgay *et al.* (2014). Contrarily, CSA S304-14 (2019) suggests strut width that varies as per the contact length of the masonry infill with the column and beam. No strut models have been recommended in the Australian, Chinese, European, and Nepalese codes.

Table 2. C_t and strut widths recommended in standards.

Codes	C_t	w	**Explanation of terms**
ASCE/SEI 41 (2017)	0.020	$\frac{K_{un}-2K_{col}}{2\cos^2\theta E_m}$	A_m : Area of masonry wall in the first storey K_{un} : Uncracked stiffness of masonry infill K_{col} : Stiffness of column d : Length of the diagonal strut t : Thickness of masonry θ: Angle between the strut and the horizontal line E_m : Modulus of elasticity of masonry $\lambda_h h$: Stiffness ratio α_h: Contact length between the masonry infill and the column α_L: Contact length between the masonry infill and the beam
TMS 402/602-16 (2017)	NG	$\frac{0.3}{(\lambda_h h)\cos\theta}$	
AS 1170.4 (2007), AS 3700 (2018)	0.0625	NG	
CSA S304-14 (2019)	NG	$\sqrt{\alpha_h^{2}+\alpha_L^{2}}$	
GB 50011-2010 (2016)	NG	NG	
Eurocode 8 (2004)	$\frac{0.075}{\sqrt{A_m}}$	NG	
IS 1893 (2016)	$\frac{0.075}{\sqrt{A_m}}$	$0.175(\lambda_h h)^{-0.4}d$	
NBC 105 (1994), NBC 201 (1994)	0.06	NG	
NZSEE (2017)	NG	$0.18(\lambda_h h)^{-0.4}d$	

ASCE/SEI 41 (2017) offers an alternate method to estimate the strut width by assuming the structure as a composite cantilever column with columns acting as a flange and the masonry wall as a web of the column. The stiffness of the composite structure is estimated as shown in Eq. (4)

$$K_{un}=\frac{1}{1/K_{ft}}+\frac{1}{1/K_{sh}} \tag{4}$$

where $K_{ft}=3E_cI_{ce}/h_I^{3}$ and $K_{sh}=A_IG_m/h_I$ are the flexural and shear stiffness of the composite cantilever, E_c is the modulus of elasticity of column, I_{ce} is the cracked moment of inertia of the transformed structure, A_I and G_m are the cross-sectional area and shear modulus of the infill. The code classifies the concrete frame as ductile or nonductile and the masonry infill as stiff or flexible and the subsequent lateral strength in evaluated by Eq. (5)

$$V_{\max}=P_{\inf}^{grav}\mu+A_IC \tag{5}$$

where $P_{\inf}^{grav}$ is the axial load on the infill due to gravity load distributed between the infill and the columns that depends on the ductility of column and the stiffness of the infill, μ is the coefficient of friction between the infill and the column, and C is the cohesion of the brick-mortar interface. In the case of the wall with opening, the standards again vary highly in considering the MIFs. ASCE/SEI 41 (2017) and NZSEE (2017) provides the stiffness equation as

$$K_{op}=\left(1-2\,{A_{op}}/{A_I}\right)K_{un} \tag{6}$$

to account for the presence of openings in the walls where K_{op} is the stiffness of MIF with opening, and A_{op} is the area of opening. While ASCE/SEI 41 (2017) states that the area of opening must be less than 40% of the infill area, no such condition is placed in NZSEE (2017). NBC 105 (1994) and NBC 201 (1994) recommend strut modeling of MIF if the area of opening is less than 10% of area of infill and is located outside the middle two-thirds of the infill. IS 1893 (2016) proposes no reduction in strut width. The rest of the codes lack recommendations to include the effect of opening in modeling.

4 SUMMARY AND CONCLUSIONS

Few of the national codes provide options to separate the masonry infill from the frame member in order to avoid the complexities involved in the interaction between the components. However, the widths of the gap that need to be maintained are different for each of them. Most codes recommend a complete integral connection of the components so that the benefits of using masonry infill are realized. In this case, most of the standard recommended that the strut widths be estimated using the stiffness ratio, but the models are all different. ASCE/SEI 41 (2017) goes a step ahead by suggesting the MIF to be a composite cantilever column. In the calculation of the infill stiffness, the standard proposes the flexural stiffness of infill and column as $K_{\inf} = 3E_m I_{\inf} / h_I^3$ and $K_c = 3E_c I_c / h_I$ which are based on the support condition as one end fixed and the other pinned. Obviously, this cannot be true in all models. The method also requires assuming the plastic hinges location in the column, which is not an easy task for MIF. Furthermore, this technique is based on a lone FE study by Martin and Stavridis (2017). The study classified MIFs into eight categories based on the values of $K_{\inf f}$ and K_c through a parametric study of six parameters. The writers of this paper have already published elsewhere that there have been as many as eleven parameters studied through experimental investigations alone by past researchers and that there are other parameters which have never been studied at all. Having said that though, this method takes into account some important parameters including the flexural and axial stiffnesses of the infill, coefficient of friction, shear strength, and plastic moment capacity of column. The code also does not discourage the use of strut modeling but cautions to apply strut models that are 'project-specific', which points to the fact that there cannot be a generic strut model for MIF. Overall, the national codes differ considerably in their approach to MIF. This can be attributed to the fact that the researchers lack to suggest a conclusive modeling strategy. The behavior of MIF depends on many parameters and is highly nonlinear, making it difficult to replicate all MIFs. Therefore, it is necessary to classify MIFs into different categories and to suggest a model for each of them.

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References

AS 1170.4, *Structural Design Actions, Part 4: Earthquake Actions in Australia,* Standards Australia, Australia, 2007.

AS 3700, *Masonry Structures*, Standards Australia, Australia, 2018.

ASCE/SEI 41, *Seismic Evaluation and Retrofit of Existing Buildings*, American Society of Civil Engineers, https://doi.org/10.1061/9780784414859, 2017.

CSA S304-14, *Design of Masonry Structures*, Canadian Standards Association, Canada, 2019.

Dorji, J., *Seismic Performance of Brick Infilled RC Frame Structures in Low and Medium Rise Buildings in Bhutan,* Queensland University of Technology, 2009.

Eurocode 8, *Design of Structures for Earthquake Resistance - Part 1: General Rules, Seismic Actions and Rules for Buildings*, The European Union, 2004.

GB 50011-2010, *Code for Seismic Design of Buildings*, Ministry of Housing and Urban-Rural Development, China, 2016.

IS 1893, *Criteria for Earthquake Resistant Design of Structures Part 1: General Provisions and Buildings*. Bureau of Indian Standards, India, 2016.

Kaushik, H., Rai, D. C., and Jain, S., *Code Approaches to Seismic Design of Masonry-Infilled Reinforced Concrete Frames: A State-of-The-Art Review,* Earthquake Spectra, 22(4), 961-983, 2006.

Mainstone, R. J., *On the Stiffnesses and Strengths of Infilled Frames*, Building Research Station, 1971.

Martin, J., and Stavridis, A., *Simplified Method to Assess Lateral Resistance of Infilled Reinforced Concrete Frames*, 2017.

Mohyeddin, A., Dorji, S., Gad, E. F., and Goldsworthy, H. M., *Inherent Limitations and Alternative to Conventional Equivalent Strut Models for Masonry Infill-Frames*, Engineering Structures*,* 141, 666-675, https://doi.org/10.1016/j.engstruct.2017.03.061, 2017.

NBC 105, *Mandatory Rules of Thumb Reinforced Concrete Buildings with Masonry Infill*, Department of Urban Development and Building Construction, Nepal, 1994.

NBC 201, *Seismic Design of Buildings in Nepal*, Department of Urban Development and Building Construction, Nepal, 1994.

NZSEE, *The Seismic Assessment of Existing Buildings*, Technical Guideline, New Zealand Society for Earthquake Engineering, New Zealand, 2017.

Stafford-Smith., *Lateral Stiffness of Infilled Frames,* Journal of the Structural Division, 88(6), 1962.

TMS 402/602-16, *Building Code Requirements and Specifications for Masonry Structures*, The Masonry Society, America, 2017.

Turgay, T., Durmus, M., Binici, B., and Ozcebe, G., *Evaluation of the Predictive Models for Stiffness, Strength, and Deformation Capacity of RC Frames with Masonry Infill Walls.* Journal of Structural Engineering, 140, 2014.

Wang, Z. *Seismic Performance and Frame-Infill Interaction of Masonry-infilled Reinforced Concrete Frames*, 2015.