Engineering Structures 141 (2017) 666–675

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Inherent limitations and alternative to conventional equivalent strut models for masonry infill-frames

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ARTICLE INFO

Article history:
Received 8 September 2016
Revised 29 December 2016
Accepted 28 March 2017

Keywords:
Infill panel
Concrete frame
Strut modelling
Masonry
Reinforced concrete
Finite element
ANSYS
OpenSees

ABSTRACT

Past studies have confirmed that the behaviour of an infill-frame can be remarkably different from that of a bare frame. This becomes specifically critical when the structure is under lateral loads such as wind and earthquake. This paper looks into the fundamentals of the most commonly used analytical method for the analysis of such structures, i.e. equivalent strut modelling. It is shown that even though several equivalent strut models have been proposed since the 1950s, none can be considered as a suitable generic tool to represent the behaviour of all infill-frame structures. It is further demonstrated that not only the total width of strut(s), but also the number and location of strut(s) may vary from one infill-frame to the next. It is also shown that even for the same infill-frame the strut properties change at different drift values. A methodology is proposed to develop an appropriate strut model incorporating the material nonlinearities for any given infill-frame. This methodology requires the analytical results of a primary FE model at a micro level to determine the geometric properties of struts.

1. Introduction

In the United States, skyscrapers were designed in the 1900s based on the assumption that there was no structural contribution from the masonry infill panel towards the structural stiffness and/or strength of the building. However, early observations of such structures under wind loading proved the opposite. Cracks which were developed in masonry infill panels demonstrated a significant contribution from infill panels in resisting lateral loads, whereas strain gauges fixed to columns did not register much strain. A substantial difference between the actual stiffness of such buildings and those calculated based on the assumption of no structural contribution from the masonry infill panel came as other evidence. For the Empire State building, for instance, such analyses determined the actual stiffness of the building to be 4.5 times greater than that of the bare frame. Similar observations noting the substantial differences between the behaviour of a bare frame and an infill-frame during past earthquakes have been reported [21,48,50,28].

The earliest comprehensive published research on infill-frames can be attributed to Polyakov [38] in which the significance of the difference between the structural behaviour of a bare-frame and that of an infill-frame was explained. Experimental research on this subject commenced in the late 1940s and has since been active. Subsequently, this was accompanied by theoretical and computational studies. Even today, the complex structural interaction between the structural frame and masonry infill panel is still being investigated.

The level of complexity is such that a parallel research streamline initiated, almost from the start, with the aim of simplifying the actual behaviour of infill-frames. The first simplifying analogy used for the analysis of infill-frames was to take the infill panel as equivalent to one concentric compressive bracing strut between the top of the windward column and the bottom of the leeward column as shown in Fig. 1. Using such an analogy the analysis of a complex composite structure would downgrade to the analysis of a simple braced frame. The possibility of such an analogy, to the knowledge of authors, was first introduced by L I Onishchik as referenced by Polyakov [38] in the late 1930s/early 1940s. Consequently the width of such a strut (denoted by "d_0" in Fig. 1) was first proposed by Holmes [20].

This paper looks into the fundamentals of the most commonly used analytical method for the analysis of infill-frames, i.e.

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http://dx.doi.org/10.1016/j.engstruct.2017.03.061
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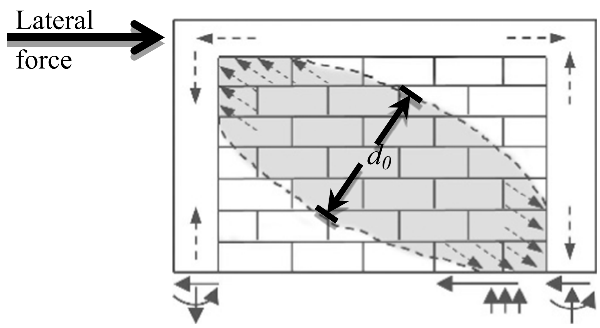


Fig. 1. Internal actions in an infill-frame under lateral loading and formation of a compressive diagonal strut.

equivalent strut modelling. It is shown that even though several equivalent strut models have been proposed since the 1950s, none can be considered as a suitable generic tool to represent the behaviour of all infill-frame structures.

2. Background

Since 1961, a large number of experimental, theoretical and numerical studies have been carried out to produce an equivalent strut model for infill-frame structures. The geometric properties of such strut(s), viz. the number of struts, total cross sectional area of strut(s), and the location of strut(s), relate to how the infill panel and frame structurally interact, and hence the contact area between the two at different levels of loading/drift. The total cross sectional area of the struts is normally calculated as the product of the calculated width and the nominal thickness of the infill panel.

Polyakov [38] gave an estimate of 20–30% of the perimeter of the infill panel to be in contact with the frame (top of the windward column and bottom of the leeward column) after the initial bond between the infill panel and frame is lost. Another early study on the contact length between the infill and frame was conducted by Stafford Smith [44] who provided a range of between 5 and 50% of the frame height (in a square infill-frame) depending on a relative stiffness parameter given in Eq. (1):

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

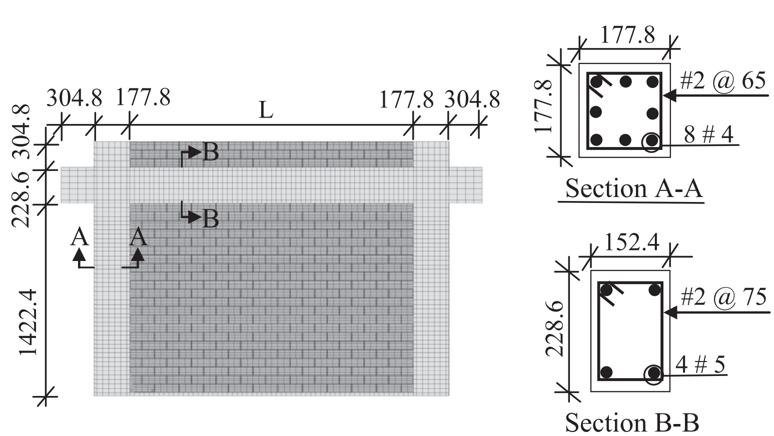
where h = the height of the frame; E_m = the modulus of elasticity of the infill panel; t = the thickness of the infill panel; θ = the angle of the infill panel diagonal to horizontal; E_f = the modulus of elasticity of the frame members; I_c = the moment of inertia of the column; and h_I = the height of the infill panel.

Eq. (1), which has been used extensively by other researchers, is a measure of the stiffness ratio of the infill panel to that of the frame when under lateral loading; the higher this value, the longer the contact length.

When using strut models, one should note that the models which have been developed based on the experimental results from steel frames have also been applied to infill-frames with reinforced-concrete (RC) frames, and vice versa. The type of masonry material, scale of the specimens, infill-frame aspect ratio (the ratio of the height to length of the infill-frame), the amount of gap between the infill panel and frame, the effects of perforation(s) in the panel, the amount of reinforcement in RC frame members (i.e. ductile and non-ductile frames), the number of storeys, and the number of bays are some of the variables that have been investigated in different studies, e.g. Holmes [20], Stafford Smith [44], Mainstone [28], Crisafulli et al. [13], Crisafulli and Carr [14], Asteris et al. [5] to name a few.

Even though, from very early attempts [28] it was observed that the width of equivalent strut(s) may change from one infill-frame to the next, the attempt has always been to develop a generic strut model to be used for the analysis of any infill-frame structure.

Some of strut models are used to calculate the initial stiffness (or natural frequency) of the infill-frame only, e.g. Stafford Smith [43], whereas others are used to calculate the ultimate strength e.g. Holmes [20]; but there are only a few that have attempted to replicate the full force-displacement response of the structure e.g. El-Dakhakhni et al. [16]. Regardless of which model is used, another concern that arises when using strut models is that the shear force and bending moment diagrams of the frame members cannot be properly predicted by these models, which has also been discussed by other researchers, e.g. Asteris [4], Crisafulli et al. [13], Asteris et al. [6]. This is because the actual contact length/area between the frame and infill panel cannot not realistically be represented in a strut model, especially when the infill is replaced by a concentric single strut. In an attempt to resolve this issue some researchers proposed multi-strut models, where the masonry panel is approximated by more than one single strut, e.g. Chrysostomou [10], Crisafulli [12], Thiruvengadam [47] and Burton and Deierlein [7]. Many more studies on the equivalent strut modelling of infill-frames can be found in the literature, e.g. Zarnic and Tomazevic [52], Sobaih and Abdin [42], Angel [2], Zarnic [51], Reinborn et al. [39], Saneinejad and Hobbs [40], Crisafulli [12], Madan et al. [27], Al-Chaar [1], Kappos et al. [22], Combescure [9], Karayannis et al. [23], Celarec et al. [8], and Su and Shi [46].



Specimen	L (mm)
8	2133.6
9	2133.6
11	2946.4

Fig. 2. Geometric properties of the infill-frames used in Specimens 8, 9 and 11 [29].