ARTICLE IN PRESS

Engineering Structures xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Engineering Structures

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

Simple design of masonry infilled reinforced concrete frames for earthquake resistance

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ARTICLE INFO

Keywords:
Design
Infilled frames
Simple
Earthquake
Damage level

ABSTRACT

The extensive use of reinforced concrete frames with masonry infill and national and European regulations, which often neglect the influence of infill, has been identified as a field of research. The reliability of a numerical model with an equivalent diagonal for the parametric analysis of model buildings was tested using various experiments with one-story, one-bay and multi-storey, multi-bay infilled frames. Variability of parameters was simplified by classifying components based on material strength (masonry infill) and the coefficients of longitudinal reinforcement (reinforced concrete frame). The number of storeys, area ratio of infilled frame area in relation to the floor area (ρ), and the variability of ground acceleration as a measure of earthquake loading were investigated.

The results show increased contribution to damage with increased number of storeys, decreased compressive strength of masonry infill, reduced longitudinal reinforcement ratio of columns, reduced area ratio, and increased peak ground acceleration (PGA) value. In the numerical model, area ratio ρ was observed to have significant importance and thus the minimum value of area ratio was defined.

The study resulted in method, which enables simple design of infilled frames. Based on the classification (masonry infill, peak ground acceleration, number of storeys) minimum infilled frame area ratio can be determined and according to calculation of real area ratio for observed building can be compared in order to infilled frame building achieve acceptable behaviour under possible earthquake event.

1. Introduction

The presence of masonry infill walls in reinforced concrete (RC) buildings is common. Even today, however, in the design of new buildings and the assessment of existing buildings, infill is usually considered to be a non-structural element and its influence on structural response is disregarded.

Ockleston [1] published the first experimental study focused on the interaction of infilled frames. This was followed by works by Benjamin and Fiorato [2,3]. The Marmara [Kocaeli] and Duzce earthquakes in Turkey and the development of major earthquake research centres in the European Union led to an increase in experimental work and the creation of new perspectives [4–10]. Nevertheless, a common vision on the effects of masonry infill has not yet been achieved. A review of the literature shows that there is no consensus on the effects of the interaction between frames and in-plane masonry walls. Some researchers [11–13] have suggested that infill walls have led to collapse of buildings and that they may detrimentally affect the response of frames [14]. Others have suggested that masonry infill panels may be beneficial [15–19].

The reason for the apparent contradiction may reside in observations made by [20,21], who stated that masonry infill panels have both positive and negative effects. Dolsek and Fajfar in [22] captured the essence of the problem, stating: “The infill walls can have a beneficial effect on the structural response, provided that they are placed regularly throughout the structure, and that they do not cause shear failures of columns.”

Opposing understandings of infilled frame behaviour within the research community have led to the negligence of infill frame systems design by many national building codes that contain warnings about the interaction of frames and walls but are mostly silent on providing recommendations and bounds on their proper consideration in design.

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https://doi.org/10.1016/j.engstruct.2018.02.072
Received 29 May 2017; Received in revised form 20 February 2018; Accepted 22 February 2018
0141-0296/

Please cite this article as: Kalman Šipoš, T., Engineering Structures (2018), https://doi.org/10.1016/j.engstruct.2018.02.072

Table 1
Recommended allowable number of storeys above ground and minimum area of shear walls for "simple masonry buildings" (Table 9.3 in [23]).

Acceleration at site $a_g \cdot S$		≤ 0.07 g	≤ 0.10 g	≤ 0.15 g	≤ 0.20 g
Type of construction	Number of storeys (n)**	Minimum sum of cross sections areas of horizontal shear walls in each direction, as percentage of the total floor area per storey ($p_{A,min}$)			
Unreinforced masonry	1	2.0%	2.0%	3.5%	n/a
	2	2.0%	2.5%	5.0%	n/a
	3	3.0%	5.0%	n/a	n/a
	4	5.0%	n/a*	n/a	n/a
Confined masonry	2	2.0%	2.5%	3.0%	3.5%
	3	2.0%	3.0%	4.0%	n/a
	4	4.0%	5.0%	n/a	n/a
	5	6.0%	n/a	n/a	n/a
Reinforced masonry	2	2.0%	2.0%	2.0%	3.5%
	3	2.0%	2.0%	3.0%	5.0%
	4	3.0%	4.0%	5.0%	n/a
	5	4.0%	5.0%	n/a	n/a

* n/a – not acceptable.
** Roof space above full storeys is not considered in the number of storeys.

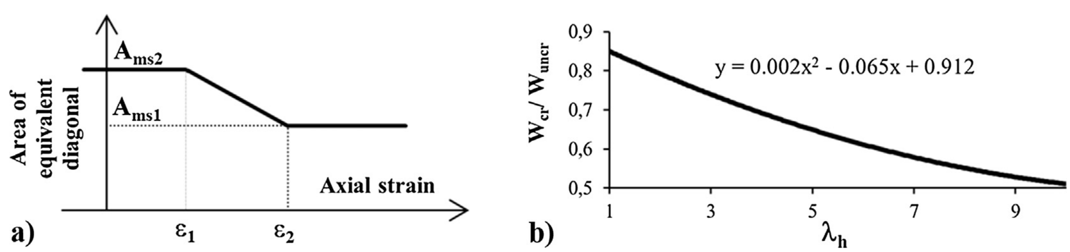

Fig. 1. (a) Variation of area of diagonals as a function of the masonry axial strain [25]; (b) Ratio of width of diagonal of cracked masonry infill (W_{cr}) and un-cracked masonry infill (W_{uncr}) in relation to relative stiffness ratio λ_h [28].

The concept of a simple design method is based on "simple masonry building" according to Eurocode 8 Part 1 [23], where the minimum cross-section area is expressed as a minimum percentage, $p_{A,min}$, of the total floor area per storey (Table 1). According to the specific masonry construction type (unreinforced, confined or reinforced) with expected earthquake ground acceleration and height of the masonry building based on number of storeys, this method limits the cross-section areas of masonry shear walls to achieve acceptable behaviour. In accordance with the above-mentioned method, parametric analysis based on reliable numerical model is used to produce a simple design for infilled frames. The main purpose of this paper is to propose an integrated seismic design approach and a reference application for this special building type. A complete design approach is presented for the reinforced concrete buildings with uniform distribution of masonry infills in plan and elevation.

The approaches and parameters investigated in this paper are based on numerical modelling of masonry infill (Section 2) according to significant effects on the stiffness and bearing capacity of infilled frames, which are included in the numerical model for the response of this type of building. The applied equivalent diagonal model is verified by results for multi-storey, multi-bay infilled frames in Section 3. Damage states for infilled frames are determined in Section 4. Parametric nonlinear dynamic analysis in Sections 5 and 6 consider the influence of certain parameters (i.e., geometric and material properties of frame and infill, different ground-motion records) and their relation to damage states, resulting in a new design-oriented approach (Section 7) for simple and reliable application in the design of infilled frames according to expected behaviour.

2. Numerical modelling of masonry infill

2.1. Definition of masonry infill model

Calibration of masonry infill macro-models was carried out using the equivalent diagonal model included in [24]. This model, previously described by Crisafulli [25], represents the behaviour of masonry infill in compression, tension and shear through two parallel diagonals and the shear springs for each direction of load. Cyclic behaviour of masonry infill is modelled by the hysteresis rule proposed by [25] to simulate the axial response of masonry. This model takes into account the nonlinear response of masonry in compression, including the effects of contact length in cracked material.

The main advantage of the infill model is the variation of the width of the diagonal (A_{ms1} – initial area, A_{ms2} – reduced area) as a function of masonry axial strain (Fig. 1a)). There are many different suggestions for calculating the equivalent diagonal width and area. As suggested in analysis in [26], initial area is calculated according to the recommendations of Stafford-Smith and Carter in [27] and relative stiffness ratio λ_h, while final area A_{ms2} is taken as the reduced size of the initial area from a recommendation by Decanini and Fantin [28] according to cracked and uncracked masonry infill (Fig. 1b). Authors in [28] expressed the relationship between the width of the diagonal of uncracked infill compared to cracked infill and reached the conclusion that the width of the diagonal is significantly reduced after the failure of infill by approximately 50–80% of the initial width. A significant reduction is seen in the case of higher values of stiffness parameter λ_h.

Another important task within calibration is the definition of axial