Construction and Building Materials 147 (2017) 677–700

Contents lists available at ScienceDirect

Construction and Building Materials

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

Strut-and-Tie Model for seismic design of confined masonry buildings

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HIGHLIGHTS

- Strut-and-Tie Model (STM) for seismic design of confined masonry walls.
- Single and multistorey wall panels with and without openings are considered.
- STM for lateral and gravity loadings are considered separately.
- Adjacent wall panels sharing a common tie-columns are also studied.

ARTICLE INFO

Article history:
Received 27 October 2016
Received in revised form 11 February 2017
Accepted 29 April 2017

Keywords:
Confined masonry
Strut-and-Tie-Model (STM)
Displacement-based design
Seismic analysis

ABSTRACT

The Strut-and-Tie-Model (STM) of a confined masonry wall, with or without opening, consists of an equivalent system, in which the masonry wall is modelled as compression struts and the reinforced concrete (RC) confining elements are modelled *as is* (*i.e.*, as present in the wall). Tension ties are ignored owing to the negligible tensile strength of masonry. Although the joints of tie-column and tie-beams are not intended for moment resisting, these are yet treated as the moment resisting in numerical model to avoid instability. Consequently, a typical compression strut is connected to the joints at either end with moment released. Purpose of this paper is to outline the guidelines for developing STMs for seismic design of confined masonry wall panels, including single- and multi-storey wall panels with and without openings. Behaviour of two single-storey adjacent panels with or without openings, are also considered. Although the main objective is to develop STMs for walls subjected to lateral seismic loading, the effect of gravity load has been also considered in the analysis. Well distinct STM configurations are noted for the single storey panels. STM for adjacent wall panels and multistorey wall are shown to be arrived at from that of the individual single storey panels. Throughout this paper, the masonry is modelled using equivalent properties and hence, the effect of relative variation of mortar and brick properties are not adequately captured. This may have considerable influence on the resulting STM configurations. Although STM should be evolutive in nature enabling prediction of different failure modes of CM walls, the scope of the analytical model in this paper is limited to the linear-elastic analysis and hence, the strut orientation is likely to be altered as the building ventures into the inelastic regime. Nevertheless, the STM proposed in this paper may be used as the basis of developing such an evolutive model enabling a displacement based design framework of confined masonry buildings.

1. Introduction

Confined masonry (CM) construction offers an alternative to the unreinforced masonry (URM) and reinforced concrete (RC) frame structures with masonry infills by involving the elements of both structural systems. A typical CM building comprises of masonry walls made from clay or concrete brick/block masonry units, and RC confining elements, tie-beams and tie-columns, enclosing the walls in horizontal and vertical directions, respectively. The reinforcement is concentrated in these confining elements only, whereas the masonry walls are usually not reinforced (often horizontal reinforcement is preferred to enhance shear resistance). The sequence of construction is different from RC frame construction, since the walls are erected first, followed by the construction of RC confining elements. Brzev [10] and Meli et al. [48] provided a comprehensive description of CM design and construction features and global applications.

The earliest global application of CM construction technology was reported in Italy, where CM buildings were exposed to the

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http://dx.doi.org/10.1016/j.conbuildmat.2017.04.200
0950-0618/

1908 Messina, Italy earthquake (M 7.2) with the death toll of 70,000. A few decades later, the use of CM was observed in Chile after the 1939 Chillán earthquake (M 7.8) [48]. The maximum shaking intensity of IX per Modified Mercalli Intensity (MMI) scale was reported in the earthquake, and the death toll was around 30,000. More than 50% of all inspected CM buildings survived the earthquake without any major damage, whereas around 60% URM buildings either partially or entirely collapsed. CM construction was exposed to several significant earthquakes in Chile and other Latin American countries, including the 1985 Llolleo, Chile earthquake (M 7.8) and the 2010 Maule, Chile earthquake (M 8.8). CM buildings performed very well in the 2010 Chile earthquake, which caused substantial damage in URM masonry and RC buildings [5]. In conclusion, CM buildings have withstood the effects of major earthquakes in the last century without collapse and largely reduced the number of fatalities in these earthquakes. This is a very important finding since the main objective of seismic design mandated by building codes is to ensure life safety. Interestingly, these buildings experienced significant damages but without collapse. In another perspective, such performances carry the promise of achieving the multiple performance objectives, the cardinal principle of modern performance based earthquake engineering, if planned, analysed, designed and constructed accordingly.

Although in general CM buildings performed well in past earthquakes, it was observed that CM walls with openings typically experience more significant damage, especially if adequate confinement is not provided, as observed in the 2010 Chile earthquake. The behaviour of CM walls with openings was examined through experimental studies [64,77,3]. Opening size in a confined masonry wall can be quantified through a percentage opening area relative to that of the panel. An opening may be considered as large if it exceeds 10% of the panel area [48] since it influences significantly the stress distribution and resulting lateral stiffness of the wall. This is confirmed by the experimental investigation of Yanez et al. [77]: stiffness of confined masonry wall specimens with an opening of up to 11% of the total wall area is close to that of the specimens without opening. Hence, panel with large opening should not be considered in seismic design unless adequately confined by tie-columns and tie-beams. Not only size of the openings, but its position also matters in seismic performance, if not adequately confined. For example, a small opening at a location away from the diagonals may not significantly alter the seismic resistance, and may be of serious concern, otherwise. Position of the opening, even when adequately confined, should be selected judiciously so as to ensure better seismic resistance. A confined wall panel with height-to-length (aspect) ratio greater than 1.5 is assumed not to be effective in resisting seismic force through shear mechanism. Even though some force transfer through flexural action is expected, which is usually neglected as not being intent for.

Even though, a set of recommendations, in line with these, have been codified elsewhere [52,48], these guidelines, however, do not light on the preferred way of analysing a confined masonry building to arrive at the appropriate design force resultants. Increasing use of the confined masonry system as a seismic resilient structural scheme, especially, under affordable housing plan in developing countries requires a reliable analytical model to determine the design member force resultants. Accurate analysis of confined masonry system is relatively difficult owing to the lack of confidence on available constitutive relation and knowledge of interface behaviour between brick and mortar bed, and masonry panel and tie-elements. The main objective of this paper is to provide guidance regarding modelling of CM walls for seismic design using the Strut-and-Tie-Model (STM) approach. A review of available modelling approaches and research studies is presented next, followed by the guidelines for developing appropriate STM configurations for CM walls.

2. Review of analysis models for seismic design of CM buildings and statement of purpose

2.1. Finite element models—numerical modelling

The available numerical approaches for modelling masonry wall (including CM) as plane structures, which are based on the use of Finite Element Method (FEM), can be classified into i) Detailed Micro Model (DMM); ii) Simplified Micro Model (SMM), and iii) Macro Model (MM) [42,30,31]. An appropriate numerical model can be selected depending on the desired balance of the accuracy level and the computational effort. When DMM [6] is used, the bricks, mortar and joints are represented separately: brick units and mortar are considered as the continuum elements whereas the joints are treated as interface elements. While DMMs are useful when the analysis objective is to capture failure mechanisms at material level since each masonry constituent material (e.g. brick and mortar) can be modelled using respective material properties, associated computational effort may be an issue for routine design applications. When SMM [12] is used, brick units and a partial layer of mortar is represented by continuum elements, whereas the interfaces is modelled by discontinuous elements. Since Poisson's effect of mortar is neglected (thickness tending to zero), accuracy of these models is considerably affected when compared to the DMM [51]. Again, owing to the computational effort, applicability of this model in routine seismic design is limited. Brick units, mortar and joints are often smeared out in the continuum approximation and termed as Macro Modelling approach [34,75]. A masonry wall is thus represented as a wall made of homogeneous material with equivalent properties. This type of modelling requires less computation effort and hence, is suitable for the routine design job wherein a compromise between the accuracy and efficiency is required [51]. In principle, numerical model is capable of accounting for a variety of complexities including geometry (shape and boundary conditions), material properties (isotropic/orthotropic) and textures [37,42,34]. The principle equally applies to strengthening of masonry with FRP reinforcement [14] and seismic design of CM buildings.

A reliable numerical model on the other hand requires a large number of input parameters owing to the dependency of the masonry behaviour on the properties of the constituting materials, textures, environmental conditions/exposure, aging etc. [7,37,6,9,8,29]. Uncertainties in the resulting parameters are also attributed from the way of implementation of the test programs [7,37,6,9,8,71]. Although, a comparison of various numerical models for pushover analysis of URM buildings is reported by Salonikios et al. [61], developing a reliable numerical model is often rejected owing to the constraint on funding in most research projects and required time in routine seismic design. The inference is true for CM buildings also and alternatively, the analytical models have been increasingly popular and are reviewed in the following section.

2.2. Line element models—analytical modelling

Confined masonry system and RC frames with infilled masonry exhibit similar response at global level when subjected to in-plane seismic loads, at least at the early stages of loading [41]. Thus, with adequate modification, both structural systems can be analyzed by similar models and approaches. Two commonly used approaches, widely used in modelling masonry structures, are reviewed here.