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Approximations of elastic lateral displacement profiles for walls with openings

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A R T I C L E I N F O

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A B S T R A C T

The assessment of lateral displacements is important in displacement-based design. Therefore, in this study the approximations obtained with different simplified methods used to assess the elastic lateral displacements of walls with openings are compared to results obtained with the finite element method using reasonably fine meshes. Multistory walls were studied, considering symmetric and asymmetric distribution of openings with respect to a vertical axis. From the obtained results it can be observed that for a single strip of asymmetric perforated walls, best approximations are obtained for slender walls using a version of the equivalent frame method where end zones are considered completely rigid, the method proposed by Coull and Choudhury, as well as a method proposed by the authors, named as the equivalent non-prismatic wide column analogy.

1. Introduction

In displacement-based design is very important to estimate accurately the lateral displacements of a given structural system. Buildings with structural walls are commonly used in seismic regions, mostly for reinforced concrete and masonry structures. Often, these structural walls have openings, particularly at the facades. Although regular opening patterns are often used, sometimes, for architectural requirements (illumination, ventilation, aesthetics), complex opening patterns are not uncommon.

The impact of openings in the lateral displacements of shear walls captured the attention of researchers and designers in the 1950s–1960s. In fact, many expressions, approximations and simplified analysis methods date back to those dates, because during those decades several midrise buildings with shear walls were built, which fostered practical research studies. Among other methods proposed at the times, one can highlight for their simplicity the following methods: a) the Equivalent Frame Method [1–5], which best simplest version is the one proposed by Schwaighofer and Microys [3] and, b) the method where coupling beams are replaced by an equivalent continuum shear media [2,6], which best simplest version is perhaps the one proposed by Coull and Choudhury [7,8], although there are more complex solutions for walls with multiple, regular openings [9–11].

Even today, the practical modeling of walls with openings is a complex task that has not been fully addressed yet. In this case, the use of the finite element method is essential if the aim is to obtain reliable results, both to estimate deformations, stiffnesses and stresses, as already shown by MacLeod [2] when comparing finite element solutions with experimental results. MacLeod [2] presented an study where he compared the approximations obtained with finite element models (assuming linear, elastic, homogeneous and isotropic behavior) for 7-story and 14-story walls with openings with experimental measurements of aluminum models (scale 45:1), obtaining very close correlations when using a reasonable fine mesh with rectangular plane stress elements (28 × 8 elements) and keeping the elements as square as possible.

In the absence of simple analytical methods that could estimate easy and reasonably the lateral stiffness matrix of walls with complex opening patterns (including asymmetries), Tena-Colunga [12–14] proposed the equivalent condensed beam method, a mixed method where the lateral stiffness matrix is obtained from equivalent condensed beams using the flexibility method and the finite element method. Although the method is accurate for practical purposes because, in essence, is a static condensation done numerically, it has the disadvantage that finite element meshes are required to define the equivalent condensed beams.

The development or improvement of simple models to analyze walls with openings has received relatively little attention in recent years [4,5], perhaps because the capabilities of personal computers since 1997 have facilitated the use of commercial finite element programs to model them reasonably. However, even today it is still impractical modeling with the required rigor, complete medium to high rise

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buildings with several walls with openings using refined finite element meshes, especially if the distribution of openings is irregular or complex in elevation. In many instances, practicing engineers do not have the time or experience needed to develop rigorous and detailed three-dimensional finite elements models that would allow them to analyze and design these types of structures, although they currently have access to the computer software and hardware capabilities to do it. Although the finite element method allows one to model such complex geometries, this method is not always practical for the analysis and design of complex and large buildings having walls with openings in the average size design firm. Therefore, approximate methods are still needed and used by structural engineers worldwide to estimate their lateral displacements using a much more reduced number of degrees of freedom. If the results obtained with such methods correlate well with those obtained from more rigorous methods, then reasonable estimates of their corresponding dynamic characteristics (periods and mode shapes), lateral displacements and story drifts can be obtained for buildings that possess walls with openings. Once lateral deformations are reasonably assessed, relative distributions of forces and stresses can be obtained using also simple methods (i.e., [15,16]) that would allow realizing suitable structural designs without the imperative need to perform more complex analyses with finite elements.

In this paper, the approximations obtained with different simplified methods to assess the lateral displacement profiles of walls with openings are compared to results obtained with the finite element method using reasonably fine meshes. Multistory walls were studied, considering symmetric and asymmetric distribution of openings with respect to a vertical axis.

2. Simplified methods under study

2.1. Equivalent frame method

In the equivalent frame method (EFM) as proposed by Schwaighofer and Microys [3], a wall system with central openings is considered (Fig. 1), which can be understood as an equivalent frame with two lines of walls or “wide-columns” connected by wide central beams. The general modeling assumptions behind the method are:

1. Centroidal axes for the cross sections of walls and connecting beams form an equivalent frame.
2. Cross section properties for all columns in the equivalent frame are identical to the corresponding sections for the walls.
3. Full cross section properties for the central beams are considered.
4. Rigid end zones in flexure are considered for the extreme sections of beams.

Schwaighofer and Microys [3] proposed equivalent areas (A_e) and moments of inertia (I_e) for the rigid end zones, as function of the opening parameters e and f (Fig. 1), where e is defined as the distance between the centroidal wall axis and the edge of wall/opening, and f is the distance between the centroid of the opening and the edge of the wall/opening. These equivalent properties are computed as:

$$A_e = K_1 A_f \tag{1}$$

$$I_e = K_2 I_f \tag{2}$$

where the proposed values for constants K_1 and K_2 are identified in Table 1. From the data provided in Table 1, the following equivalent equations were obtained:

$$K_1 = 100\left(\frac{e}{f}\right) \tag{3}$$

$$K_2 = 0.0593\left(\frac{e}{f}\right)^4 + 99.348\left(\frac{e}{f}\right)^3 + 302.43\left(\frac{e}{f}\right)^2 + 296\left(\frac{e}{f}\right) + 1.7778 \tag{4}$$

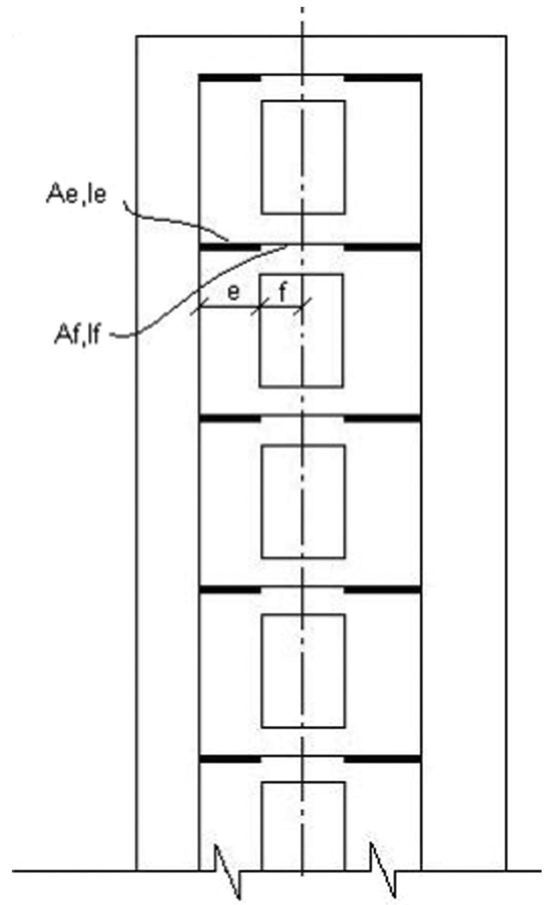

Fig. 1. Equivalent frame method as proposed by Schwaighofer and Microys.

Table 1
Constants proposed by Schwaighofer and Microys.

e/f	K_1	K_1
0.5	50	238
1.0	100	700
2.0	200	2600
3.0	300	6300
5.0	500	21,500

Although the EFM is widely used for the modeling of walls with openings, it is uncommon that engineers would compute constants K_1 and K_2 as proposed by Schwaighofer and Microys. For example, in Mexico beam end zones are considered as infinitely rigid end zones in flexure, and modeled as rigid links according to what it is described in the literature [14,17]. Some other people consider that infinitely rigid end zones should be considered also for the equivalent wide columns that represent the walls (Fig. 2). Therefore, three different modelings were evaluated for the equivalent frame method:

a) Model SM1. The EFM assuming perfectly rigid end zones at beam ends ($A_e \to \infty$ and $I_e \to \infty$, Fig. 1).
b) Model SM2. The EFM as originally proposed by Schwaighofer and Microys (computing A_e and I_e, Fig. 1).
c) Model SM3. The EFM assuming perfectly rigid end zones at beam and wall ends (Fig. 2).

2.2. Equivalent shear connection method

Coull and Choudhury [7,8] proposed a simple method to estimate