Simplified Method for the Seismic Analysis of Masonry Shear-Wall Buildings

Arturo Tena-Colunga, M.ASCE[1]; and Jesús Cano-Licona[2]

Abstract: In this paper, an improved version of a simplified method to assess lateral shear forces attracted by shear walls of regular, low-rise masonry structures is presented. This simplified method for seismic analysis (SMSA) is allowed by Mexican building codes since the 1970s. The impact of shear deformations in the three-dimensional distribution of the forces absorbed by these walls is assessed for different wall aspect ratios (H/L). Based on extensive parametric studies, effective shear area factors (F_{AE}) originally proposed in the SMSA are modified to improve the estimates of shear forces using this method. New F_{AE} are proposed for three different performance levels for the structure: (1) elastic response; (2) completely nonlinear (cracked) response of all walls along the building height; and (3) partially nonlinear (cracked) response along the height.

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Introduction

Low-rise masonry or reinforced concrete (RC) shear-wall buildings with rigid RC diaphragms are used extensively worldwide, particularly in Latin-American countries, but they are also used in European and Asiatic nations. Low-rise masonry structures accounts for almost 70% of the engineered construction in Mexico, as most housing and many public school projects nationwide are built using low-rise masonry structures with RC floor systems. Therefore, depending on the complexity of the low-rise structure, design engineers use state-of-the-art software for irregular buildings or the simplified method for seismic analysis (SMSA) allowed by Mexican building codes since 1977 for somewhat regular structures. The SMSA is also often used by structural engineers to do quick, gross checks in the design of more complex irregular structures (R. Jean, personal communication, 2004).

The SMSA is then commonly used in Mexico for the analysis and design of low-rise shear-wall structures. In order to use the SMSA, the following requirements must be complied with: (1) the walls must carry more than 75% of the gravitational loads; (2) all walls must be connected to a rigid and strong floor diaphragm; (3) the distributions of walls in plan must be as symmetric as possible, but some asymmetry is allowed, so a maximum static eccentricity at any level, e_{si}, must not exceed 10% of the maximum floor dimension (B_i) perpendicular to the direction of analysis, that is, $e_{si} \leq 0.1 B_i$ (Fig. 1); (4) the plan aspect ratio should not exceed two ($L_1/L_2 \leq 2$, Fig. 2); (5) the ratio between the height of the structure and the shorter plan side should not exceed 1.5 ($H_T/L_2 \leq 1.5$, Fig. 2); and (6) the structure shall not be higher than 5 stories in height or 13 m (42.7 ft), whichever is smaller.

If the six requirements listed above are met, then it is allowed to design the building by just computing the seismic shear forces that each wall has to carry according to its relative shear stiffness, as described in paragraphs ahead, and then assessing if the masonry wall (or RC wall) has enough strength to carry the attracted shear force or if horizontal steel reinforcement is needed. Once all walls are correctly designed by shear forces, the design procedure is over, as no further reviews are needed, for example, to assess if lateral drifts meet code requirements, etc. Therefore, the SMSA is very attractive as it allows studying quickly different options for the design of low-rise buildings with a small computational effort, as a modest computer with a spreadsheet program becomes a powerful tool to implement the SMSA.

The six requirements imposed to the SMSA have a purpose. Requirement 1 warranties that the walls compose the main structural system. Requirement 2 asks for a strong and rigid floor system. Requirement 3 asks for a symmetric structure if possible, but allows for a 10% static eccentricity to limit torsional responses. Requirement 4 limits the plan aspect ratio to reduce the possibility of flexible diaphragm amplification taking into account that RC slab systems are most commonly used in Mexico. Requirement 5 limits the possibility of important overturning moments and other slenderness effects (P-Δ). Finally, Requirement 6 restricts the applicability of the method to low-rise buildings.

Whereas the SMSA is allowed for masonry, RC, and wood low-rise shear buildings with rigid diaphragms, it is most commonly used for masonry structures and sometimes for RC structures. It is worth noting that wood structures are not commonly used in Mexico and Latin-American countries for housing or low-rise construction, in contrast to the practice of the United States, Canada, and many other countries.

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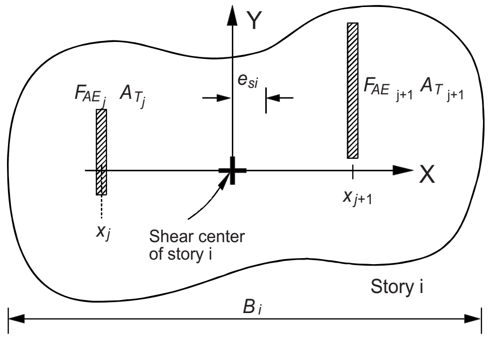

Fig. 1. Definition of static eccentricity for the SMSA of Mexican Codes (NTCM-2004 2004)

Theoretical Background for the SMSA

The SMSA is based on an idealized distribution of lateral forces of symmetric shear-wall structures with rigid diaphragms, as schematically depicted in Figs. 3 and 4. When a symmetric shear-wall structure with rigid diaphragms is subjected to lateral loading V_i, a uniform displacement D_i is experienced at each floor level i. This uniform displacement D_i is imposed to the resisting wall elements, so each wall j at level i takes its share of the shear force V_{ji} in terms of its lateral shear stiffness k_{ji} (Fig. 1); this is

$$V_i = \sum_{j=1}^{n} V_{ji} = \sum_{j=1}^{n} k_{ji} D_i; \quad \rightarrow D_i = \frac{V_i}{\sum_{j=1}^{n} k_{ji}} \tag{1}$$

$$V_{ji} = k_{ji} D_i = \frac{k_{ji}}{\sum_{j=1}^{n} k_{ji}} V_i \tag{2}$$

The lateral stiffness of a wall primarily depends on its shear deformation. Therefore, neglecting bending deformations, the lateral stiffness of a wall j at level i, k_{ji}, can be approximated by its shear stiffness alone which is given by the product of the shear modulus G and the effective shear area of the wall divided by the story height H_i, in the following way as proposed by Mexican codes

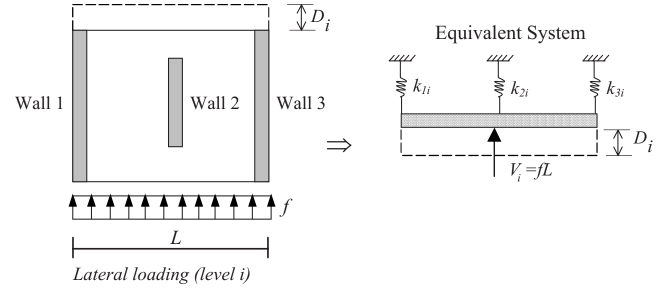

Fig. 3. Rigid diaphragm hypothesis related to the SMSA

$$k_{ji} = \frac{G F_{AE_{ji}} A_{T_{ji}}}{H_i} \tag{3}$$

where $F_{AE_{ji}}$ = effective shear area factor of wall j at level i (proposed by SMSA) and $A_{T_{ji}}$ is the cross section area (axial area) of wall j at level i. Therefore, from Eqs. (3) and (2), it is obtained that the shear force attracted by wall j at level i, V_{ji} is

$$V_{ji} = V_i \frac{F_{AE_{ji}} A_{T_{ji}}}{\sum_{j=1}^{n} F_{AE_{ji}} A_{T_{ji}}} \tag{4}$$

The effective shear area factor F_{AE} proposed by Mexican codes for the SMSA [for example, MOC-93 (1993), NTCS-2004 (2004), and NTCM-2004 (2004)] depends on the aspect ratio of the wall (L/H) as follows:

$$F_{AE} = 1 \quad \text{if} \quad \frac{H}{L} \leq 1.33 \tag{5}$$

$$F_{AE} = \left(1.33 \frac{L}{H}\right)^2 \quad \text{if} \quad \frac{H}{L} > 1.33 \tag{6}$$

In elevation, the SMSA assumes that any shear wall j [Fig. 4(a)] can be represented by a shear model [Fig. 4(b)], therefore, the lateral stiffness matrix $[K_D]_j$ of wall j is tridiagonal and given by:

$$[K_D]_j = \begin{bmatrix} k_{jk} + k_{jl} & -k_{jl} & 0 \\ -k_{jl} & k_{jl} + k_{jm} & -k_{jm} \\ 0 & -k_{jm} & k_{jm} \end{bmatrix} \tag{7}$$

Finally, the approximate formula to compute the static torsional eccentricity (e_{si}) proposed by SMSA (NTCM-2004 2004) is based

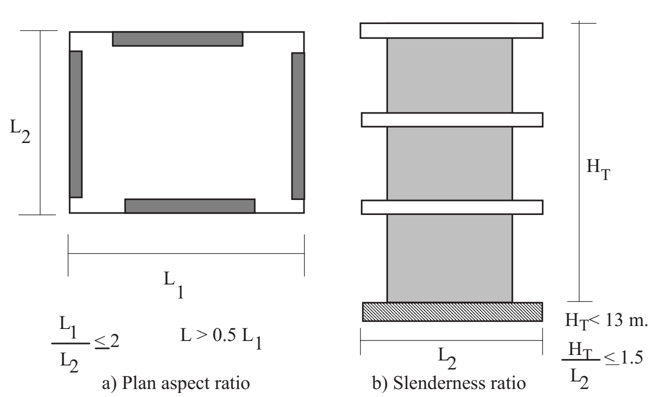

Fig. 2. Plan and slenderness requirements for the SMSA

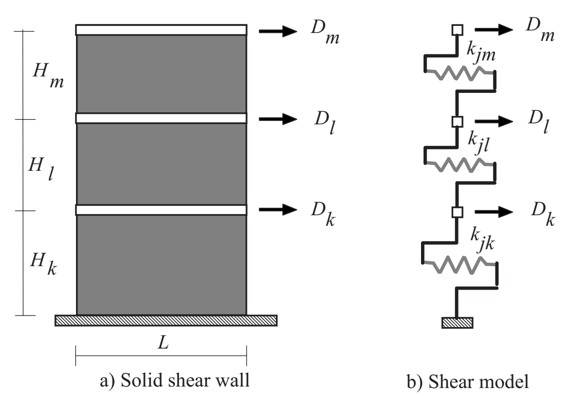

Fig. 4. Shear-wall modeling assumption related to the SMSA

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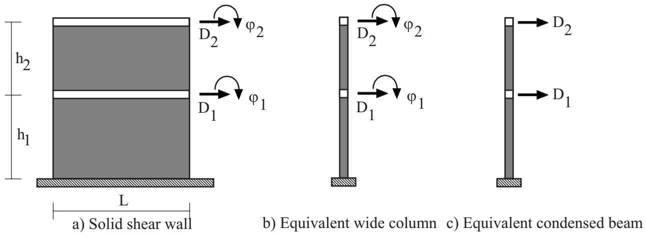

Fig. 5. Flexural wall modeling

on a centroid of the effective shear area for a given distribution of resisting elements, as shown in Fig. 1, and is

$$e_{si} = \frac{\sum_{j=1}^{n} x_j F_{AEj} A_{Tj}}{\sum_{j=1}^{n} F_{AEj} A_{Tj}} \leq 0.1 B_i \qquad (8)$$

Initial Review for the SMSA

As described, the SMSA of Mexican codes is conceptually strong for the design of squatty, low-rise symmetric wall structures with rigid diaphragms. However, there are some aspects that required an in-depth review for a method that was proposed in the late 1970s.

The first modification since the 1970s for the method from the analysis viewpoint is the required review for compliance for a maximum static eccentricity of 10% given in Eq. (8), introduced in 2000 during the review process of the masonry regulations of Mexico's Federal District Code (NTCM-2004 2004).

Another mandatory review was to assess the accuracy of the SMSA when compared to rigorous, three-dimensional (3D) analysis. It is evident from Fig. 4(b) that as the SMSA is based on a shear modeling of the walls, it is neglecting the impact of wall rotations. Tena-Colunga and Pérez-Osornio (2001, 2002, 2005) performed the initial review of the SMSA for elastic response by including the impact of wall rotations and shear deformations through the equivalent wide column analogy of the walls [Fig. 5(b)] described, among other works, in Schwaighofer and Microys (1969), in the parametric study of symmetric and asymmetric low-rise masonry structures that complied with all the requirements to apply the SMSA.

Tena-Colunga and Pérez-Osornio (2005) reported in their study many interesting findings regarding the impact of shear deformations in: (1) the distribution of shear forces in plan and (2) the shifts of the centers of torsion (or the twist axis) from an ideal elastic vertical axis because of the impact of shear deformations on the rotational degrees of freedom of the walls.

In addition, Tena-Colunga and Pérez-Osornio (2001) found, using the same 3-story building models reported in Tena-Colunga and Pérez-Osornio (2005), that there were important differences in the story shear forces attracted by walls of symmetric and asymmetric buildings when computed with the SMSA (V_{SMSA}), with respect to those computed with rigorous 3D analysis of buildings where walls are modeled as equivalent wide columns (V_{3D}), as shown in Fig. 6.

As observed in Fig. 6, the SMSA and rigorous 3D analysis only have a perfect correlation ($V_{3D}/V_{SMSA}=1$) when all walls are square (aspect ratio $H/L=1$). Indeed, the wall aspect ratio (H/L) is an important parameter that impacts shear deformations, then the stiffness distribution and the attraction of shear forces. Therefore, when there are short walls in the perimeter ($H/L<1$), usually the shear forces computed for the perimeter walls with the SMSA are underestimated with respect to those obtained from a rigorous 3D analysis, then $V_{3D}/V_{SMSA}>1$. On the other hand, when there are slender walls in the perimeter ($H/L>1$), usually the shear forces computed for the perimeter walls with the SMSA are overestimated with respect to those obtained from a rigorous 3D analysis, then $V_{3D}/V_{SMSA}<1$.

From the analysis of several results similar to those presented in Fig. 6, including those for more complex and asymmetric buildings where the differences are larger, it was concluded that in order to improve the accuracy of the SMSA, an in-depth review of the effective shear area factors (F_{AE}) proposed by the method [Eqs. (5) and (6)] was needed first. Given that the shear strength of masonry in Mexico is very low because the mechanical properties of bricks and blocks are low compared to U.S. standards, an inaccurate estimate of design shear may have a

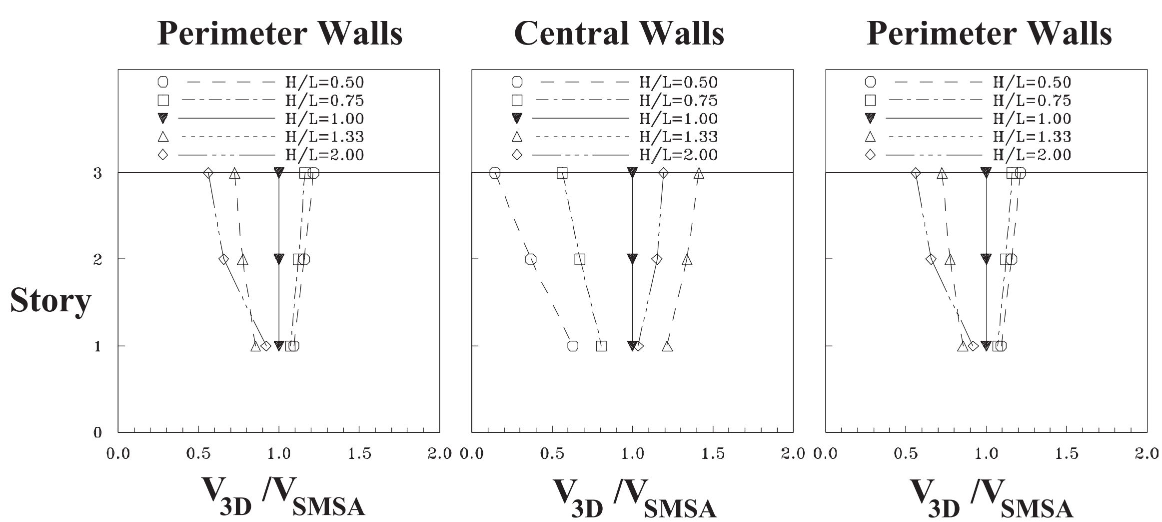

Fig. 6. V_{3D}/V_{SMSA} ratio for symmetric shear-wall buildings studied by Tena-Colunga and Pérez-Osornio (2001) when subjected to unidirectional lateral load forces

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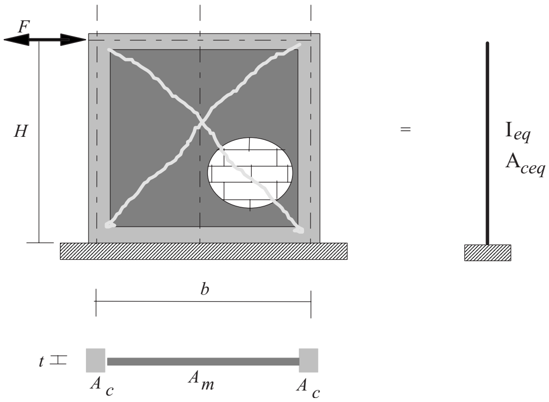

Fig. 7. Equivalent cracked wide column analogy proposed by Bazán and Meli

negative impact in the expected structural performance of confined masonry structures designed with the SMSA. The review of current F_{AE} and the formulation of new effective shear area factor for three different structural performance levels will be briefly described in following sections.

Review and Proposal of Effective Shear Area Factors for the SMSA

The first steps to improve the effective shear area factors for the SMSA were: (1) review the shortcomings of Eqs. (5) and (6) with a larger parametric study; (2) study how the F_{AE} equation should look like from theory; and (3) study how the F_{AE} equations should be considering desirable structural performances for extreme earthquakes, where a degree of nonlinear response (cracking) is allowed in the masonry to survive the earthquake.

Therefore, for modeling elastic response of the masonry walls, the equivalent wide column analogy, where shear deformations are included, was used [Fig. 5(b)]. In order to consider equivalent properties of cracked masonry walls in reasonable damaged ranges, the equivalent cracked wide column analogy (Fig. 7) proposed by Bazán and Meli (1998) from the analysis of experimental data of several confined masonry walls designed according to the Mexican practice in the 1970s was used, given by the following equations:

$$I_{eq} = A_c \frac{b^2}{2} \tag{9}$$

$$A_{ceq} = (0.37 - 0.12\zeta + 0.023\lambda)(A_m + 2A_c) \tag{10}$$

$$\zeta = \frac{b}{H} \tag{11}$$

$$\lambda = \frac{E_c A_c}{G_m A_m} \tag{12}$$

where I_{eq}=equivalent cracked moment of inertia; A_{ceq}=equivalent cracked area; A_c=area of the confining vertical element; A_m=area of the masonry; E_c=elastic modulus of the concrete of the confining elements; G_m=shear modulus of the masonry; ζ=aspect ratio parameter valid for the following range: $0.75 \leq \zeta \leq 2.5$; and λ=parameter that measures the relative axial stiffness of the confining elements with the shear stiffness of the masonry and is valid for the following range: $0.9 \leq \lambda \leq 11$. The equivalent cracked wide column analogy proposed by Bazán and Meli has also been reviewed with the experimental data of confined masonry walls and buildings tested in Mexico from 1990 to 2007 and found to be in good agreement as well [for example, Tena-Colunga et al. (2009)].

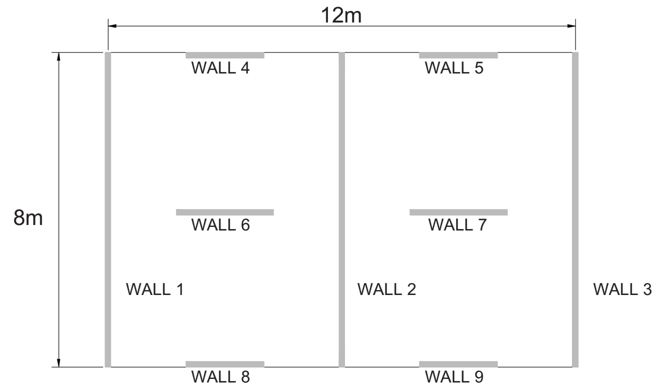

Fig. 8. Typical symmetric plan for the bearing wall building models

Models Used

For the parametric studies, a set of simple yet representative building models of 3 and 5 stories that comply with the six requirements of the SMSA were used. The typical symmetric plan of such models is depicted in Fig. 8. All walls were supposed to have a thickness of 14 cm and a height of 2.5 m. In the parametric study, Walls 1–3 remain constant, as the parametric study was based on the walls running in the horizontal direction (Walls 4–9). The properties of Walls 4–9 varied from model to model, particularly in terms of the aspect ratio H/L, as identified in Table 1. For all models, (1) Central Walls 6 and 7 were identical and (2) Perimeter Walls 4, 5, 8, and 9 were identical as well.

It is observed from Table 1 that for each building height (three or five stories), 43 models were studied for each fixed H/L relation of the central walls, as the perimeter walls were the ones which properties varied in terms of their aspect ratio H/L at 0.05 increments. As five different H/L relations were fixed for the central walls (0.5, 1.0, 1.5, 2.0, and 2.5), then 215 different models were studied for each building height, giving a total of 430 models for the 3- and 5-story building layouts. Besides, each model was analyzed using (1) a rigorous 3D static analysis and (2) the SMSA at least twice in order to calibrate proposed effective shear area factors. Therefore, at least 1,290 different analyzes were run for each structural performance objective. Three case studies were studied regarding structural performance objectives: (1) completely elastic response (Fig. 9); (2) partially nonlinear

Table 1. Models for the Parametric Study for Each Structural Performance and Building Height

Parametric case	Total number of models	Aspect ratio H/L Central Walls 6 and 7	Aspect ratios H/L Perimeter Walls 4, 5, 8, and 9
1	43	0.5	0.4–2.5 (0.05 increments)
2	43	1.0	0.4–2.5 (0.05 increments)
3	43	1.5	0.4–2.5 (0.05 increments)
4	43	2.0	0.4–2.5 (0.05 increments)
5	43	2.5	0.4–2.5 (0.05 increments)

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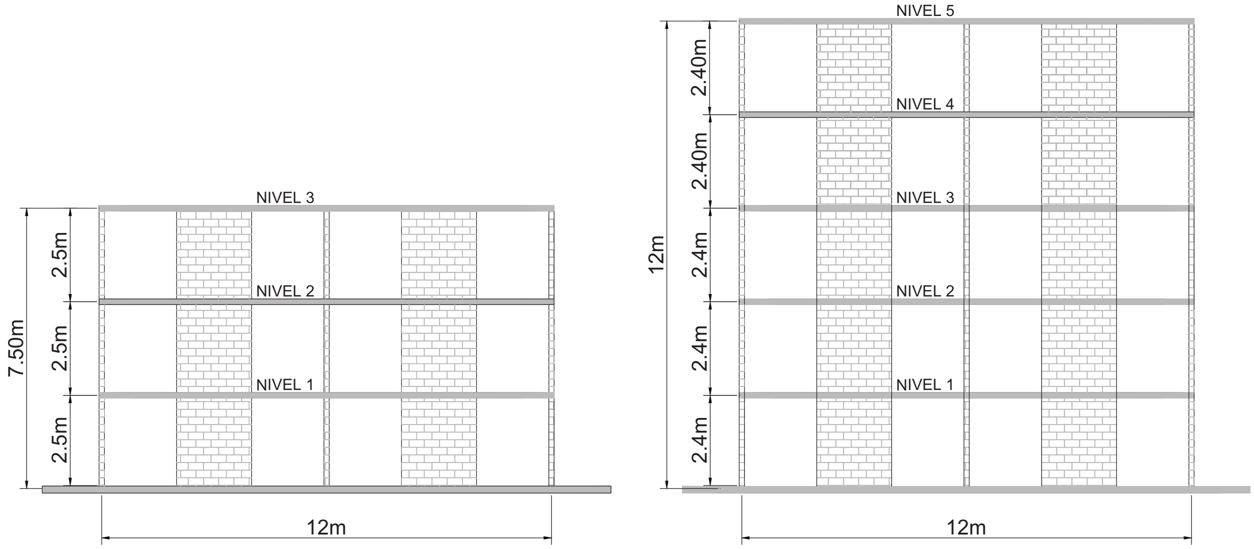

Fig. 9. Elevation of walls running in the horizontal direction for elastic response

(cracked) response of all walls along the height of the building (Fig. 10), based on the observed performance of confined masonry structures from experimental testing (i.e., Alcocer et al. 2004); and (3) completely nonlinear (cracked) response of all walls along the building height (Fig. 11), which is unfortunately an observed performance in severe earthquakes for unreinforced masonry and/or poorly confined masonry. Therefore, the total number of analysis initially conducted in this parametric study was 3,870.

In this research, shear forces attracted by shear walls according to the SMSA are compared with respect to those obtained with 3D static analysis. Usually, the critical story for design under lateral earthquake loading is the 1st story. Therefore, the 1st story was monitored to assess the differences in the story shear forces attracted by walls of the symmetric buildings when computed with the SMSA (V_{SMSA}) with respect to those computed with 3D static analysis of buildings where walls are modeled as equivalent wide columns (V_{3D}), through the V_{3D}/V_{SMSA} ratio. This ratio was the basis to evaluate the adequacy of current effective shear factors F_{AE} and to propose new effective shear area factors for the structural performances levels considered (Figs. 9–11), as briefly described in following sections with the results presented in Figs. 12–17, where it is worth noting that solid lines identify the results obtained for the 1st story (N1) whereas broken lines depict the results obtained for the 2nd (N2) and 3rd (N3) stories.

Review of F_{AE} Proposed by NTCM-2004

The V_{3D}/V_{SMSA} ratios for the 3-story models are presented in Fig. 12 when the behavior of the walls for the 3D analyzes is elastic (Fig. 9) and the effective shear area factors proposed by NTCM-2004 [Eqs. (5) and (6)] are used in the SMSA for Cases 1, 2, and 5 identified in Table 1. The solid line identifies the ratios for the 1st story (N1), and broken lines depict the ratios obtained for the 2nd (N2) and 3rd (N3) stories. It can be confirmed from the observation of these figures that the effective shear area factors proposed by NTCM-2004 [Eqs. (5) and (6)] are not good enough, particularly when $H/L \leq 1$ for the central walls. These F_{AE} only

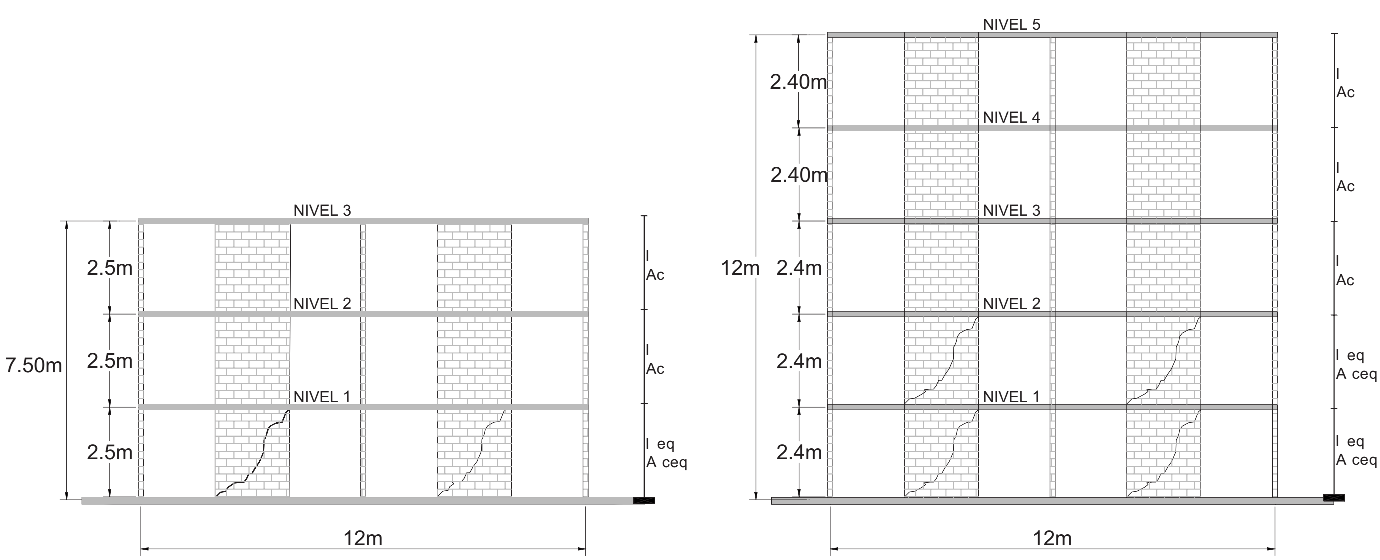

Fig. 10. Elevation of walls running in the horizontal direction for partially cracked response

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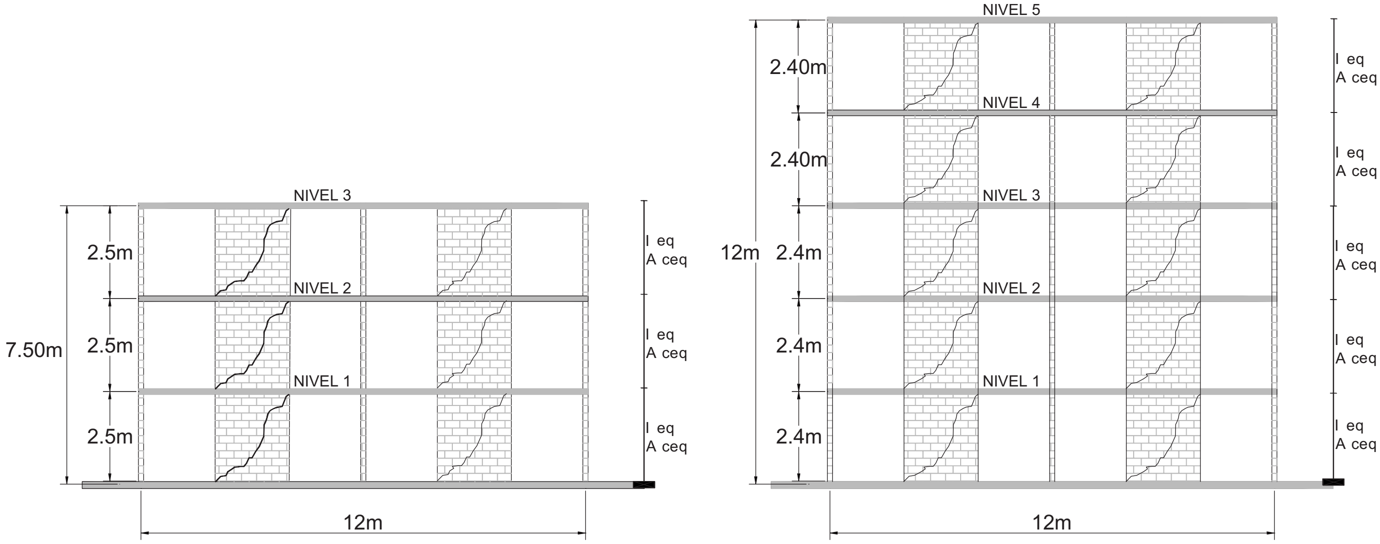


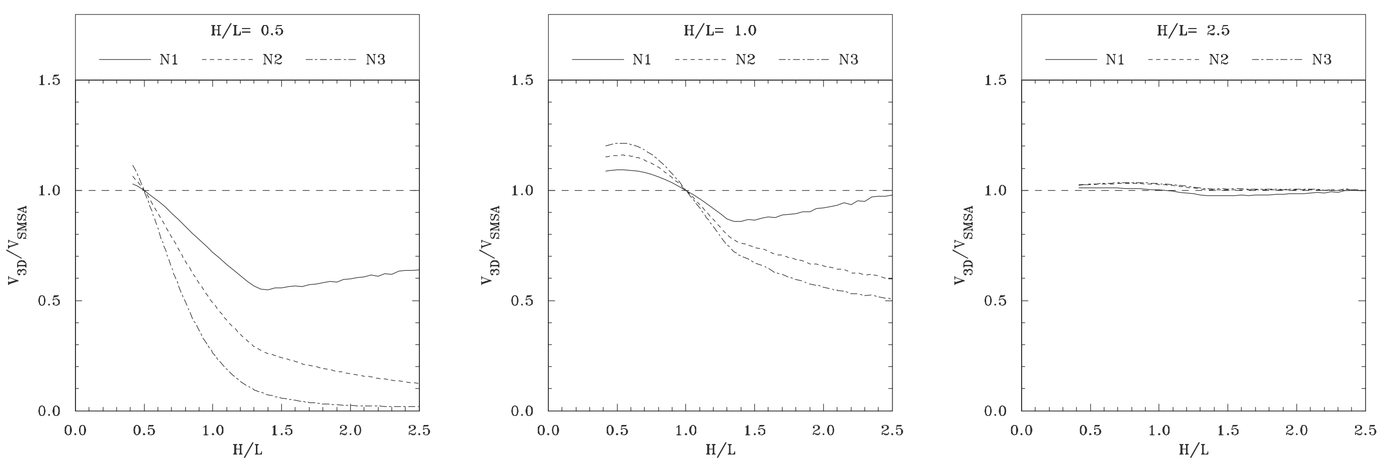
Fig. 11. Elevation of walls running in the horizontal direction for total cracked response

seem to be good enough when there are more slender walls in the center ($H/L=2.5$) and in the perimeter [Fig. 12(c)].

The V_{3D}/V_{SMSA} ratios for the 3-story models are presented in Fig. 13 when the behavior of the walls for the 3D analyzes is the partially cracked response expected for confined masonry buildings (Fig. 10) and the effective shear area factors proposed by NTCM-2004 [Eqs. (5) and (6)] are used in the SMSA for Cases 1, 2, and 5 identified in Table 1. The solid line identifies the ratios for the 1st story (N1). It can be confirmed from the observation of these figures that using the effective shear area factors proposed by NTCM-2004 would lead in many instances to unsafe predictions of the shear attracted by the 1st story walls, particularly when $H/L \leq 1$ for the central walls. Similar results were obtained when assuming at total cracked response (Fig. 11), as shown in Fig. 14. Therefore, it was evident that an improvement of the effective shear area factor was indeed needed in the SMSA to have better predictions.

New Proposal of F_{AE} for Elastic Response

As briefly described in the previous section, the current proposal of NTCM-2004 for the effective shear area factors was not good enough for elastic response, so new factors should be found to match closely the elastic response. The first step was to rationalize from elastic structural analysis theory how these equations should look like if one considers that multistory elastic walls can be represented by equivalent wide columns where shear deformations are included (Fig. 5). The details of this development are presented in Cano-Licona (2005) and Cano-Licona and Tena-Colunga (2005) and are briefly summarized. From static condensation of the assembled stiffness matrix for the walls depicted in Fig. 5, it was obtained that the stiffness coefficients of the resulting lateral stiffness matrix $k_{ij\Delta}$ are of the form



a) H/L=0.5 for central walls b) H/L=1.0 for central walls c) H/L=2.5 for central walls

Fig. 12. V_{3D}/V_{SMSA} ratios for symmetric shear-wall buildings for elastic behavior using current F_{AE} for the SMSA when subjected to unidirectional static lateral loads

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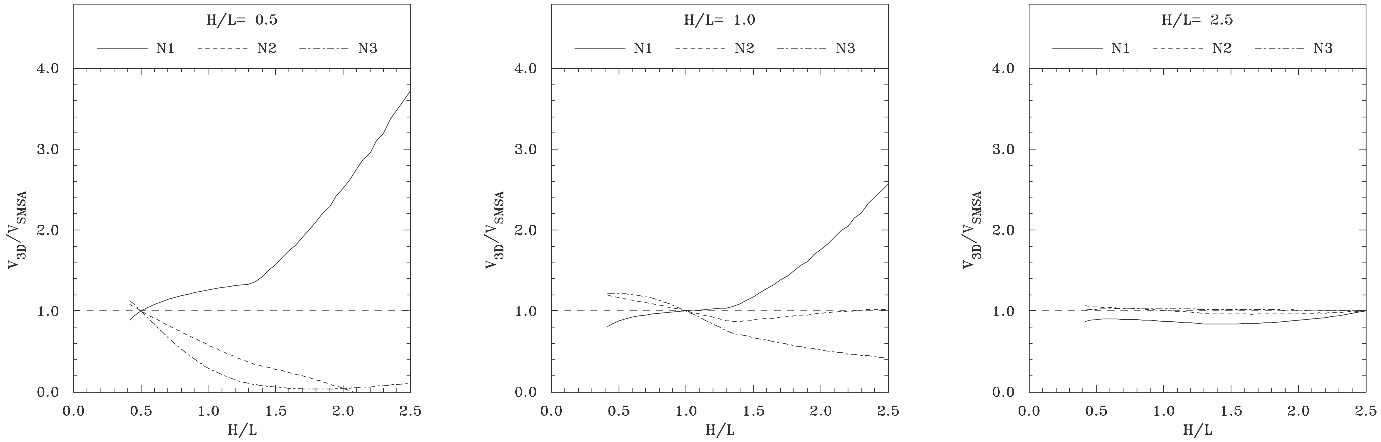


a) H/L=0.5 for central walls b) H/L=1.0 for central walls c) H/L=2.5 for central walls

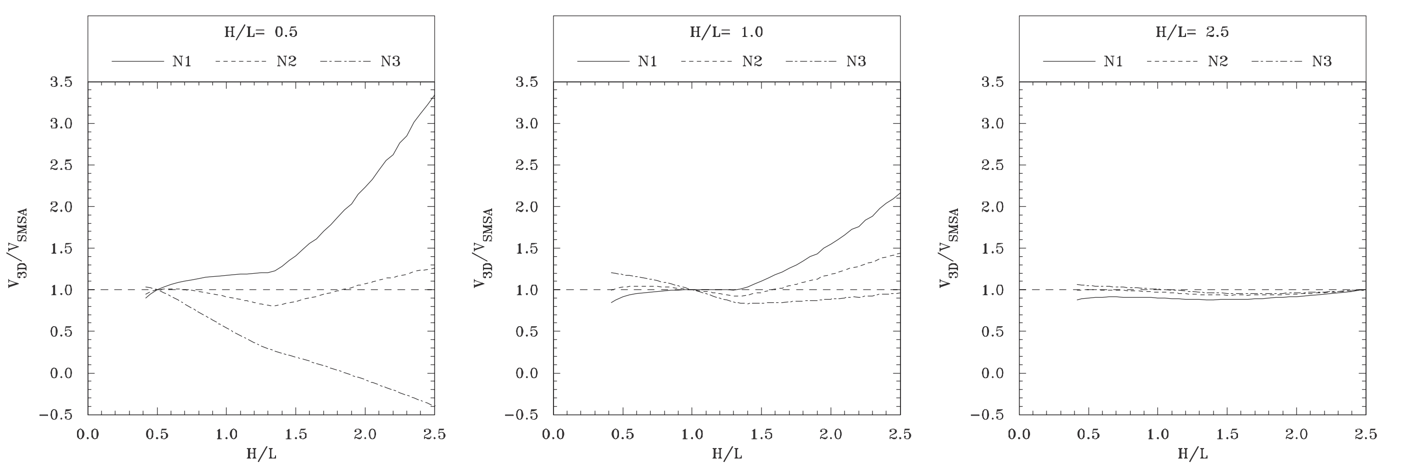
Fig. 13. V_{3D}/V_{SMSA} ratios for symmetric shear-wall buildings for partially cracked response using current F_{AE} for the SMSA when subjected to unidirectional static lateral loads

$$[k_{ij\Delta}] = \frac{aEt}{1+3\frac{L^2}{H^2}}\left[1-\frac{b+c\frac{L^2}{H^2}}{d+e\frac{L^2}{H^2}+f\frac{L^4}{H^4}}\right] \tag{13}$$

where a to f=numerical coefficients that depend on the static condensation. One can observe the following from this development: (1) there are polynomial expressions in terms of the H/L ratio involved in $k_{ij\Delta}$ and (2) if one wants to improve the approximations for the SMSA for all stories, a matrix involving different F_{AE} will be needed. Therefore, as Item 2 is unpractical, what it was decided was to improve the approximations for the SMSA for the 1st story walls, as the 1st story is commonly the critical one for the seismic design of low-rise wall structures. From Eq. (13) it was clear that a simple polynomial form could be used to improve the estimates of the SMSA to match closely those obtained from a 3D static analysis, therefore

$$V_{3D} = \left[c_1 + c_2\frac{H}{L} + c_3\left(\frac{H}{L}\right)^2\right]V_{SMSA} = F_{AE}V_{SMSA} \tag{14}$$

In order to propose new F_{AE} for elastic behavior the following steps were taken: (1) the results from the 3D static analysis (V_{3D}) for the 1st story were normalized with those obtained with the SMSA using F_{AE}=1, to examine the form of the resulting curves and (2) different polynomial functions similar to Eq. (14) were studied from regression analyzes and later used to evaluate their accuracy for the 1st story. The final expressions obtained from such procedure are given in Eqs. (15) and (16), and the corresponding V_{3D}/V_{SMSA} ratios for the 3-story models are presented in Fig. 15, where it can be confirmed that the prediction is improved when compared to the F_{AE} currently proposed by NTCM-2004 (Fig. 12)



a) H/L=0.5 for central walls b) H/L=1.0 for central walls c) H/L=2.5 for central walls

Fig. 14. V_{3D}/V_{SMSA} ratios for symmetric shear-wall buildings for total cracked response using current F_{AE} for the SMSA when subjected to unidirectional static lateral loads

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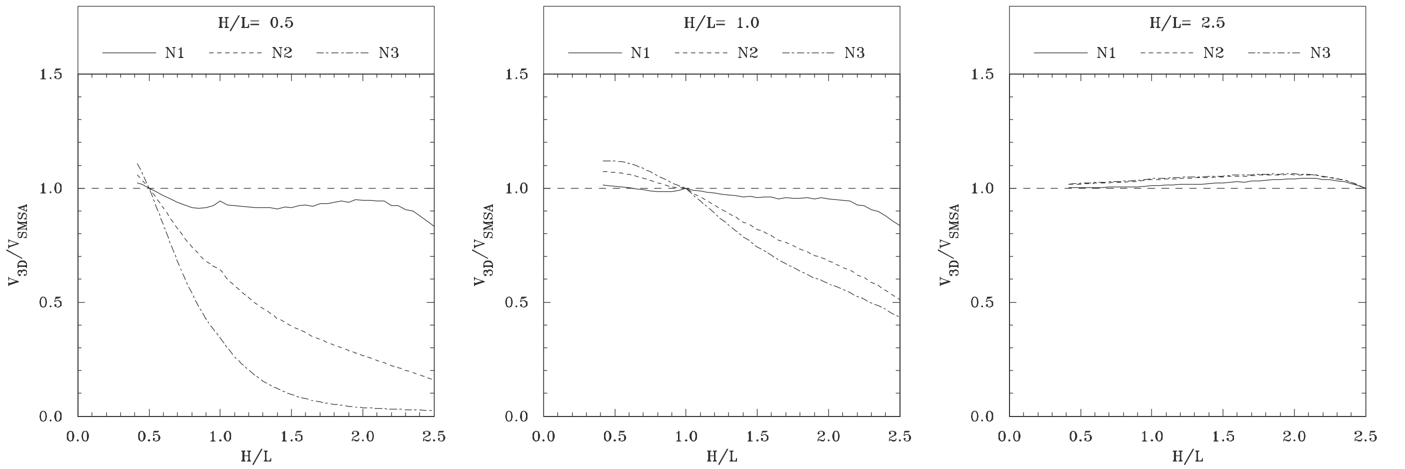


a) H/L=0.5 for central walls b) H/L=1.0 for central walls c) H/L=2.5 for central walls

Fig. 15. V_{3D}/V_{SMSA} ratios for symmetric shear-wall buildings for elastic behavior using proposed F_{AE} for the SMSA when subjected to unidirectional static lateral loads

$$F_{AE} = 1.5 + \frac{H}{L} - 1.5\left(\frac{H}{L}\right)^2 \quad \text{if} \quad 0.4 \le \frac{H}{L} \le 1.0 \qquad (15)$$

$$F_{AE} = 2.2 - 1.5\frac{H}{L} + 0.3\left(\frac{H}{L}\right)^2 \quad \text{if} \quad 1.0 < \frac{H}{L} \le 2.5 \qquad (16)$$

New Proposal of F_{AE} for Partially Cracked Response

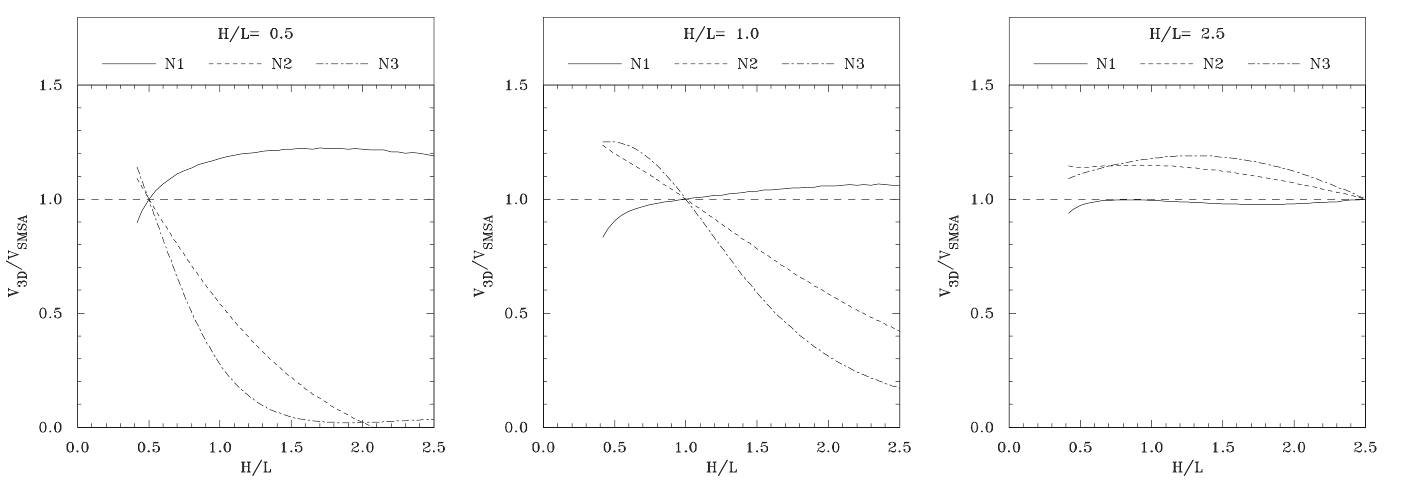
The structural performance called here as partially cracked response is depicted in Fig. 10 and has been experimentally reproduced in shaking table tests for confined masonry buildings designed according to the Mexican norms (Alcocer et al. 2004). The procedure used to obtain an effective shear area factor for partially cracked response (F_{AEPA}) is similar to the one described above for elastic response, with the difference that for the 3D static analysis, cracked walls were modeled according to the cracked equivalent wide column analogy proposed by Bazán and Meli [Eqs. (9)–(12)] and elastic walls were modeled as a Bernoulli-Euler beam column with shear deformations. The resulting expression is

$$F_{AEPA} = 0.6 + 0.6\frac{H}{L} - 0.3\left(\frac{H}{L}\right)^2 + 0.05\left(\frac{H}{L}\right)^3 \quad \text{if} \quad 0.4 \le \frac{H}{L} \le 2.5 \qquad (17)$$

The corresponding V_{3D}/V_{SMSA} ratios for the 3-story models are presented in Fig. 16, where it is observed that for this complicated performance the proposed F_{AEPA} is reasonable when $H/L > 1$ for the central walls and the entire H/L range for the perimeter walls [Figs. 16(b and c)]; however, the predictions for the 1st story walls (N1) are not conservative when the central walls have H/L=0.5 [Fig. 16(a)].

New Proposal of F_{AE} for Totally Cracked Response

The structural performance called here as totally cracked response is depicted in Fig. 11 and it very commonly observed in old



a) H/L=0.5 for central walls b) H/L=1.0 for central walls c) H/L=2.5 for central walls

Fig. 16. V_{3D}/V_{SMSA} ratios for symmetric shear-wall buildings for partially cracked response using proposed F_{AEPA} for the SMSA when subjected to unidirectional static lateral loads

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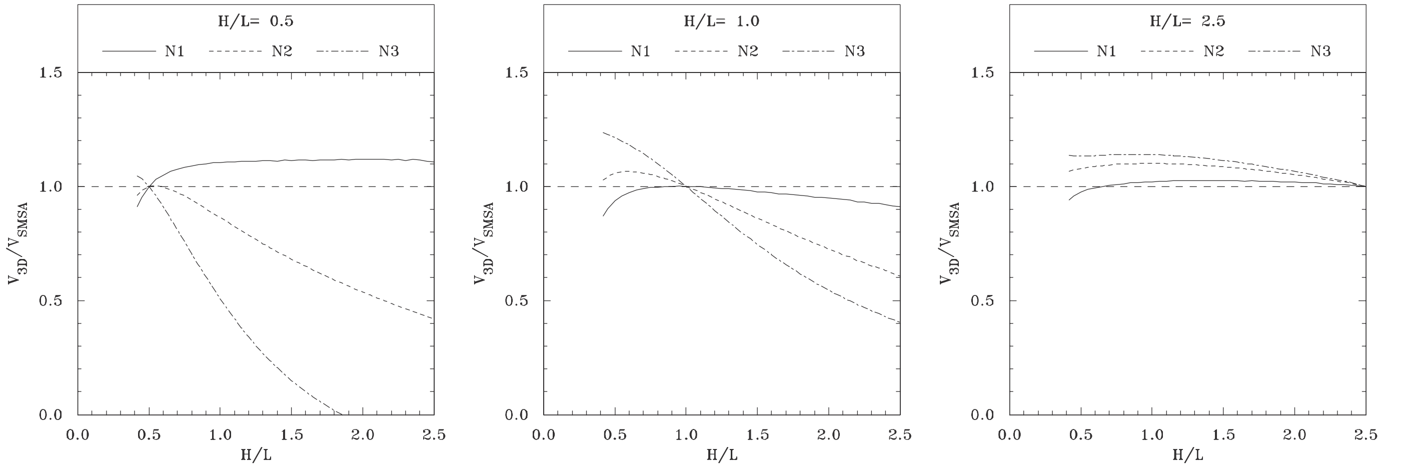

a) H/L=0.5 for central walls b) H/L=1.0 for central walls c) H/L=2.5 for central walls

Fig. 17. V_{3D}/V_{SMSA} ratios for symmetric shear-wall buildings for totally cracked response using proposed F_{AETA} for the SMSA when subjected to unidirectional static lateral loads

unreinforced masonry buildings or deficiently confined masonry buildings during strong earthquakes. The procedure used to obtain an effective shear area factor for this condition (F_{AETA}) is similar to the one described before for the other two structural performances. For the 3D static analysis, cracked walls were modeled according to the proposal by Bazán and Meli. The resulting expression is

$$F_{AETA} = 1 + 1.1\left(\frac{H}{L}\right) - 0.6\left(\frac{H}{L}\right)^2 + 0.1\left(\frac{H}{L}\right)^3 \quad \text{if} \quad 0.4 \leq \frac{H}{L} \leq 2.5 \tag{18}$$

The corresponding V_{3D}/V_{SMSA} ratios for the 3-story models are presented in Fig. 17, where it is observed that the proposed F_{AETA} is very reasonable when $H/L > 1$ for the central walls and the entire H/L range for the perimeter walls [Figs. 17(b and c)]. However, similar to what was observed for the partially cracked response, the predictions for the 1st story walls (N1) are not conservative when the central walls have $H/L = 0.5$ [Fig. 17(a)].

Concluding Remarks

In this paper, shear forces attracted by shear walls according to the SMSA allowed by Mexican Codes were compared with respect to those obtained with rigorous 3D static analysis. The impact of shear deformations in the 3D distribution of the forces absorbed by these walls was assessed for different wall aspect ratios (H/L).

Based on extensive parametric studies, effective shear area factors (F_{AE}) originally proposed in the SMSA were evaluated and modified to improve the estimates of shear forces using this simple method. New effective shear area factors were proposed for three different performance levels for the structure: (1) elastic response [F_{AE}, Eqs. (15) and (16)]; (2) completely nonlinear (cracked) response of all walls along the building height [F_{AETA}, Eq. (18)]; and (3) partially nonlinear (cracked) response along the height [F_{AEPA}, Eq. (17)]. These new effective shear area factors were calibrated to reasonably estimate the shear forces attracted by the first story walls, which are the critical ones for seismic design. In general, the proposed F_{AE}, F_{AEPA}, and F_{AETA}, while relatively simple, are successful enough to improve the estimates using the SMSA (have a good correlation with a conventional 3D static analysis) for an important range of wall aspect ratios (H/L) for both central walls (shown) and perimeter walls [not shown, Cano-Licona (2005)].

The proposed F_{AEPA} and F_{AETA} allow the use of the SMSA to estimate expected shear force demands when nonlinear behavior is expected, then extending the use of the SMSA of the Mexican Codes toward performance-based design goals. It is worth noting that the proposed equations for elastic response [F_{AE}, Eqs. (15) and (16)] and partially nonlinear (cracked) response along the height [F_{AEPA}, Eq. (17)] are now included in the draft guidelines for the seismic design of building structures of the updated Manual of Civil Structures to be publish in 2008 (MOC-2008 2008), as in the design of all structures, including masonry structures, engineers should design for what is it call the service earthquake and the maximum credible earthquake.

Finally, it is also worth noting that the proposed improvements for the SMSA were done to have a better correlation with a conventional 3D static analysis advocated by Mexican seismic codes. These results have not been yet compared with solutions obtained from pushover analyzes or nonlinear time-history analyzes for such structures, studies that are planned to do in the future.

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