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KINEMATICS OF OUT-OF-PLANE BEHAVIOR OF WALL PANELS UNDER IN-PLANE DISPLACEMENT ARISING FROM COMPATIBILITY

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Abstract

When buildings resist seismic action in a given direction (say, N-S direction), simplified seismic assessment procedures, generally, consider wall panels oriented along the direction of the shaking (*i.e.*, walls along N-S direction) to resist only in-plane loads and wall panels oriented perpendicular to the direction of shaking (*i.e.*, walls along E-W direction) to resist only out-of-plane loads. In short, these procedures for seismic assessment of existing buildings, typically, do not consider the interaction of walls meant to resist in-plane and out-of-plane loads. Therefore, independently verified are the adequacy of walls meant to resist in-plane loads and out-of-plane loads. However, in reality, when walls resist in-plane lateral loads, it deforms laterally along the same direction. Moreover, for buildings with a rigid diaphragm and good wall diaphragm connection, this lateral displacement (in N-S direction) results in a relative displacement between the bottom and top part of out-of-plane walls (*i.e.*, walls along E-W direction) (Fig. 1). This relative displacement is due to the displacement compatibility between the walls oriented along the in-plane and out-of-plane directions. This paper presents the effects of the relative displacement between the bottom and top part of out-of-plane walls on its overall stability and load resisting capacity in the out-of-plane direction. Developed moment-displacement relationships of out-of-plane walls indicate a reduction in the out-of-plane displacement capacity, with an increase in relative displacement between the top and bottom part of the wall. This reduction in the out-of-plane capacity is inversely proportional to the level of axial load on the wall. Unlike the out-of-plane displacement capacity, the developed relationships do not show a significant drop in moment capacity. However, the out-of-plane stability of walls, particularly in the post-peak region, is better represented by the attainment of an ultimate displacement rather than the force capacity. Finally, this paper presents a simple seismic assessment procedure to verify the adequacy of out-of-plane walls.

Keywords: Masonry; Seismic Assessment; In-plane and out-of-plane interaction, out-of-plane capacity

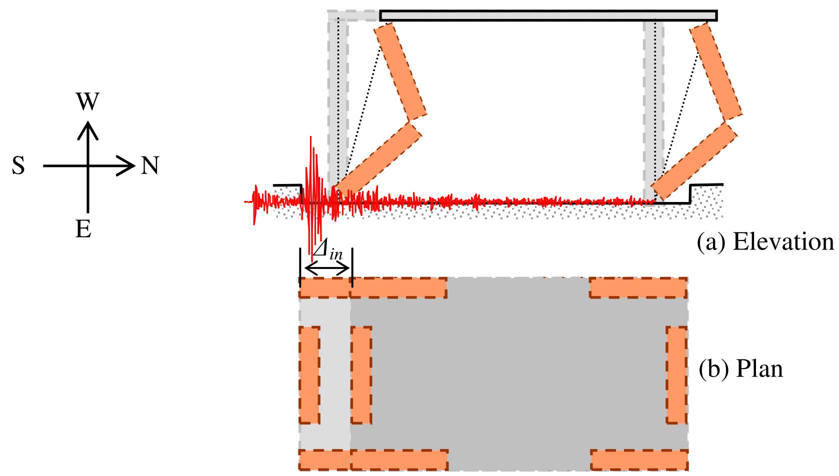


Fig. 1 – Effect of in-plane displacement on stability of out-of-plane walls
(Note: Displacements are amplified for better visibility)

1. Introduction

Out-of-plane instability of walls is an undesirable mode of failure. Seismic design codes attempt to minimise this failure mode for new buildings by recommending a minimum slenderness ratio of wall panels [1]. However, this mode of failure is a concern in existing buildings. Validating this concern is the failure of several *Un-Reinforced Masonry* (*URM*) buildings, during past earthquakes, due to out-of-plane mode of failure of walls.

In general, seismic assessment of *URM* buildings is one of the ways to identify an undesirable mode of damage such as failure of walls in out-of-plane mode during earthquake shaking. Currently, seismic assessment procedures, such as the storey-shear mechanism for masonry, independently verify the capacities of in-plane and out-of-plane wall panels [2]. Further, widely used is the kinematic limit analysis to assess the vulnerability to out-of-plane mechanisms of wall panels [3, 4]. The said method of analysis does not consider the influence of the imposed relative displacement (Δ_{in}) between the top and bottom part of the out-of-plane wall panel while assessing the stability of out-of-plane wall (Fig. (1)). In theory, there is a possibility that the Δ_{in} adversely influence the out-of-plane behaviour of masonry wall panels. In light of this, present in this paper are:

(a) An analytical framework that incorporates the influence of relative displacement between the top and bottom part of the out-of-plane wall on the stability response of out-of-plane walls, and
(b) A stepwise procedure to assess the stability of out-of-plane walls incorporating the influence of relative displacement between the top and bottom part of the out-of-plane wall.

The scope of this paper is limited to *URM* buildings with both rigid diaphragm action and good wall-diaphragm connection. Additionally, for brevity, the scope is limited to quantifying the influence of in-plane displacement on the stability of out-of-plane walls.

2. Existing Method to Assess Out-of-plane Stability of Wall Panels

2.1 Out-of-Plane Capacity of Wall Panels

Assumptions considered in the existing method to estimate the out-of-plane stability of the wall subjected to inertial forces are:

(a) wall panels crack at mid-height dividing each one of them into two identical rigid blocks under the action of out-of-plane loads/deformation (*i.e.*, considered is one-way bending of walls),
(b) floor/roof slab-bounding each wall panel offers full lateral translational restraint and no rotational restraint; and return walls (if any) does not provide either translational or rotational restraint to the wall panel,
(c) floor/roof slabs bounding each wall panel move in-phase with each other and does not sustain any relative displacements between them, and
(d) masonry, as a material, is assumed to have a linear elastic stress-strain response (Fig. 2(a)) [5].

With these assumptions, the free-body of the wall panel indicating the forces acting on it is shown in Fig. 2(b); where N, W, p, and Δ_{out} refer to the axial loads on the wall panel, self-weight of the wall panel, inertial force per unit length of the wall panel, and lateral out-of-plane displacement demand at the mid-height of the wall panel, respectively. Additionally, denoted using H_{top} and H_{bot} are the horizontal resisting force developed in the wall panels at its contact with slabs (Fig. 2(b)). Lastly, represented using R and α are the resultant force at the interface of top and bottom rigid blocks and the distance of the resultant force from the center of the wall panel, respectively (Fig. 2(c)). Equilibrium analysis indicates that the instability of the wall panel occurs when Δ_{out} equals half the thickness (t) of the wall panel (*i.e.*, $\Delta_{out} = t/2$) (Fig. 2(d)). Also, Fig. 2(d) shows the (generalized) mid-height, moment versus lateral out-of-plane displacement (Δ_{out}), response of wall panels when subjected to inertial forces in the out-of-plane direction.

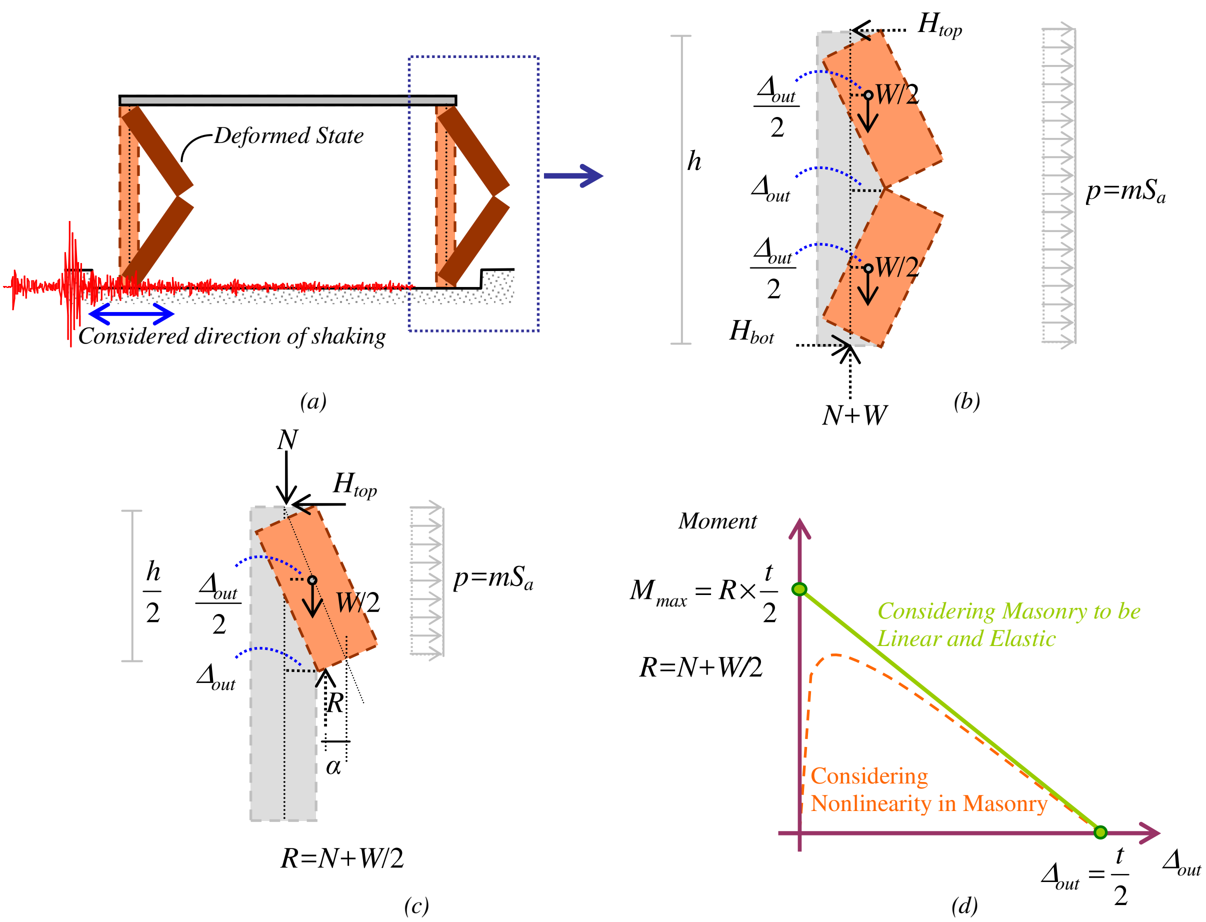


Fig. 2 – (a) One of the possible lateral displacement profile of wall panel (*not to scale*), (b) Forces acting on wall panels (when subjected to inertial forces in the out-of-plane direction), (c) Free-body diagram of forces acting on the top block of wall panel, and (d) Mid-height, moment versus lateral displacement, response of wall panel.

In the recent past, studies have improved the (generalized) mid-height, moment versus lateral displacement relationship by accounting for material nonlinearity [5, 6 and 7]. Results of these studies indicate: (a) moment capacity of wall panels reduces significantly with an increase in axial loads on the wall panel, and (b) lateral displacement (Δ_{out}) that leads to instability does not change significantly with an increase in axial loads [7]. Notwithstanding the recent improvement, the existing method considers NO relative displacement between the top and bottom wall panels (as shown in Fig 1(a)).

2.2 Out-of-Plane Displacement Demand of Wall Panels

Following are the factors that influence the lateral out-of-plane displacement demand (Δ_{out}) of wall panels: (a) aspect ratio of the wall panel (*h/l*), (b) slenderness ratio of the wall panel (*h/t*), (c) mechanical properties of the masonry, (d) natural period of the wall panel in out-of-plane bending (T_{1out}), (e) natural period building in the considered direction (T_{1IN}), (f) height of the wall panel above the base of the building (h_i), and (g) design ground shaking in the considered direction. Seismic design codes, encompassing these factors, recommend closed-form expressions to estimate the out-of-plane spectral acceleration (S_a) of wall panels (Fig. (2(b)). Subsequently, estimated is the out-of-plane displacement demand of wall panels using expected S_a and T_{1out}.

3. Proposed Method to Assess Out-of-plane Stability of Wall Panels

During earthquake shaking in a given direction, the in-plane wall panels in the URM building deforms in the direction of shaking (Fig. 1). The displacement of in-plane wall results in relative displacement between the bottom and top part of the out-of-plane wall panels (Fig. 1). Equilibrium analysis is used to incorporate the influence of relative displacement on the out-of-plane response of wall panels.

3.1 Instability of Out-of-plane Wall Panels

Free-body of the wall panel indicating the forces acting on it is shown in Fig. 3(a); where Δ_{in} refers to the relative displacement between the top and bottom portion of the out-of-plane wall panel, induced due to the displacement of the in-plane wall while resisting earthquake shaking. In Fig. 3(a), moment about the base of the wall panel is given as:

$$H_{top}h = N\Delta_{in} + \frac{W}{2}\left(\frac{\Delta_{out}}{2} + \frac{3\Delta_{in}}{4}\right) + \frac{W}{2}\left(\frac{\Delta_{out}}{2} + \frac{\Delta_{in}}{4}\right) + ph\left(\frac{h}{2}\right). \tag{1}$$

Using Eq.(1), estimate of H_{top} is given as:

$$H_{top} = N\left(\frac{\Delta_{in}}{h}\right) + \frac{W}{2h}\left(\Delta_{out} + \Delta_{in}\right) + p\left(\frac{h}{2}\right). \tag{2}$$

Using the free-body diagram of top block of wall panel (Fig. 3(b)), moment of all forces about the pivot point (*i.e.*, point A in Fig. 3(b)) is given as:

$$R\alpha = N\left(\Delta_{out} - \frac{\Delta_{in}}{2}\right) + \frac{W}{2}\left(\frac{\Delta_{out}}{2} - \frac{\Delta_{in}}{4}\right) + H_{top}\left(\frac{h}{2}\right) - \left(\frac{ph}{2}\right)\left(\frac{h}{4}\right). \tag{3}$$

Substituting Eq.(2) in Eq.(3) leads to,

$$R\alpha = N\left(\Delta_{out} - \frac{\Delta_{in}}{2}\right) + \frac{W}{2}\left(\frac{\Delta_{out}}{2} - \frac{\Delta_{in}}{4}\right) + \left[N\left(\frac{\Delta_{in}}{h}\right) + \frac{W}{2h}\left(\Delta_{out} + \Delta_{in}\right) + p\left(\frac{h}{2}\right)\right]\left(\frac{h}{2}\right) - \left(\frac{ph}{2}\right)\left(\frac{h}{4}\right), \tag{4}$$

Simplifying Eq.(4) and substituting R=(N+W/2) lead to,

$$R\alpha = R\Delta_{out} + \frac{W\Delta_{in}}{8} + p\left(\frac{h^2}{8}\right). \tag{5}$$

Rearranging terms in Eq.(5) leads to,

$$p = \left[R\left(\alpha - \Delta_{out}\right) - \frac{W\Delta_{in}}{8}\right]\left(\frac{8}{h^2}\right). \tag{6}$$

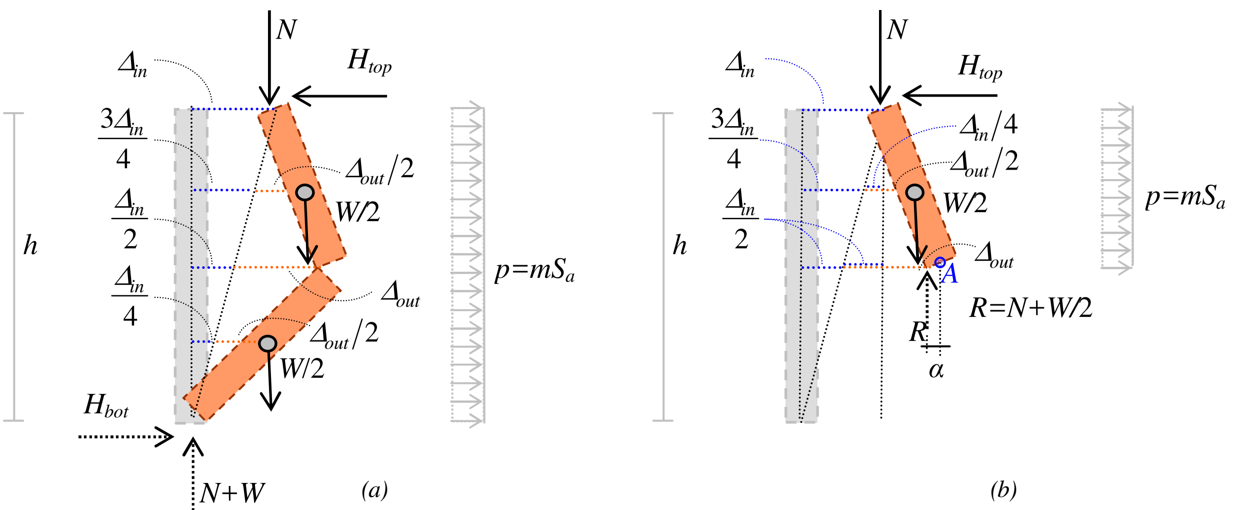


Fig. 3 – (a) Forces acting on the wall panel along with the imposed in-plane displacement and (b) Free-body diagram of forces acting on the top rigid block (*Note: displacements are amplified for better visibility)*

When p=0 the wall panel loses its capacity to resist out-of-plane loads. In Eq. (6), p=0 when

$$\alpha = \left(\frac{W}{8R}\right)\Delta_{in} + \Delta_{out} = \left(\frac{0.125}{(N/W)+0.5}\right)\Delta_{in} + \Delta_{out} . \tag{7}$$

Substituting the maximum value of α (=t/2) in Eq. (7) leads to,

$$\Delta_{out} = \left(\frac{t}{2}\right) - \left(\frac{0.125}{(N/W)+0.5}\right)\Delta_{in} . \tag{8}$$

Eq.(8) indicates that the maximum Δ_{out} demand the out-of-plane wall can sustain, during earthquake shaking, decreases with (a) an increase in Δ_{in} and (b) decrease in N/W ratio.

3.2 Mid-height Moment-Lateral Displacement Response of Out-of-plane Walls

Following are additional assumptions considered to estimate mid-height moment-lateral displacement response of out-of-plane walls:

(a) As available in the literature [6], defined using a parabolic nonlinear $\sigma - \varepsilon$ relation is the axial compressive response of masonry (Eq.(9)); also, 0.0035 is the maximum compressive (ε_{max}) and *zero* the tensile strain limits of masonry;

$$\sigma = 4 f_u \left[\left(\frac{\varepsilon}{\varepsilon_u}\right) - \left(\frac{\varepsilon}{\varepsilon_u}\right)^2\right] \qquad 0 < \varepsilon < \varepsilon_{max} , \tag{9}$$

where $\varepsilon_u = 2\varepsilon_0$; f_u and ε_0 are the maximum compressive stress and the compressive strain corresponding to the maximum compressive stress, respectively; and

(b) As considered in the literature [6], the out-of-plane displacement at the mid section is given as:

$$\Delta = \left(\frac{\Delta_{cr}}{\phi_{cr}}\right)\phi \qquad \phi > \phi_{cr} , \tag{10}$$

where ϕ , ϕ_{cr} , and Δ_{cr} are the curvature of mid section of the wall panel, curvature at which cracking initiates in the mid section of the wall panel and the lateral displacement at which cracking initiates in the mid section of the wall panel, respectively.

Cracking moment (M_{cr}) at the mid height of the wall panel is,

$$M_{cr} = M_1 + M_2 , \tag{11}$$

where M_1 (=$W\Delta_{in}$ /8) and M_2 (=ph^2/8) are the moment induced due to Δ_{in} and p, respectively. The curvature of the wall panel section (ϕ_{cr}) when cracking initiates is given as:

$$\phi_{cr} = \left(\frac{1}{EI}\right)\left[\frac{W\Delta_{in}}{8} + \frac{ph^2}{8}\right], \tag{12}$$

where EI is flexural rigidity of mid section of the wall panel. Using Eq. (12), the out-of-plane load (p) resisted by wall panel is given as:

$$p = \left(\frac{8EI\phi_{cr} - W\Delta_{in}}{h^2}\right). \tag{13}$$

Similar to the moment at mid height of the wall panel, estimated using principle of superposition is the lateral displacement when cracking initiates; this is given as,

$$\Delta_{cr} = \Delta_1 + \Delta_2 , \tag{14}$$

where Δ_1 and Δ_2 are the lateral displacement induced due to Δ_{in} and p, respectively. Estimated using conjugate beam method is the former and is given as:

$$\Delta_1 = \left(\frac{11}{768}\right)\frac{W\Delta_{in}h^2}{EI} . \tag{15}$$

The latter is given as:

$$\Delta_2 = \frac{5}{384}\frac{ph^4}{EI}. \tag{16}$$

Substituting Eqs. (15) and (16) in Eq. (14) gives,

$$\Delta_{cr} = \left(\frac{11}{768}\right)\frac{W\Delta_{in}h^2}{EI} + \frac{5}{384}\frac{ph^4}{EI}. \tag{17}$$

Substituting Eq. (13) in Eq. (17) gives,

$$\Delta_{cr} = \left(\frac{11}{768}\right)\frac{W\Delta_{in}h^2}{EI} + \frac{5}{384}\frac{h^4}{EI}\left(\frac{8EI\phi_{cr} - W\Delta_{in}}{h^2}\right) = \left(\frac{5}{48}\right)\phi_{cr}h^2 + \left(\frac{1}{768}\right)\frac{W\Delta_{in}h^2}{EI}. \tag{18}$$

Following is the step-wise procedure to develop mid-height moment-lateral displacement response of out-of-plane walls:

Step 1: Estimate the strain (ε_{cr}) that leads to cracking in the mid-section of the wall panel (Fig. 4(a)); Eq. (19) is derived considering equilibrium of forces.

$$\varepsilon_{cr} = \left[\frac{1.5 \pm \sqrt{2.25 - 12\beta}}{2}\right]\varepsilon_u, \tag{19}$$

where ε_u is as defined in Eq. (9) and β is a non-dimensional factor given as,

$$\beta = \frac{\left(N + \frac{W}{2}\right)}{4ltf_u}, \tag{20}$$

where N and W are the imposed axial load and self weight of the wall panel, respectively; further, l and t are the length and thickness of the wall panel, respectively; and f_u is as defined in Eq.(9).

Step 2: Estimate ϕ_{cr} using ε_{cr} (Eq. 21).

$$\phi_{cr} = \left(\frac{\varepsilon_{cr}}{t}\right). \tag{21}$$

Step 3: Estimate the location of resultant force ($=\alpha_{cr}$) when cracking of wall panel initiates (Fig 4(a)).

$$\alpha_{cr} = t\left[\frac{\left(\frac{1}{12}\right) - \left(\frac{1}{12}\right)\frac{\varepsilon_{cr}}{\varepsilon_u}}{\left(\frac{1}{2}\right) - \left(\frac{1}{3}\right)\frac{\varepsilon_{cr}}{\varepsilon_u}}\right] \tag{22}$$

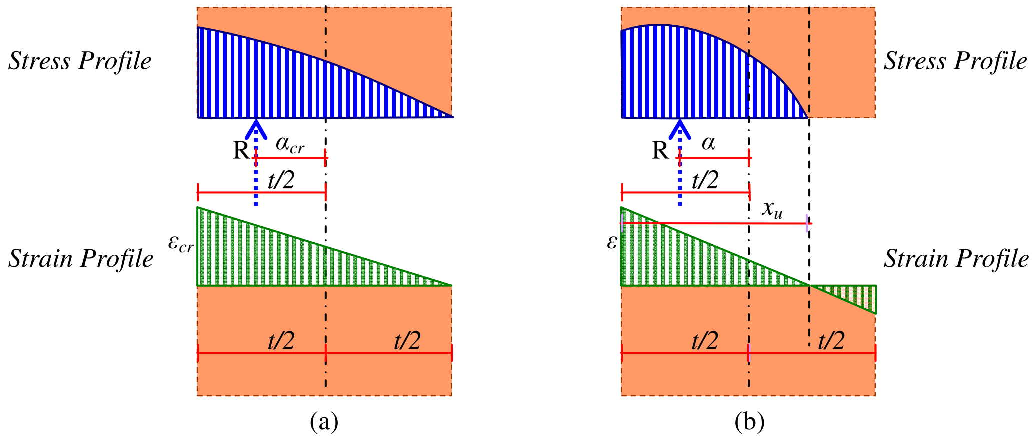


Fig. 4 – (a) State of stress and strain in the mid section of the wall panel when cracking initiates and (b) the state of stress and strain post cracking of the section (*adapted from* [6])

Step 4: Estimate the displacement ($=\Delta_{cr}$) when cracking of wall panel initiates using Eq. (23).

$$\Delta_{cr}=\left(\frac{5}{48}\right)\left(\frac{\varepsilon_{cr}}{t}\right)h^2+\left(\frac{1}{768}\right)\frac{W\Delta_{in}h^2}{EI}. \tag{23}$$

Step 5: Estimate the cracking moment ($=M_{cr}$) using Eq. (24).

$$M_{cr}=\left(N+\frac{W}{2}\right)(\alpha_{cr}-\Delta_{cr})-\left(\frac{W\Delta_{in}}{8}\right). \tag{24}$$

Step 6: Choose at least 10 values of ε between ε_{cr} and ε_{max}. For each value of ε, estimate Δ and M using Steps 7 to 10.

Step 7: For a considered ε between ε_{cr} and ε_{max}, estimate the location of fiber with zero strain from the maximum compressed fiber (x_u) (Fig. 4 (b)); Eq. (25) is derived considering equilibrium of forces.

$$x_u=\frac{\left(N+\frac{W}{2}\right)}{4f_u l\left[\left(\frac{1}{2}\right)\left(\frac{\varepsilon}{\varepsilon_u}\right)-\left(\frac{1}{3}\right)\left(\frac{\varepsilon}{\varepsilon_u}\right)^2\right]}. \tag{25}$$

Step 8: For the considered ε between ε_{cr} and ε_{max}, estimate the displacement (Δ) in the mid section of the wall panel using Eq. (26).

$$\Delta=\left(\frac{\Delta_{cr}}{\phi_{cr}}\right)\left(\frac{\varepsilon}{x_u}\right). \tag{26}$$

Step 9: For the considered ε between ε_{cr} and ε_{max}, estimate the location of resultant force ($=\alpha$) using Eq.(27) (refer Fig 4(b)).

$$\alpha=\left(\frac{t}{2}\right)-x_u\left[\frac{\left(\frac{1}{6}\right)-\left(\frac{1}{12}\right)\left(\frac{\varepsilon}{\varepsilon_u}\right)}{\left(\frac{1}{2}\right)-\left(\frac{1}{3}\right)\left(\frac{\varepsilon}{\varepsilon_u}\right)}\right]. \tag{27}$$

Step 10: For the considered ε between ε_{cr} and ε_{max}, estimate the moment using Eq.(28).

$$M=\left(N+\frac{W}{2}\right)(\alpha-\Delta)-\left(\frac{W\Delta_{in}}{8}\right). \tag{28}$$

Evident from the derived equation is that the mid-height moment-lateral displacement response of the out-of-plane wall depends on Δ_{in} (Eqs. (23), (24), (26) and (28)).

3.3 Influence of the in-plane displacement demand on the out-of-plane response

Fig. 5 (a) shows the decrease in the out-of-plane capacity ($\Delta_{out,c}$) of a typical wall panel with increase in Δ_{in} (Eq. (8)); the considered wall panel is of length 1m, height 3m, thickness 0.13m, sustains NO axial load (N=0) and has a self-weight of 7.8kN. The $\Delta_{out,c}$ reduces by 30% while sustaining Δ_{in} of 60mm (an inter-storey drift of 2% in the orthogonal direction). For discussion, consider the out-of-plane demand ($\Delta_{out,d}$) increases in proportion to Δ_{in}, then the maximum $\Delta_{out,d}$ resisted by wall panel before out-of-plane failure is 52mm (Fig. 5(b)). This indicates that the out-of-plane reaches its displacement capacity before the in-plane wall panel (present in the orthogonal direction) resists an inter-storey drift demand of 2%. In general, several factors influence the Δ_{in} and $\Delta_{out,d}$ of out-of-plane wall panel; few are listed in Section 2.2. Nevertheless, encompassing these factors, it is possible to relate $\Delta_{out,d}$ with the Δ_{in} imposed by the wall present in the orthogonal direction; details of a framework to relate these is present in Section 4.

Shown in Fig. 6(a) are mid-height moment-lateral displacement responses of the typical wall panel (described above) determined by (a) considering the demand imposed by Δ_{in} (say, $\Delta_{in}=\Delta_{out,d}$) and (b) not considering the demand imposed by Δ_{in} (*i.e.,* by assuming Δ_{in} =0). As expected, the out-of-plane capacity of the wall panel is 65mm (=*t*/2) when the demand imposed by Δ_{in} is not considered. In contrast, the out-of-plane capacity of the wall panel reduces to 52 mm when the demand induced by Δ_{in} is considered.

Similar to Fig. 6(a), shown in Fig. 6(b) are the moment-lateral displacement responses of the same wall panel considering material nonlinearity. Adopted to develop the response shown in Fig 6(b) are masonry compressive strength of (f_m) 4MPa, ε_u of 0.0057 and E of 700f_m. In general, considering material nonlinearity leads to (a) significant reduction (about 20%) in the out-of-plane load resisting capacity and (b) minor reduction (about 5%) in the out-of-plane displacement capacity of the wall panel.

In contrast, considering Δ_{in} significantly reduces the post-peak behaviour of moment-lateral displacement responses of the wall panel compared to the initial elastic portion. Furthermore, considering Δ_{in} results in reduction of the out-of-plane displacement capacity by about 30%; this is significant compared to the reduction of about 5% due to material nonlinearity. Lastly, Fig. 7 shows the out-of-plane response of the wall panel loaded with axial load of 7.8kN (i.e., N=7.8 kN). Lower is the reduction in the out-of-plane dispalcement capacity of wall panel with an increase in axial load.

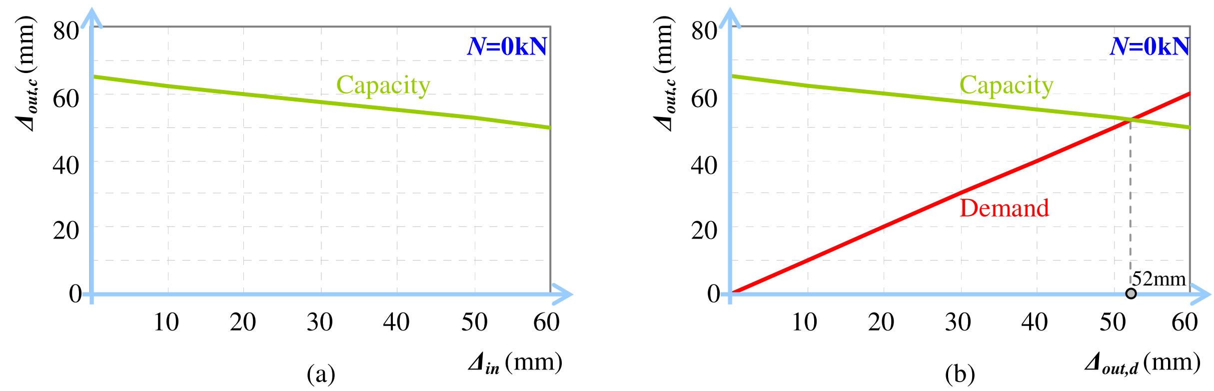


Fig. 5 – (a) Decrease in out-of-plane displacement capacity of a wall panel (*without pre-compression*) with increase in in-plane displacement and (b) Comparison between out-of-plane demand and capacity of the wall panel

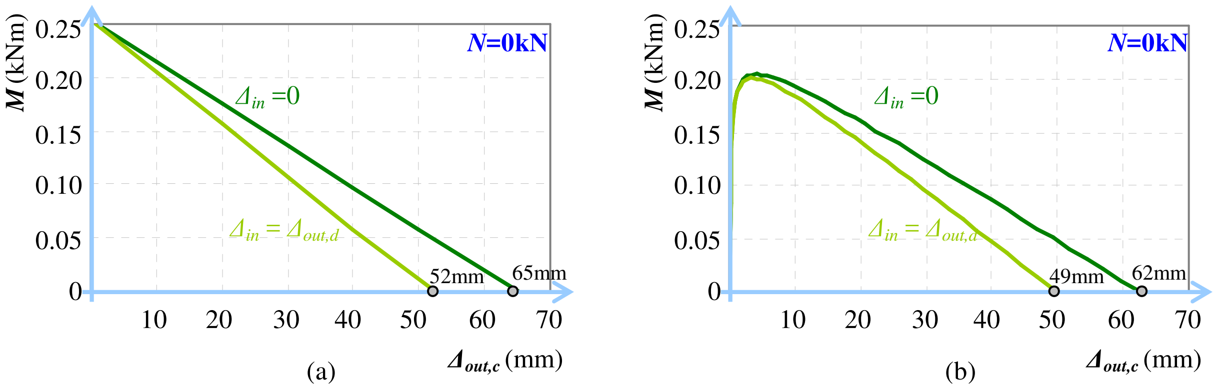


Fig. 6 – Mid-height moment-lateral displacement response of a wall panel (*without pre-compression*) developed considering (a) the wall panel as rigid blocks and (b) the material nonlinearity of masonry

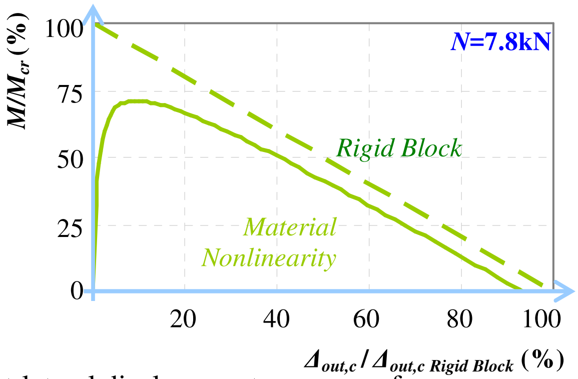


Fig. 7 –Mid-height moment-lateral displacement response of a *pre-compressed* wall panel developed considering the material nonlinearity of masonry normalized with cracking moment and out-of-plane displacement capacity determined by considering rigid blocks

4. Theoretical Framework for Seismic Safety Assessment of URM Buildings

Increase in intensity of earthquake shaking in a considered direction increases the, (a) in-plane displacement demand in wall panel and (b) out-of-plane displacement demand in wall panels. Further, depending on the displacement demand-to-capacity ratio, of each wall panel, the failure of the out-of-plane wall may precede the failure of in-plane wall or vice versa. Thus, the critical aspect towards seismic safety assessment is the estimation of displacement demand and capacity of wall panels. Based on the discussion present in Section 3.3, it is evident that the $\Delta_{out,c}$ of wall panel depends on multiple factors, including the Δ_{in} imposed by wall panels present in the orthogonal direction. Thus, required is the relation between Δ_{in} and $\Delta_{out,d}$ to estimate displacement demand-to-capacity ratio of out-of-plane wall panels. Present in this section is a *Displacement-Based Approach* (*DBA*) to assess the seismic safety of *URM* buildings. For brevity, the discussion is limited to simple single storey *URM* (Fig. 1); notwithstanding this, the stated method can be modified to suit multi-storey *URM* buildings. Following are assumptions considered in *DBA*:

(a) The lateral displacement demand of *stiff* and *flexible* wall panels is given by principles of *equal energy* and *equal displacement*, respectively;

(b) The boundary condition of all out-of-plane wall panels is such that one-way bending (as shown in Fig. 3(a)) is the critical mode of failure;

(c) The in-plane lateral force-displacement response of the wall panel is known (Fig. 8(a));

(d) The building is symmetric and does not have either strength or stiffness eccentricities; and

(e) The diaphragm slabs are sufficiently rigid and the building has good wall to diaphragm connections.

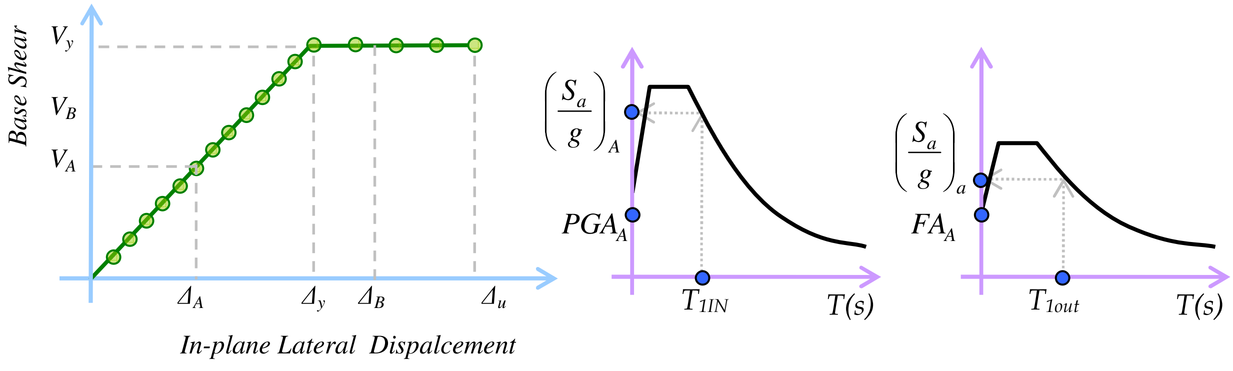
Following is the step-wise procedure of *CBDA*:

Step 1: Determine the in-plane force-displacement response of the *URM* building. Estimate the displacement corresponding to critical points (such as yield displacement (Δ_y) and ultimate displacement capacity (Δ_u)). After that, consider a displacement (say Δ_A) that is less than Δ_y (as shown in Fig. 8(a)). Next, using Eq. (29), estimate the spectral acceleration ($(S_a/g)_A$) resisted by the in-plane wall when the building sustains the considered displacement Δ_A,

$$\left(\frac{S_a}{g}\right)_A = \frac{V_A}{W_B}, \tag{29}$$

where V_A is the base shear resisted by the building while sustaining Δ_A and W_B the seismic weight of the building.

Step 2: Scale the 5% damped *Design Spectrum* such that the spectral acceleration corresponding to the lateral translational period of the building (T_{IIN}) in the direction of earthquake shaking equals the spectral acceleration $(S_a/g)_A$ (Fig. 8(b)). After that, estimate the peak ground acceleration (PGA_A). The estimated (PGA_A) induces the displacement Δ_A on the building along the direction of shaking.



(a) (b) (c)

Fig. 8 – (a) Base-shear *versus* in-plane lateral displacement response of the building, (b) Scaled Design Spectrum for which the spectral acceleration corresponding to T_{1IN} equals $(S_a/g)_A$ and (c) Scaled Design spectrum for which the spectral acceleration corresponding to zero period equals FA_A

Step 3: Estimate the expected *Floor Acceleration* (FA_A), when the buildings sustain PGA_A, using the seismic design code recommended provisions. Thereafter, scale the 5% damped *Design Spectrum* such that the spectral acceleration corresponding to zero period is equal to FA_A (Fig. 8(c)). Next, estimate the spectral acceleration ($(S_a/g)_a$) sustained by the out-of-plane wall panel using the natural period of the wall panel in the out-of-plane direction (T_{1out}). Finally, using $(S_a/g)_a$ and T_{1out}, estimate the out-of-plane displacement demand $(\Delta_{out,d})_A$ sustained by the wall panel when the in-plane wall sustains a displacement of Δ_A.

Step 4: Estimate the out-of-plane displacement capacity of the wall $(\Delta_{out,c})_A$ when the imposed Δ_{in} equals Δ_A. Compare $(\Delta_{out,d})_A$ with $(\Delta_{out,c})_A$ to assess the adequacy of out-of-plane wall to sustain the displacement demand. If out-of-plane walls have adequate displacement capacity then replace Δ_A with Δ_y in *Step 1* and re-estimate the adequacy of the out-of-plane walls. Again, if the out-of-plane wall has adequate displacement capacity to sustain the imposed demand proceed to Step 5.

Step 5: Consider a displacement (say Δ_B) that is more than Δ_y (as shown in Fig. 8(a)). Estimate V_B for *stiff* and *flexible* building using Eq. (30); V_B represents the expected elastic force sustained by building had it remain elastic while sustaining the displacement Δ_B. Thereafter, using Eq. (31) estimate the spectral acceleration ($(S_a/g)_B$) resisted by the in-plane wall when it sustains the considered displacement Δ_B.

$$V_B = \begin{cases} \left(\dfrac{V_y}{\Delta_y}\right)\left(\sqrt{2\Delta_y\Delta_B - \Delta_y^2}\right) & \textit{Stiff Building} \\ \left(\dfrac{V_y}{\Delta_y}\right)\Delta_B & \textit{Flexible Building} \end{cases} . \tag{30}$$

$$\left(\frac{S_a}{g}\right)_B = \frac{V_B}{W_B} . \tag{31}$$

Step 6: Following Steps 2 to 4, estimate (a) PGA_B that induces the displacement Δ_B on walls present along the in-plane direction, (b) FA_B when the building sustains PGA_B, (c) $(\Delta_{out,d})_B$ when the out-of-plane wall sustains FA_B, and (d) $(\Delta_{out,c})_B$ when the imposed Δ_{in} equals Δ_B. Compare $(\Delta_{out,d})_B$ with $(\Delta_{out,c})_B$ to assess the adequacy of out-of-plane wall to sustain the displacement demand. If out-of-plane walls have adequate displacement capacity then replace Δ_B with Δ_u in *Step 5* and re-estimate the adequacy of the out-of-plane walls. If the out-of-plane wall has adequate displacement capacity to sustain Δ_u then in-plane failure precedes out-of-plane failure of wall panel.

Thus, using Steps 1 to 6 (present in this section) it is possible to assess the sequence of damage to walls and the final mode of failure of the building.

5. Summary and Conclusion

Safety assessment involves estimation of displacement capacity and demand of *URM* wall panels in a building. The current seismic assessment of *URM* does not consider the relative displacement between the top and bottom part of the out-plane wall (induced due to displacement of the in-plane wall in the orthogonal direction). In light of this, derived are closed-form equations to include the above mentioned relative displacement while assessing the seismic safety of out-of-plane walls. The derived equations indicate that the imposed relative displacement significantly reduces the out-of-plane displacement capacity of the wall panel; this reduction can be as high as 30% for wall panels with no pre-compression. In contrast, the out-of-plane load resisting capacity is not influenced by the imposed relative displacement. Finally, this paper presents a *Displacement-Based Approach* to assess the seismic safety of simple *URM* buildings.

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