NEW METHOD FOR THE DESIGN OF LOW ASPECT RATIO WALLS AGAINST SEISMIC ACTIONS

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ABSTRACT :

In the present work, the measurements that resulted from the tests of eleven wall specimens with aspect ratio of 1.0 and 1.5 are used, in order to set up analytical models for the calculation of the displacements due to the deformation of each considered strength resisting mechanism. For this reason the flexural, web shear and sliding shear mechanisms are distinguished. The novel subjects of the present study are the calculation methodologies of the sliding shear strength and of the top displacement due to the deformation of the sliding shear mechanism. The quantity and arrangement of the specimen reinforcement were chosen so as to ensure a flexural type of failure. It was found that web shear deformation increased, until maximum strength was achieved. After the point of maximum strength, web shear deformations decreased, while sliding shear deformations along the base main flexural crack increased. Relationships proposed to describe these phenomena are derived from appropriately modified existing models along with new, semi-empirical, ones. The analytical calculated quantities are compared with the experimental measurements and a good match is noted. It is concluded that in shear walls with low aspect ratio, sliding shear deformations appeared at the base plastic hinge, even in the case that flexural response initially dominates. Neglecting such shear deformations results in underestimating shear forces at the base of other vertical structural elements. According to this methodology, strength and deformation quantities are calculated permitting thus the use of the proposed methodology in both cases of force and displacement based design methods.

KEYWORDS: Shear walls, Experimentation, Nonlinear response, Plastic hinges, Ductility, Lateral displacement, Shear deformation, Flexural strength, Shear strength.

1.FROM THE SPECIMEN TO PROTOTYPE

The construction scale of the tested specimens was 1:2.5 and the height/length ratio was 1.0 & 1.5. Since tested walls were constructed under scale, the theory of models should be applied for the calculation of the exact strengths and deformations. The construction materials that were used for the specimens were not under scale (was not used micro concrete). In this case the models theory is applied on the dimensions of the specimens. By considering that the developed stresses should be the same in the specimen and the prototype results the following relation:

$$\sigma_{spec} = \sigma_{prot} \Rightarrow \frac{P_{spec}}{\alpha \times \beta} = \frac{P_{prot}}{A \times B} \Rightarrow \frac{P_{spec}}{\alpha \times \beta} = \frac{P_{prot}}{s.\alpha \times s\beta} \Rightarrow s^2 \times P_{spec} = P_{prot} \qquad 1.1$$

This relation is applied for axial and shear forces. For the case of bending moments, the relation between specimen and prototype is:

$$s^3 \times M_{spec} = M_{prot} \qquad 1.2$$

In the aforementioned relations was considered a construction scale "1:s", specimens dimensions a, b and prototype dimensions A and B.

The relation between specimens and prototypes deformation results when it is considered that the normalized deformations in both cases are equal. Then, the following expression gives:

$$\varepsilon_{spec} = \varepsilon_{prot} \Rightarrow \frac{\Delta L_{spec}}{L_{spec}} = \frac{\Delta L_{prot}}{L_{prot}} \Rightarrow \frac{L_{prot}}{L_{spec}}.\Delta L_{spec} = \Delta L_{prot} \Rightarrow s \times \delta_{spec} = \delta_{prot} \tag{1.3}$$

In the aforementioned relation have been considered a construction scale “1:s”.

2. STRENGTH CALCULATION

When the aspect ratio of the walls is less than 1.5, the following calculations are recommended:

- Calculation of the shear strengths of the walls that corresponds to the flexural strengths. Flexural yield “V_{yfl}”, maximum flexural strength “V_{fl}” and final flexural failure “V_{ufl}”.
- Calculation of the shear strengths of the walls that corresponds to diagonal compression strength “V_{Rd2}” and to diagonal tension strength “V_{Rd3}”.
- Calculation of the shear strength that corresponds to the sliding shear failure “V_{usl}” after the flexural yield.

For the aforementioned calculations there are available many equations, except for the case of sliding shear failure after the flexural yield. For this case, the following equations are given:

I) Existence of horizontal and vertical web reinforcement together with diagonal reinforcement in the critical region of the wall:

$$V_{usl} = T_{cfr} + \frac{1 + \frac{0.1.l_i}{0.8.l_w}}{a_s}.(0.27T_d + 2T_{dg}\cos\varphi) \tag{2.1}$$

II) Existence only of horizontal and vertical web reinforcement in the critical region of the wall:

$$V_{usl}=T_{cfr}+T_d \tag{2.2}$$

Where:

$$T_d = 0.385\frac{f_u A_{sfl}}{a_s}, \quad T_{dg}=f_y.A_{sd}, \quad T_{cfr} = \frac{2.15v}{a_s}(0.75\frac{M_{max}}{d_v} + \frac{N}{2}), \quad \nu = \frac{N}{f_c A_c} \tag{2.3}$$

“T_d” is the term of contribution of dowel action, “T_{dg}” is the term of contribution of diagonal reinforcement and “T_{cfr}” is the term of contribution of the concrete friction in the sliding shear strength “V_{usl}”. The aforementioned equations were documented in reference Salonikios (2002). In the proposed methodology have not been used any safety factors for the materials and for the actions. In the case of check and/or design of a wall, these safety factors should be used as recommended by the codes. The most possible mode of failure is given by the comparison of the calculated shear strengths. This way the shear-flexure interaction is taken into account by the use of direct comparable shear forces.

3. CALCULATION OF TOTAL DISPLACEMENT COMPONENTS

In the case that the failure mode of the wall is the sliding shear failure after the flexural yielding the displacement quantities are given by the equations that follow.

3.1. Plastic Hinge Length

In order to calculate the displacement components, a plastic hinge length is needed. It is a very important quantity, because the correct calculation of the plastic hinge length affects the estimated displacements. After a parametric study in Salonikios (2007), it was found that for walls with aspect ratio lower or equal with 1.5 the plastic hinge length is:

$$L_p=0.044h_w+0.014d_bf_y \tag{3.1}$$

3.2. Top Displacement Available Ductility

By the use of plastic hinge length, the top displacement available ductility results from the following equation:

$$\mu_\delta = 1+\frac{3}{C}(\mu_\varphi - 1)\frac{L_p}{h_w}(1-0.5\frac{L_p}{h_w}) \tag{3.2}$$

In this equation, term C is given by the following equation:

$$C = \frac{\delta_{cr,sh} + \delta_{y,fl}}{\delta_{y,fl}} \tag{3.3}$$

where: $\delta_{y,fl} = \frac{\varphi_y h_w{}^2}{3}$, $\delta_{cr,sh} = \frac{d}{2E_s}(\frac{V_{sh}}{A_h} + \frac{\sqrt{2}V_d}{A_d})\frac{a_s{}^2}{2.25}$ 3.4

Equation for the term $\delta_{cr,sh}$ was documented in reference Salonikios (2004). In the case that sliding shear displacements are developed, after the inelastic flexural deformation Eqn.3.2 should be used in the following form:

$$\mu_\delta = 1+\frac{3}{C}(\mu_\varphi - 1)\frac{L_p}{h_w}(1-0.5\frac{L_p}{h_w})+\frac{3}{C}\frac{\delta_{sl}}{\varphi_y h_w{}^2} \tag{3.5}$$

This equation was documented in reference, Salonikios (2007). For the complete definition of the problem the displacement due to sliding shear deformation "δ_{sl}" should be calculated. The method for the calculation of this quantity is differed in relation with the main parameters that are taken into account. In the case of axial force with value greater than the 10% of the compressive strength, of the wall, the friction term is most important in resisting sliding shear force. When diagonal reinforcement exists in the critical region of the wall, then this reinforcement directly resists on the applied sliding shear force. The following three cases are distinguished for the calculation of top displacement due to sliding shear deformation in the flexural plastic hinge of the wall.

3.2.1 Sliding shear displacement in walls with classical web reinforcement without axial force

The displacement at the top of the specimens due to the deformation of sliding shear mechanism along base main flexural crack is given by Eqn. 3.6. As resulted from the experimental records, sliding shear displacements were developed, when permanent elongation was observed at the compressed part of the cross section of the walls. The compression forces that resulted from bending moments, were resisted by the reinforcement that was elongated at the previous half cycle of loading. In that case an open flexural crack was formed at the base of the specimens. Thus an equivalent reduced modulus of elasticity is considered ($Y.E_c$). Term "Y" was calibrated in relation to the experimental measurements. In Eqn. 3.6 the modulus of elasticity is used, instead of shear modulus, in order to emphasize the fact that these displacements resulted after inelastic flexural deformations. Term Y is given as a third order polynomial in relation to the imposed drift ratio in figure 1.

$$\delta_{sl}\,(m) = \frac{V h_w}{Y E_c l_w b} \tag{3.6}$$

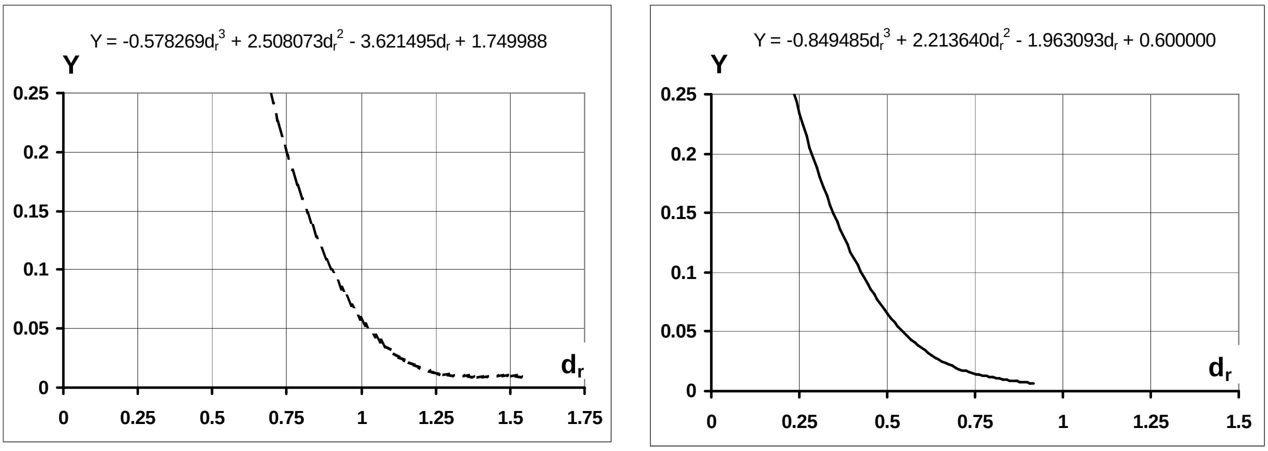


Figure 1 Factor "Y" in relation with the drift ratio "$d_r=\delta_{top}/h_w$" for walls with classical web reinforcement, without axial force and aspect ratio 1.5 (left) and 1.0 (right)

The proposed polynomials give reliable results within the range of 0-1.50% for walls with aspect ratio 1.5 (figure 1 left), while for walls with aspect ratio 1.0 the corresponding range is 0-0.92% (figure 1 right).

3.2.2 Sliding shear displacement in walls with classical web reinforcement and with axial force

For the walls with axial force equal with the 10% of the compressive strength, sliding shear displacement is given by the following equation:

$$\delta_{sl}(m) = \frac{Vh_w}{YE_cA_{comp}} \qquad 3.7$$

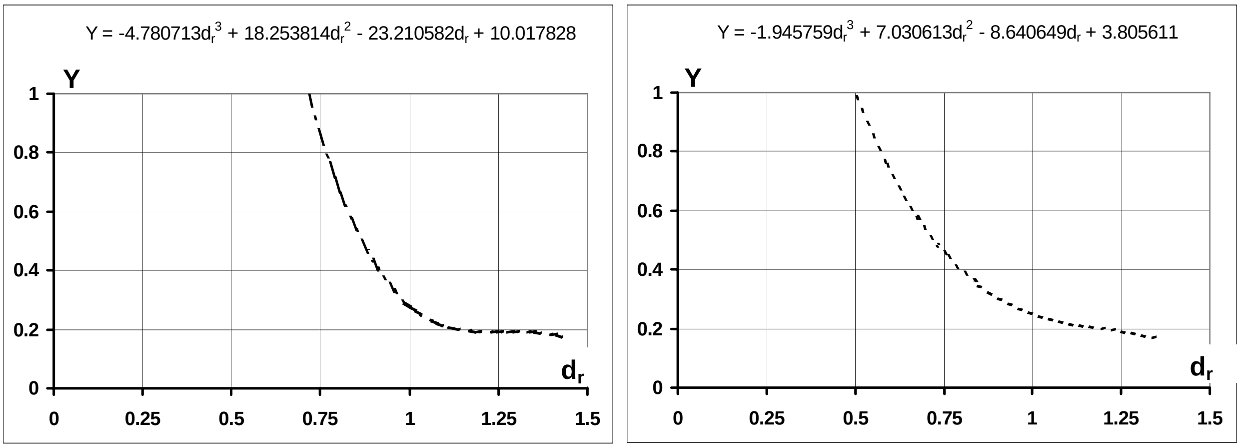


Figure 2 Factor "Y" in relation with the drift ratio "$d_r=\delta_{top}/h_w$" for walls with classical web reinforcement, with axial force and aspect ratio 1.5 (left) and 1.0(right)

The proposed polynomials give reliable results within the range of 0-1.45% for walls with aspect ratio 1.5 (figure 2 left), while for walls with aspect ratio 1.0 the corresponding range is 0-1.35% (figure 2 right).

3.2.3 Sliding shear displacement in walls with diagonal reinforcement without axial force

In the case that diagonal reinforcement is used in the web at the critical region of the wall, the load resisting mechanism has been significantly altered. In that case the diagonal reinforcement is directly stressed in tension from the sliding shear force. Two cases are distinguished. The case where the diagonal reinforcement does not yield:

$$V_{sd} < T_{ydiag} \qquad \delta_{sl} = \frac{V_{sd}.Y.h_w}{2E_s A_{sd}} \tag{3.8}$$

The case where diagonal reinforcement yields:

$$V_{sd} \geq T_{ydiag} \qquad \delta_{sl} = (\frac{T_{ydiag}}{2E_s A_{sd}} + \frac{V_{sd} - T_{ydiag}}{0.1E_s 2A_{sd}})Y.h_w \tag{3.9}$$

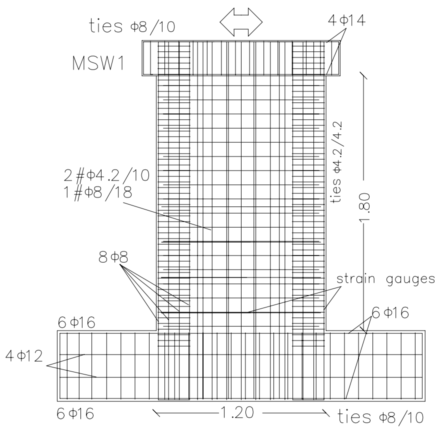
For the walls with aspect ratio 1.5, term "Y" resulted 0.78, while for the walls with aspect ratio 1.0 term "Y" resulted 0.64. These values resulted from the postprocessing of the experimental measurements.
For the cases of walls with axial force, classical web reinforcement and additional diagonal web reinforcement the total resisted shear force is distributed to each mechanism (friction term, dowel term and term for diagonal reinforcement) by the use of Eqns. 2.1 to 2.3. The sliding shear displacements are calculated by the use of Eqns. 3.6 to 3.9. For intermediate values of normalised axial force (between 0 and 0.1) an interpolation method should be applied.
In all specimens, the strength that corresponds to the flexural strength has been achieved. This strength should be considered for total displacement ductility equal to 2.0. The reduced strength at the end of the experiments (where sliding shear deformations dominate) is given from Eqns. 2.1 to 2.3. For displacement ductilities more than 2.0 until the failure displacement, linear interpolation should be applied for the calculation of the exact strength. Term A_{comp} in Eqn. 3.7 represents the area of the compressed part of the cross section. This term can be easily calculated, by solving the problem of a section that is subjected to bending moment with axial compression. In Eqns. 3.6, 3.7 term Y is calculated by the use of total top displacement that is not fully defined. In that case an iterative procedure should be applied for the consideration of top displacement δ_{top}, for the values of δ_{sl} that result in every step, until satisfactory convergence is achieved.

$$\delta = \delta_{y,fl} + \delta_{cr,sh} + \delta_{p,fl} + \delta_{sl} \tag{3.10}$$

Term $\delta_{y,fl}$ and term $\delta_{cr,sh}$ are calculated by Eqns. 3.4 and term $\delta_{p,fl}$ is initially calculated by the use of Eqn. 3.2 and is finally defined by Eqn. 3.5.

4. COMPARISON OF EXPERIMENTAL MEASUREMENTS WITH ANALYTICAL CALCULATIONS

In Figures 3 to 5 representative diagrams of the top displacement – shear force hysteresis loops that were recorded during the experiment are shown. In these diagrams the corresponding envelope curves that were calculated according to the aforementioned methodology are also comparatively drawn.



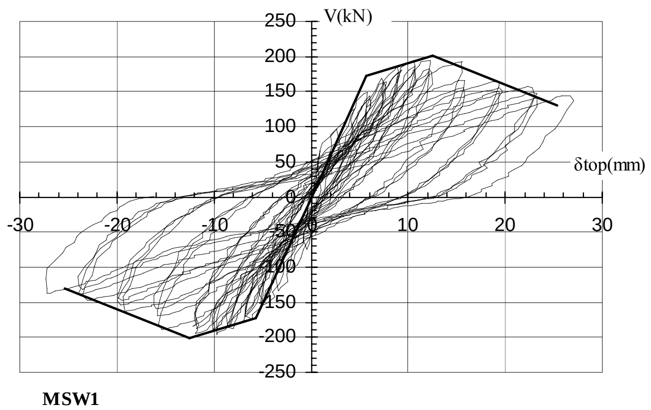


Figure 3 Reinforcement details and comparative diagrams of the recorded hysteresis loops and for the analytically calculated envelope curve, for specimen MSW1

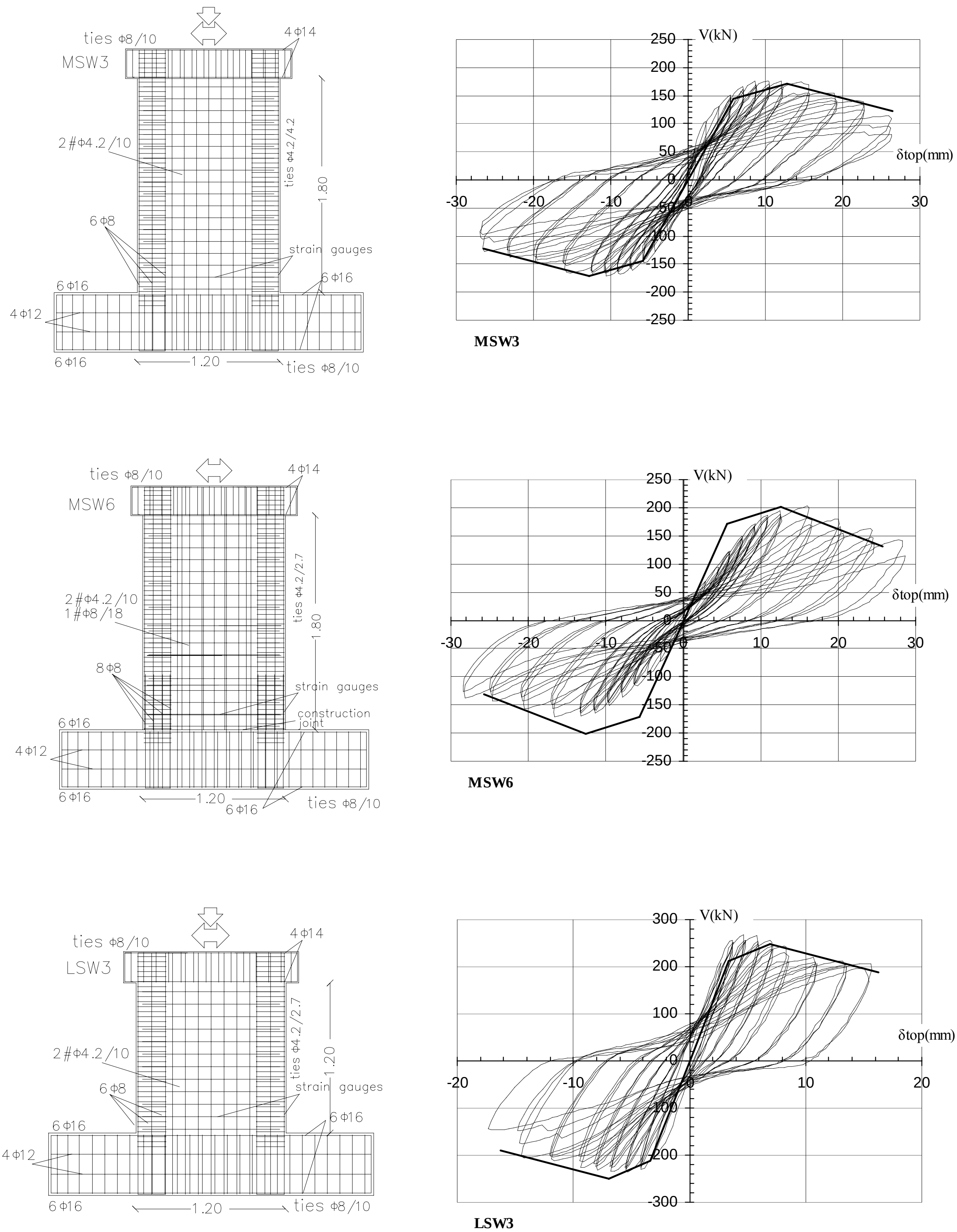


Figure 4 Reinforcement details and comparative diagrams of the recorded hysteresis loops and for the analytically calculated envelope curve, for specimens MSW3 (axial force 165kN), MSW6 and LSW3 (axial force 165kN)

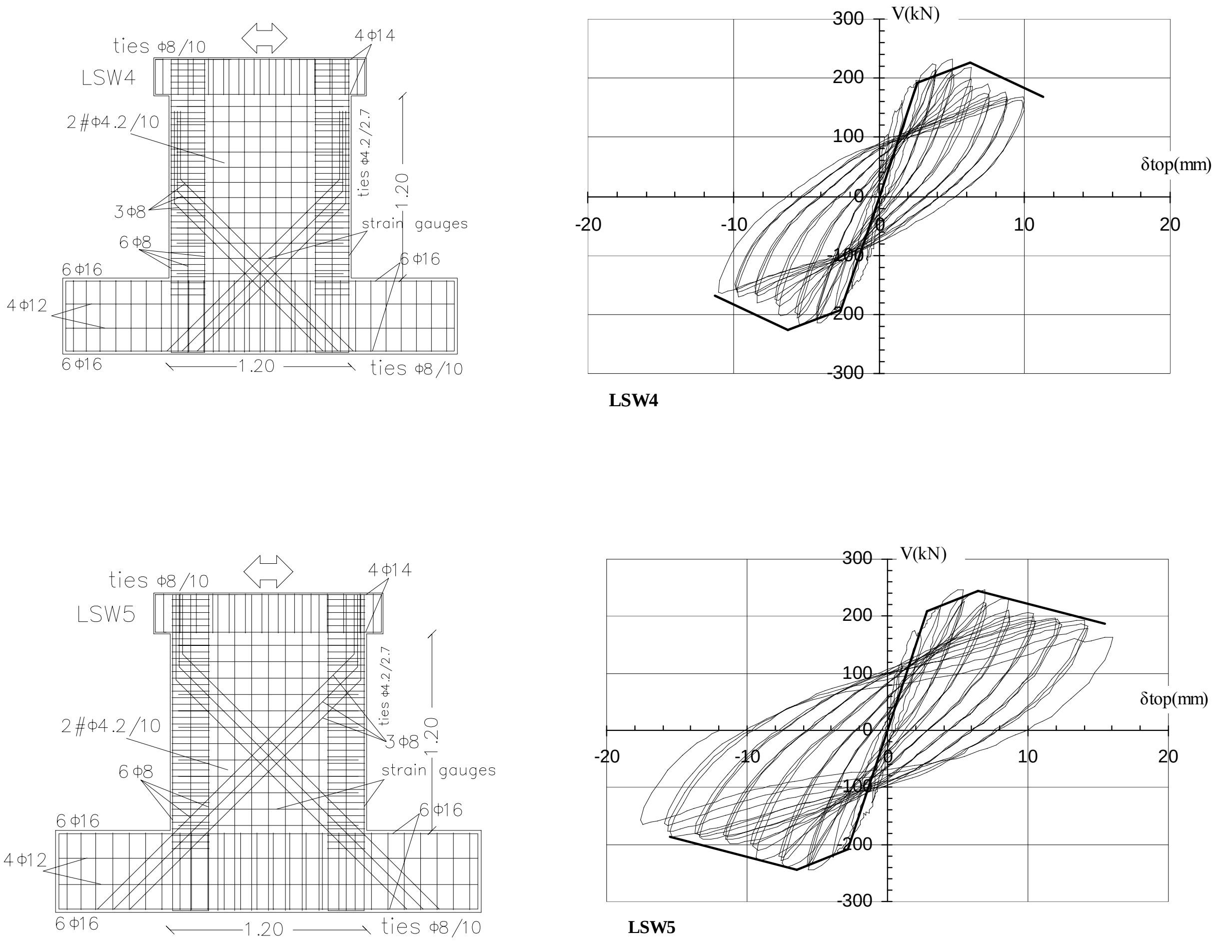


Figure 5 Reinforcement details and comparative diagrams of the recorded hysteresis loops and for the analytically calculated envelope curve, for specimens LSW4 and LSW5

5. CONCLUSIONS

In order to design new structures or for the seismic evaluation of existing ones, force or displacement based design methods can be applied. In this work, equations for the design of R/C walls with both methods, are provided. The novel element in the proposed methodology is the definition of sliding shear failure after inelastic flexural deformation. In the displacement based design, inelastic deformations are considered and thus such sliding shear failure should be taken into account. By ignoring this type of deformation, the shear forces and deformations of the columns at the critical base floor are underestimated. These sliding shear deformations were found to be 25% of the total top displacement. This sliding displacement component is all developed into the plastic hinge at the base of the wall and thus at the columns of the base floor of the building. The proposed methodology has been re-tested on wall specimens and the resulted envelope curves satisfactorily approach the recorded hysteresis loops.

NOTATION

A_c = cross section area of the specimens;
A_{comp}= area of compressed part of the cross section;
A_d = area of diagonal reinforcement in two directions;
A_h = area of horizontal web reinforcement;

A_{sd} = area of diagonal reinforcement in one direction;
A_{sfl} = area of tensioned flexural reinforcement;
a_s = aspect ratio of the specimens;
b = thikness of specimens' cross section;
d = effective depth of the cross section;
d_b = bar diameter of flexural reinforcement;
d_v = internal lever arm between tensiled reinforcement and the center of compressed zone;
E_c = modulus of elasticity for concrete;
E_s = modulus of elasticity for steel reinforcement;
f_c = stress of concrete;
f_y = yield stress of steel reinforcement;
f_u = ultimate tensile stress of flexural reinforcement;
h_w = height of the specimens;
L = length;
L_p = plastic hinge length;
l_i = distance between the centers of the axes of diagonal reinforcement at the base of the specimens;
l_w = cross section length;
M = bending moment;
N= applied axial force;
T_{cfr} = concrete friction strength inside the flexural crack;
T_d = dowel action strength inside the flexural crack;
T_{dg} = tension strength of diagonal reinforcement;
T_{ydiag} = yield force of diagonal reinforcement;
V_{sd} = shear force that is resisted by diagonal reinforcement;
V_{sh} = shear force resisted by web reinforcement;
V_{usl} = sliding shear strength along the base flexural crack;
$\delta_{cr,sh}$ = displacement at the top of the specimens due to diagonal shear cracking;
$\delta_{p,fl}$ = displacement at the top of the specimens due to plastic deformation of flexural reinforcement;
δ_{sl} = displacement at the top of the specimens due to sliding shear deformation along the base flexural crack;
δ_{top} = displacement at the top of the specimens due to the deformation of all mechanisms;
$\delta_{y,fl}$ = displacement at the top of the specimens due to the deformation of flexural reinforcement at yield;
μ_δ = displacement ductility;
μ_φ = curvature ductility;
φ_y = yield curvature;

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