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Web Shear Deformations of R/C Walls with Flexural Failure Subjected to Cyclic Loading

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Summary

Presented in the present work are results from the post processing of measurements that were recorded during laboratory tests of R/C wall specimens. In these specimens yielding of flexural mechanism was observed initially, while the maximum strength that was achieved was the shear force corresponding to flexural strength. Finally, for high inelastic level of deformation the sliding shear displacements at the specimens' base were significantly increased. Presented herein are the envelope curves of the component of the horizontal displacement at the top of the specimens that resulted from the deformation of the shear mechanism in the web of the specimens. Also presented is a simplified methodology for the analytical estimation of top displacement due to web shear deformation of walls that failed in a flexural mode. Both experimental measurements and simplified analytical results are presented in comparative diagrams of the shear component of top displacement versus measured shear force. Useful conclusions result for the response of web shear mechanism in walls where the flexural mechanism develops and failure occurs due to the inelastic deformation of flexural and sliding shear mechanisms.

Introduction

In R/C elements of structures subjected to seismic excitation of their base all strength-resisting mechanisms are developed. These mechanisms are the flexural, shear, and sliding shear mechanisms [1], [2]. From the concurrent deformation in these three mechanisms result the end displacements at the structural elements of structures subjected to seismic loading. As shown in experiments on walls with aspect ratio 1.0 and 1.5, designed according to Eurocode 8, the flexural and web shear mechanisms lead to cracking almost for the same shear force. By increasing the imposed displacement (for the experiments carried out within the present work) yielding in the flexural mechanism is initially observed. Afterwards, an increase is observed of the top displacements resulting due to the deformation in the flexural and sliding shear mechanisms. Although during those experiments, for the achievement of the specimens top displacement, flexural and

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sliding shear mechanisms contributed with their inelastic deformations, web shear mechanism contributed with the displacements that corresponded to the deformation after cracking and before yielding. In order to estimate the contribution of web shear mechanism to total deformation of walls the shear forces that were recorded during the experiments as the resistance of the specimens should be used. These forces were analytically estimated in a recently published work [3]. These forces represent the shear force corresponding to the flexural yielding and the highest flexural strength. For a displacement ductility ratio over 3, these forces are reduced and represent the strength when the sliding shear mechanism prevails. That mechanism's strength (sliding shear mechanism along flexural cracks) is reduced after high inelastic deformation of the flexural mechanism, contributing thus to total displacement with high inelastic deformation [2].

The top displacement's component due to web shear deformation, used in this work, was estimated based on the post processing of measured (during the experiments reported in [2]) deformations by purposely located diagonal displacement transducers (LVDT's). For the analytical estimation of those displacements a simplified methodology is applied that takes into account the parameters varied among specimens. For the development of this analytical model are taken into account the basic principles of truss mechanism. This mechanism is composed by concrete diagonal struts and web reinforcement in tension, which are taken into account for the formation and the calibration of the proposed analytical model. The theoretical background on which the analytical model is based is presented in the following.

Theoretical Background and Analytical Model

The analogy between the shear resistance of a parallel chord truss and a web-reinforced concrete element is an old concept in concrete structures. The analogy, postulated by Moersch at the beginning of the 20^{th} century, implies that the web of the equivalent truss consists of stirrups acting as tension members and concrete struts running parallel to diagonal cracks generally at 45^o to the element's axis. The concrete compression zone and the flexural reinforcement form the top and bottom chords of this analogous pin-jointed truss are considered. Shear forces that are resisted by that truss, result from the consideration of equilibrium between imposed and resisting forces. Indeed according to figure 1 the following relations result:

$$V_s=C_d\sin\alpha=T_s\sin\beta \quad (1)$$

$$s=jd(\cot\alpha+\cot\beta) \quad (2)$$

From equations (1) and (2), the stirrup force per unit length is:

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$$\frac{T_s}{s} = \frac{V_s}{jd \sin\beta(\cot\alpha + \cot\beta)} = \frac{A_\upsilon f_s}{s} \tag{3}$$

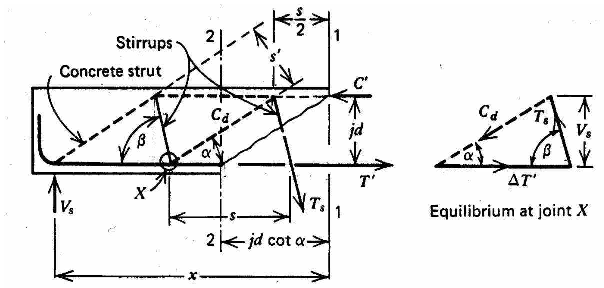

Fig. 1. Internal forces in an analogous truss

where A_υ is the area of the web reinforcement spaced at a distance s and f_s is the stirrup stress. The applied shear force is resisted partially by the concrete and partially by the reinforcement. In terms of stresses, this is expressed as [4]:

$$\upsilon_u = \upsilon_c + \upsilon_s \tag{4}$$

where: $$\upsilon_s = \frac{V_s}{b_w jd} \approx \frac{V_s}{b_w d} \tag{5}$$

In the proposed model the contribution of concrete in resisting shear force is considered only in the case where axial force is applied and is calculated from equation [5]:

$$V_{Rd1}=[\tau_{Rd}k(1.20+40\rho_l)+0.15\sigma_{cp}]b_w d \tag{6}$$

From equations (3) and (5) the required web reinforcement results (assuming $f_s=f_y$) [4]:

$$A_\upsilon = \frac{\upsilon_s}{\sin\beta(\cot\alpha + \cot\beta)} \frac{sb_w}{f_y} \tag{7}$$

For the web horizontal reinforcement ($\beta=90^o$) assuming an inclination of concrete struts $\alpha=45^o$ results:

$$f_y = \frac{\upsilon_s sb_w}{A_\upsilon} \tag{8}$$

while for inclined reinforcement ($\beta=45^o$) assuming again an inclination of concrete struts $\alpha=45^o$ results:

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$$f_y = 0.707 \frac{\upsilon_s s b_w}{A_\upsilon} \tag{9}$$

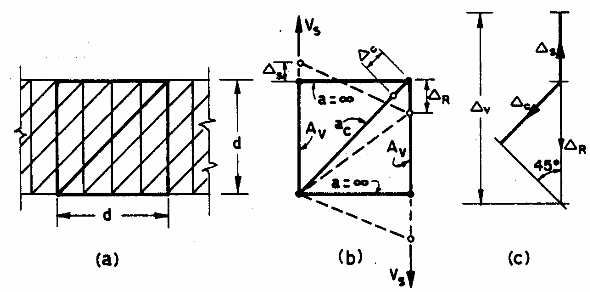

Fig. 2. Shear deformations in the web of a R/C element modelled on the web members of an analogous truss

The elongation of the horizontal web reinforcement due to shear force according to figure 2 is given by [4]:

$$\frac{\Delta_s}{d} = \frac{f_s}{E_s} \Rightarrow \Delta_s = \frac{f_s}{E_s} d \tag{10}$$

Ignoring the contribution of displacement due to the deformation of the compressed strut, from equations (5), (7), (8), (9) and (10) results:

$$\Delta_s = \frac{V_s d}{E_s} \left(\frac{1}{A_{sh}} + \frac{\sqrt{2}}{A_{sd}} \right) \tag{11}$$

Application of Model to Wall Specimens

Equation (11) is applied to the specimens that were tested in experiments at the Laboratory of Concrete Structures of the Aristotle University of Thessaloniki [2]. Specimens and experimental results were presented in detail in references [3],[6],[7]. For the calculations presented herein the web horizontal reinforcement that passes through an inclined (at 45^o) section of the web (A_{sh}) was considered, as well as the total area of bidiagonal reinforcement in cases that such reinforcement was used (A_{sd}). The shear force used was measured during the experiments. This force was analytically estimated in reference [3]. In the diagrams that follow continuous lines represent the envelope curve of top displacement hysteresis loops due to web shear deformation of the specimens. These values resulted from the post processing of experimental measurements. Dashed lines represent the previously mentioned displacement as calculated from

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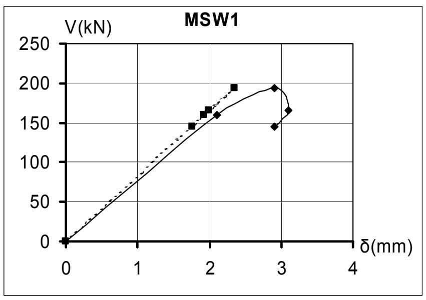
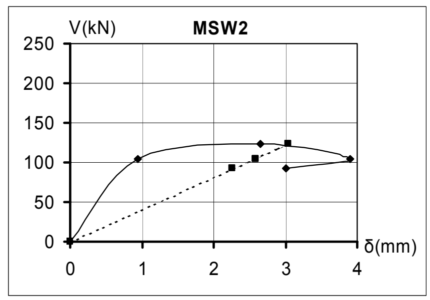
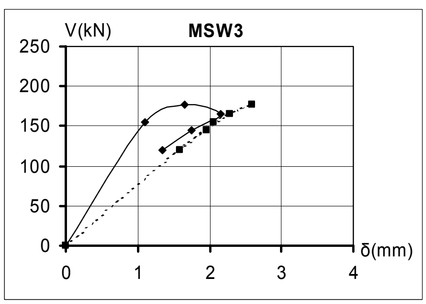
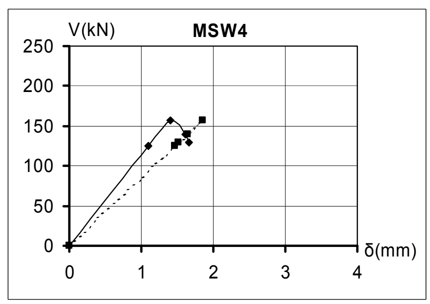
relation (12). Equation (12) resulted from equation (11) and was calibrated against experimental results. For that reason equation (12) is considered to be a semi empirical relation (where α_s is the shear ratio of the walls) :

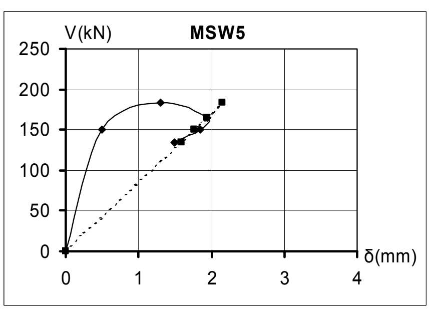
$$\Delta_s = \frac{V_s d}{E_s}\left(\frac{1}{A_{sh}} + \frac{\sqrt{2}}{A_{sd}}\right)\frac{\alpha_s^2}{2.25} \qquad (12)$$

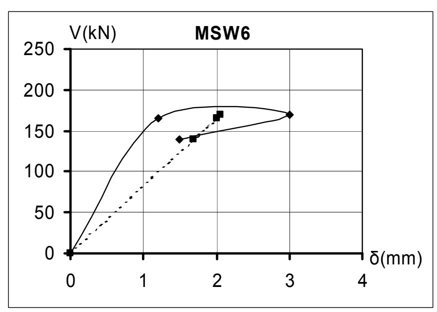












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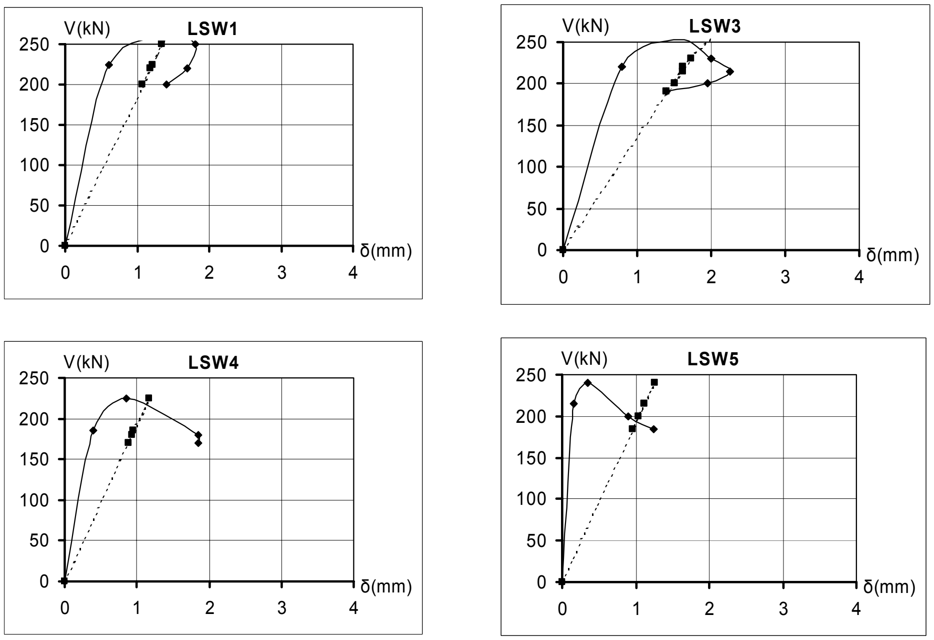

Fig.3. Envelope curves of measured shear force versus top displacement due to web shear deformations (_____ experimental values, --------- analytical values).

Discussion and Conclusions

From the consideration of the diagrams useful conclusions result for the contribution of the deformation due to web shear mechanism to the total displacement at top, in specimens were failure occurred due to other mechanisms (flexural and sliding shear mechanisms). The reduction of shear force observed in the diagrams results due to the degradation of the sliding shear mechanism at the specimen's base along flexural cracks. The fact that along the descending branch at most diagrams in figure 3 reduction of the attained displacement (inversion of inclination) is observed, indicates that at the truss mechanism that formed at the web yielding of reinforcement did not occur. This phenomenon is detected in specimens MSW1-MSW6 and in specimens LSW1 and LSW3. The slope of that branch is smaller than the slope of the ascending branch, thus indicating a reduced stiffness. This phenomenon occurs due to the diagonal cracking of the web. It must be kept in mind that the diagrams in figure 3 show the envelope curves of the corresponding hysteresis loops. By the dashed lines are drawn the envelope curves as estimated from equation (12). It must be noted that after attaining the maximum value, the dashed line descends due to the reduction of shear force. For better matching the experimental curves, as indicated from the

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diagrams of figure 3, consideration of higher initial stiffness is needed, as well as calibration of equation (12) in order to obtain an inelastic branch characterised by higher strength. For all these reasons, the magnitude of shear displacement is so small, that a more accurate approach does not seem to be warranted. In the suggested relation (12), matching of the experimental results is succeeded by using the equivalent reduced stiffness. Envelope curves of the response of web shear resisting mechanism are drawn for the case that yielding and failure is observed in flexural and sliding shear mechanisms. In these cases, after reaching maximum strength, the contribution of web shear mechanism to total displacements is reduced. Also, some preliminary conclusions can be drawn regarding the contribution to total displacements resulting from the deformation due to flexural and sliding shear mechanisms. In the specimens of this work increase of the imposed displacement was accompanied by significant increase in the deformation due to the sliding shear mechanism. The contribution of flexural mechanism to the total displacement at the top (in the case of high inelastic deformations of the walls) was significantly lower than the corresponding contribution of sliding shear mechanisms, and in some cases was reduced (like web shear mechanism in this work). This phenomenon was observed clearly for total displacement ductility level above three. Such conclusions, together with some other novel results will be presented in future publications.

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