Shear Deformations of Slender Reinforced Concrete Walls under Seismic Loading. Paper by Katrin Beyer, Alessandro Dazio, and M. J. Nigel Priestley

Discussion by Shiming Chen and Kang Ge

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The discussers appreciate the authors' comprehensive work to analyze and evaluate the shear deformations in rectangular and nonrectangular reinforced concrete (RC) walls derived from the available quasi-static cyclic tests. The significance of the development of shear deformation in the plastic hinge zones is analyzed and assessed. A simplified estimation of the expected shear deformations in walls controlled by flexure was proposed, which could be a supplement to deformation computation using normal inelastic beam elements. Some findings are interesting to the discussers and worthy of further discussion.

SHEAR MECHANISMS

Whereas flexural members are subjected to inelastic reversing, cyclic rotations' shear deformation may be expected to develop in the plastic hinge zone, which leads to a large part of the stiffness degradation.[34,35] For calculation of the top displacement that corresponds to flexural yielding, the deformation in the web-shear mechanism should also be considered, together with the deformation in the flexural mechanism.

In RC shear walls subjected to seismic loads, the flexural mechanism—both web shear and sliding shear—would be activated. These two shear deformations have high values, even in the case where the structural elements are designed to exhibit flexural behavior. It was found that in shear walls with a low aspect ratio, sliding shear deformations appear at the base plastic hinge, even in the case where the flexural behavior initially predominates the response. The displacement at the top of the walls due to the deformation of the sliding shear mechanism at the base of these walls was found to be significantly increased after the displacement ductility reached 2.5.[36] Hence, for the calculation of the top displacement ductility, the deformation of all load-resisting mechanisms, such as the flexural and shear mechanisms of the two, should be taken into account.

Sliding shear displacements were not considered for the typical wall designs in the paper. It is not clear if the typical design was adopted for all walls studied or just for the U-shaped walls. The aspect ratio of the shear walls varies from 2.0 to 4.0 and no special joint detailing is illustrated. Can the authors demonstrate what detailing or criterion was used for these typical walls, where the sliding shear deformation can be neglected?

For the calculation of the displacement ductility, the contribution of the shear mechanisms to the top displacement should be added to the inelastic deformations after yield. Does the ductility demand adopted in the analysis include the contribution of the shear deformation?

AXIAL STRAINS' DISTRIBUTION OVER CROSS SECTION

Figure 4 shows the distribution of shear and axial strains for U-shaped Wall TUA at a certain ductility level when the lateral loads are exerted parallel to the web (Position A). It appears that although the shear force is kept the same, the shear deformation is not evenly distributed. It varies along the wall height, and the magnitude of the shear deformation depends not only on the shear force but also on the inelastic flexural deformations.

The discussers wonder how the axial strains were captured in the tests. Were they captured by strain gauges or by the Demec measurements at the side surface of the wall? The axial strains illustrated by the gray shaded areas do not distribute uniformly across the cross sections of the U-shaped wall along the wall height, even at a place far beyond the plastic hinge region, as it appears. Because the axial load was kept the same during the tests, the developed axial strains should contribute by the lateral force. It is not clearly explained and understood that the west flange has a very small axial strain (tensile strain?), whereas the east flange develops a larger axial strain (compressive strain?). At the lower section near the plastic region, however, both the west and east flanges were subjected to the (compressive) axial strain but with different magnitudes.

The cross sections of the U-shaped wall do not remain plane at the deflection ductility of 3.0 or even less. The axial strain distributions likely suggest that the U-shaped wall distorts warping. It is also not clear whether the lateral force parallel to the web acted through the shear center of the U-shaped section. Otherwise, the shear deformation contributed from the twisting force would be included.

Can the authors clarify whether similar distortions and strains occurred in the other rectangular section RC walls?

SHEAR-TO-FLEXURAL DISPLACEMENT RATIOS

It has been verified that the response of low-aspect-ratio walls differs significantly from the response of RC walls with aspect ratios over 2.0.[36] The shear force that corresponds to diagonal cracking in a low-aspect-ratio wall has a lower value than the shear force that corresponds to flexural cracking, whereas slender RC walls—for example, with aspect ratios greater than 2.0 or 3.0—behave in a ductile flexural mode other than shear failure when loaded beyond the elastic limit.

Figure 6 shows the variation of Δ_s/Δ_f ratios with top drift for cantilever RC walls tested under cyclic loading. It appears that the walls with shear-controlled behavior (PCA Phases I and II) developed a drift ratio of 3%, whereas the capacity-designed RC walls[11] developed less drift. Axial load should contribute to improve the ductile performance of shear walls. The shear deformation and associated stiffness degradation develop progressively as inelastic cyclic rotations are applied to a hinge zone. Because a drift ratio of 3% is a very large value of interstory deformation, it will typically accompany a severe drop in the load resistance of the structure. Which shear-to-flexural displacement ratios are expected at a typical, accepted drift ratio—say, 1% or even less?

The shear-to-flexural displacement ratios vary considerably between the walls. As the ratio of shear-to-flexural displacement remains approximately constant over the entire ductility range in the RC walls governed by flexure and with

a stable shear-transfer mechanism, a simple model for estimating the Δ_s/Δ_f ratios was proposed. In the case of a wall with a degrading shear-transfer mechanism, however, the shear-to-flexural displacement ratio increases with ductility demand and Δ_s/Δ_f is also strongly dependent on the loading history. It would be interesting to develop a simple rule or have a criterion to distinguish between these two differently behaving walls in design practice.

REFERENCES

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AUTHORS' CLOSURE

The authors thank the discussers for their interest in the paper on shear deformations of slender RC walls. The issues raised will be commented on in the order presented in the discussion.

SHEAR MECHANISMS

1. The discussers state that the top displacement that corresponds to flexural yielding should also consider the shear deformation. The authors agree with the discussers on this point. The computation of the yield displacement was not a subject of the paper, however, but is covered elsewhere.[37]

2. The discussers point out the importance of sliding deformations for squat walls. For slender walls, which are the subject of the paper, the authors' own experimental results[7,11,13] have, however, shown that sliding deformations constitute only a relatively minor part of the total deformations. For the U-shaped walls, for example, the sliding deformations were measured at the base of the web and flanges and the sliding displacements contributed between 2 to 5% to the total top displacements.[7] The shear deformations in the Δ_s/Δ_f ratio comprise both the shear deformations of the wall and the sliding displacements along the joint between the wall and foundation. The authors agree with the discussers that the design for sliding shear resistance requires additional research and found that some design guidelines for sliding shear can lead to very conservative designs requiring diagonal reinforcement.[7] None of the walls that were included in the database of the paper, however, featured diagonal reinforcement.

3. The discussers wonder whether the ductility demand adopted in the analysis includes shear deformations. The displacement ductility μ was computed for total deformations, which is standard practice—that is, it included flexural and shear deformations.

AXIAL STRAINS' DISTRIBUTION OVER CROSS SECTION

1. The discussers note that the shear deformations are not only related to the shear force but also vary over the height of the wall. This is correct and was discussed at length in the paper. The shear deformations are, for example, also a function of the axial strains caused by flexural deformations, which are not constant over the height of the wall.

2. The discussers wonder how the axial strains shown in Fig. 4(a) were captured in the tests. Similar to the shear strains, the axial strains were obtained from Demec measurements (refer to the legend in Fig. 4(a)).

3. The discussers observe that the axial strains are not uniformly distributed over the wall section, particularly above the plastic hinge zone. The authors assume that the discussers expected a linear distribution of strains. The photos of the U-shaped test[7] units show that the crack spacing in the upper part of the wall was larger than the base length of the vertical Demec measurements (200 mm [7.87 in.]). For this reason, the Demec measurements do not result in linear strain profiles.

4. The discussers wonder about the axial strain distribution shown in Fig. 4(a). The tensile axial strains are plotted above the line representing the midheight of the Demec measurement length, whereas the compression strains are plotted below this line. At Position A (Fig. 1(b)), the compression zone lies in the west flange. It should be noted, however, that the compression zone depth is smaller than the flange thickness. Because the Demec measurements were taken on the inside faces of the wall, the axial strains of the west flange at Position A are also positive but, of course, are considerably smaller than the axial strains in the east flange.

5. The discussers state that it does not become clear whether the actuator force parallel to the web acted through the shear center of the U-shaped section. The purpose of this paper was not to explain in detail the test setup for the U-shaped wall tests—the test setup, loading history, boundary condition, and so on are published elsewhere.[7] It is recalled herein, however, that twisting of the top of the U-shaped wall was prevented throughout the test, with the only exception of selected load steps, where the torsional stiffness of the wall was explicitly investigated. The shear center of an RC U-shaped wall subjected to inelastic deformations is not at a constant distance to the web. With increasing inelastic deformations, the shear center moves closer to the web.[7]

SHEAR-TO-FLEXURAL DISPLACEMENT RATIOS

1. The discussers state that "slender RC walls…behave in a ductile flexural mode other than shear failure, when loaded beyond the elastic limit." The authors disagree with this statement and point out that slender RC walls can also fail in shear.

2. The discussers wonder what Δ_s/Δ_f ratio is expected at drift ratios of 1% or less. The authors point out that the question is answered by Fig. 6, which shows the Δ_s/Δ_f ratios for drift values between 0.2% and failure. Moreover, an important finding of the paper is that "for walls forming a flexural hinge and a stable shear-transfer mechanism, the ratio of shear-to-flexural displacement remains approximately constant over the entire ductility range once the walls have reached their nominal strength" (refer to the conclusions of the paper). Equation (8) for estimating the Δ_s/Δ_f ratio is therefore applicable to the entire ductility range.

3. The discussers propose the development of a simple rule for differentiating between walls that are failing in flexure and walls that are failing in shear. The purpose of the paper was not to develop new equations for the flexural and shear resistance of RC walls but instead to study the deformation components of slender RC walls. Strength equations that allow for the estimation of whether a flexural or shear failure occurs are included in all structural design codes.

REFERENCES

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