Shear Failure in Reinforced Concrete Walls

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from experience

Introduction

Following the January 17, 1994 Northridge Earthquake, numerous reinforced concrete and masonry shear walls experienced cracks of different types and sizes. The extent of the damaged walls spread over a large geographical area within Southern California.

The shear failure in many concrete and masonry shear wall buildings has lead the structural engineering community to investigate how to measure the loss of capacity of these failed walls. The debate that was generated lead to FEMA funding of ATC 43 ("Evaluation of Earthquake Damaged Concrete and Masonry Wall Buildings") and the publishing of FEMA 306, 307, and 308).

The evaluation proposed here is a quick check on loss of capacity in shear walls and does not suggest, by any means, that the conclusions arrived at can be used as a criterion for the evaluation of cracked walls.

Properties of Concrete & Reinforcing Steel

The properties of these two important dissimilar materials, when used together, give the strength and ductility needed for proper response to all types of loading conditions.

Tension stresses are of particular concern in view of the low tensile strength of concrete, of various inclinations and magnitudes. These stresses can impair the integrity of the element if not adequately provided for in the design. It is for this reason that the inclined tension stresses, known as diagonal tension, must be carefully considered in reinforced concrete design and repair.

Diagonal tension cracks form at an average, or nominal, stress $v_{cr} = V_{cr}/bd = 3.5\sqrt{f'c}$ where V_{cr} is that shear force at which the formation of the crack is observed. It is evident that at the instant a diagonal crack develops, the average shear stress is larger than that given by $v = V/bd$. This is because the pre-existing tension crack has reduced the area of the uncracked concrete, available to resist shear. The amount of this reduction will vary, depending on the length and width of the pre-existing crack. Tests have shown that in a pre-existing cracked section the nominal shear stress at which diagonal cracks form is given by $1.9\sqrt{f'c}$.

In the early stages of reinforced concrete design, diagonal cracking was considered to be undesirable. However, it is now recognized that diagonal cracking under service load condition is acceptable, provided crack widths remain within the same limits accepted for flexure.

The strength of reinforced concrete under the combined stress phenomena is not a complete comprehensive science and is based mainly on results gathered from experimental work. For the most effective reinforcing action, steel and concrete must deform together. This can be achieved by the following criteria:

1. A strong bond by chemical adhesion of concrete and the roughness of the steel surface which provides an interlock mechanism.
2. The thermal coefficients of the two materials are "fairly" close which minimizes cracking due to change in temperature.
3. The confinement of steel which possesses high thermal conductivity, and concrete with low thermal conductivity. This limits damage that may be caused by fire to the concrete surface. Hence, the strength of the reinforced concrete element is maintained.
4. The confinement of steel with concrete will lend itself to protect steel from corrosion.

Strength of Reinforced Concrete Members

While concrete is best used to resist compression stresses, its tension strength gives rise to structural members resistance to shear and torsional stresses. Steel, on the otherhand, is a high strength material in compression as well as in tension with a usual strength approximately 10 times that of concrete. Steel modulus of elasticity is accepted at 29×10^6 psi, while that of concrete depends on its compressive strength and is estimated at: $57{,}500\sqrt{f'_c}$, ($E_c = 3.64 \times 10^6$ psi for $f'_c = 4000$ psi and 4.45×10^6 psi for $f'_c = 6000$ psi).

Based on the assumption that the strain in a well confined reinforcing steel bar is the same as that of the concrete, hence, as one material deforms the other must follow (due to the adhesion and interlock mechanism as mentioned above). The second assumption is that concrete, prior to cracking, does resist tension stresses of small magnitude which contributes to concrete shear strength as expressed by the UBC formula;

$$V_n = A_{cv} \left(\alpha_c \sqrt{f'_c} + \rho_n f_y \right).$$

In the above formulation the two most important parameters are the compressive strength of concrete (reached at 0.002 to 0.003 strain), which is much smaller than the steel can sustain by itself (steel reaches its ultimate strength, 75 ksi for grade 40 steel and 100 ksi for grade 60 steel, at strain of about 0.1), and the second parameter is the yield stress of steel.

As an illustration consider $f_y = 40$ ksi, the yield strain just before yielding occurs can be estimated from $\in_s = f_y / E_s = 40/29 \times 10^3 \sim 0.0014 < 0.002$, which means that concrete has not reached its ultimate strength.

Evaluation of Elongations of Reinforcing Steel

The following is a table for various lengths of walls and piers. It would be fair to assume that if the crack exceeds these sizes, that the reinforcing steel bars have yielded and that the design shear capacity of the element has been reduced to a value less than $A_{cv}\ \rho_n f_y$ i.e. ($V_n < A_{cv}\ \rho_n f_y$).

Conclusion

In the above brief discussion we were able to establish criteria to see the effect of concrete cracking and steel yielding on the behavior of reinforced concrete shear wall capacity. This criterion is yet to be verified by testing and more rigorous analysis. Mattock and Hawkins, ("Shear Transfer in Reinforced Concrete", **PCI, V. 17, No. 2, Mar-Apr. 1972, pp 55-75**) have shown that initially cracked concrete sections have less shear capacity than uncracked sections, with low values of $\rho_n f_y$ at about 100 psi. The reduced capacity is approximately in the neighborhood of 40% of the uncracked section subjected to the same shear load.

The above findings are based mainly on engineering judgment and limited testing on damaged walls at Santa Monica Community College, and reflect only the opinion of the authors and not the agencies or organizational affiliations they may have.■

Pier or wall length	4′-0″	8′-0″	10’’-0	20′-0
Grade 60 Steel	0.1″>3/32″	0.2″>3/16″	0.25″=¼″	0.5″=½″
Grade 40 Steel	0.07″>1/16″	0.13″>2/16″	0.17″>3/16″	0.33″>5/16″

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Evaluation Criteria for Damaged Shear Walls

The table below summarizes the damage Criterion for Reinforced and Reinforced Masonry Shear Walls:

TYPE OF DAMAGE	EVALUATION CRITERIA
Crack width ≤ 1/16 inch	No reduction in capacity. Wall must be restored to its pre-event condition considering fire rating of the existing construction.
Crack width > 1/16 inch ≤ 3/16 inch and extending through the thickness of the wall.	Contribution of the concrete to the shear capacity of the wall or pier shall be reduced by 50%. Consideration must be given whether or not steel has yielded.
Crack width > 3/16 inch ≤ 1/2 inch.	Contribution of the concrete to the capacity of the wall or pier shall be reduced by 80%. If the reinforcing, across the crack has yielded, the effective length of the wall or pier shall be reduced by the horizontal projection of the crack zone plus two times the wall thickness.
Crack width > 1/2 inch.	Capacity shall be the capacity of the reinforcing steel considering permanent elongation of the bars. If the reinforcing across the crack has yielded, the effective length of the wall or pier shall be reduced by the horizontal projection of the crack zone plus 2 times the wall thickness.
Crushing of the concrete at the ends of the wall or pier to include spalling and exposing the vertical reinforcing.	The effective length of the wall or pier for overturning considerations shall be reduced by the distance from the end of the wall or pier through the width of the crushed zone plus the distance to the closest, undamaged vertical bar.
Crack width ≤ 1/16 inch.	No reduction in capacity. Pier must be restored to its pre-event condition considering fire rating of the existing construction.
Crack width > 1/16 inch ≤ 3/16 inch.	Contribution of the concrete to the shear capacity of the pier shall be reduced by 50%. Consideration must be given whether or not steel has yielded.
Crack width > 3/16 inch < 1/2 inch.	Contribution of the concrete to the capacity of the pier shall be reduced by 80%. If the reinforcing, across the crack has yielded, the pier shall be dropped from the system.
Crack width > 1/2 inch.	The pier shall be considered as having no capacity and dropped from the system.