SHEAR TRANSFER BEHAVIOR OF R/C WALL STRUCTURAL SYSTEMS UNDER CYCLIC LOADS

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SUMMARY

Building systems in which part on all of the seismic load is resisted by reinforced concrete shear walls experience nonlinear degrading behavior under lateral loads well below service level. The nonlinearity in the system is initiated by cracking. The resistance mechanism of the system will predominately be related to shear transfer behavior cyclic load.

An experimental investigation of the cyclic behavior of shear transfer is presented. The specimen geometry and reinforcement are designed to represent and outer portion of a rectangular-cross-section shear wall. The behavior is investigated under varying axial pressure states and load histories. A constitutive model for shear transfer and hysteretic relationships are presented.

INTRODUCTION

Provisions for seismic design require that reinforced concrete systems and structures be designed as ductile energy absorbing structural systems (Ref. 5,6,7). Most steel and reinforced concrete structures in medium to tall range are designed as systems in which part or all of the seismic load is to be resisted by a reinforced concrete shear wall. The lateral design forces are then distributed to the ductile frame and shear wall in accordance with their relative rigidities and considering the interaction of the shear wall and frames. The elastic superposition concept was allowed based on the design philosophy that structures are expected to resist "frequent minor earthquakes" without damage and "occasional moderate earthquates" without structural damage but may experience some none structural damage (Ref. 5,6,7). That is, under service level earthquake loads the structual response is expected to remain elastic. In addition the structural system is expected to resist major structures without collapse.

Structural systems that include shear walls as part of the lateral load carrying system will have degrading stiffness characteristics under seismic load cycles below service level. Consequently, the lateral load distribution to the shear wall and frame can no more be accomplished using initial stiffness properties of the system. This unaccounted behavior of stiffness degration of the shear wall component will push the moment resisting frame component into the undesired damage zone during the middle parts of the ground motion.

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This paper will present a nonlinear behavior model and verifying experiments for the shear wall behavior under service level loads, (minor and moderate earthquakes) and discuss the achieveable ductility levels under loads above service loads (major earthquakes).

SHEAR WALL BEHAVIOR UNDER SERVICE LEVEL LOAD

Cracking of R/C shear walls occurs after a few cycles of low level seismic loading. The direction of cracking near the outer boundaries is generally along the transverse axis of the wall (Ref. 2,3,4). After, cracking the shear force transfer mechanism changes. The shear force is transferred across the crack by aggregate interlock and dowel action. In addition to dowel action reinforcement contributes to the transfer at the crack interface, in ratio to the angle of the crack with respect to the axis of reinforcement by axial forces (Ref. 2,3). However, after cracking the stress redistribution will occur and the portions of the crack under axial compression demand major portion of the shear force (Ref. 1). Therefore, analysing the combined bending and shear force behavior, the outer boundaries of the shear wall will be under axial compression and will demand and transfer major portion of the shear force. The modelling of the shear wall behavior reduces to modelling of shear transfer of an orthogonally reinforced crack under axial compression (Ref. 4).

In an orthogonally reinforced crack interface shear stresses are transmitted through aggregate interlock and dowel action. Shear slip along the crack is accompained by an increase in crack opening because of the rough crack surface. The presence of reinforcement orthogonal to crack surface restrains the crack opening, thus induces tensile forces in reinforcement. The tensile forces in the reinforcement in turn induce compressive stresses on concrete acting on both faces of the crack interface. The magnitude of clamping force applied on the crack interface is directly proportional to the shear transfer capacity on the crack by aggregate interlock. From the nature of these forces, it is clear that the magnitude of the clamping force is equal to the tensile forces generated in reinforcing steel and therefore is equal to the sum of bond stresses generated in concrete (Ref. 6). Additional axial stresses are imposed by the presence of bending stresses on the cross-section which also influences the shear stiffness of the crack interface.

Figure 1(a) shows the crack distribution on a section of a rectangular cross-section shear wall at below service level lateral loads and figure 1(b) shows the isolated view of an element at the outer boundary of the wall.

The shear transfer demand along the cros-section is a function of the shear transfer stiffness distribution along the section. Investigations have shows that if the variables pertaining to the characteristics of concrete are held constant (ie. compressive strength, aggregate gradation and shape) the shear stiffness of a portion of the wall can be defined in terms of loading history, size and amount of reinforcement and axial stress on the crack interface (Ref. 4).

MODELLING OF SHEAR TRANSFER

In the modelling of shear transfer the crack is isolated as an element and the behavior is defined as:

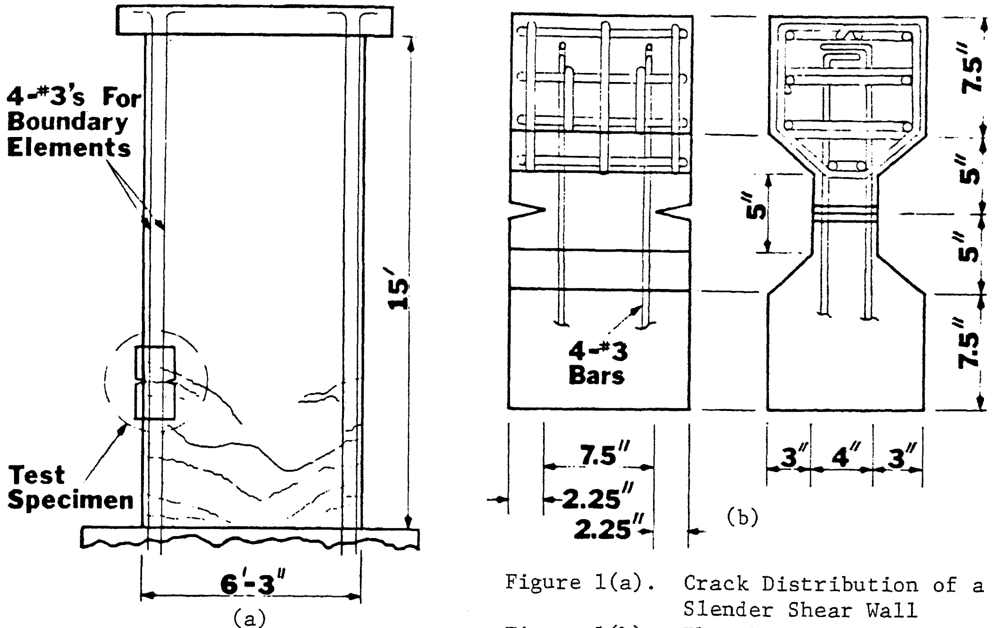
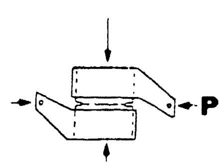
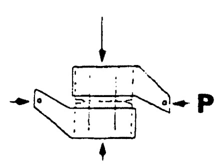
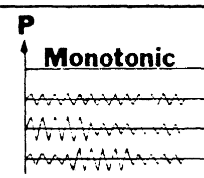
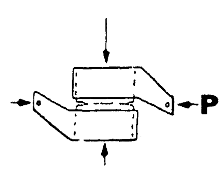
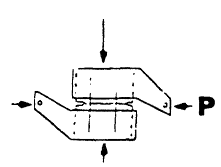
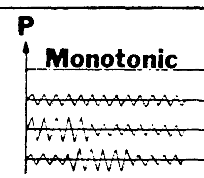
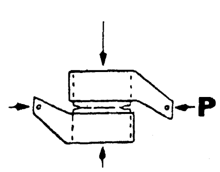
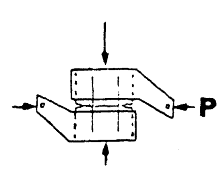
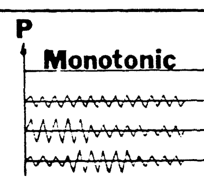


Figure 1(a). Crack Distribution of a Slender Shear Wall

Figure 1(b). The Shear Transfer Experiments Specimen Geometry and Reinforcement

Table 1. Shear Transfer Experiment Summary and Variables

Axial Load	Plain Concrete Specimens	Reinforced Concrete Specimens	Shear Loading Cases
$.2 f'_c$	 P	 P	
$.4 f'_c$	 P	 P	
$.6 f'_c$	 P	 P	

$$\begin{Bmatrix} \sigma \\ \tau \end{Bmatrix} = \begin{bmatrix} k_{nn} & k_{ns} \\ k_{sn} & k_{ns} \end{bmatrix} \begin{Bmatrix} \omega \\ \delta \end{Bmatrix} \quad (1)$$

σ, τ are the normal and shear stress components on the crack interface and ω, δ are the crack opening and crack slip respectively.

The stiffness coefficients k_{nn}, k_{ns}, k_{sn} and k_{ss} define the interaction between aggregate interlock, dowel action and'axial restraining forces in the reinforcing steel.

The stiffness term k_{nn} relating axial compression stiffness to crack opening is simply the uniaxial stiffness of concrete and is well expressed in other studies (Ref. 2). Also, analytical modelling necessitates that the consitutive relation to be symmetrical reduces the undefined stifness coefficients to k_{ss} and k_{ns}. The objective of this paper is to define the hystertic behavior of these two stiffness coefficents.

EXPERIMENTAL METHOD

A set of experiments are designed and are being conducted to obtain the hysteretic variation of k_{ns} and k_{ss}. The experiments are designed to investigate the effect of axial pressure and loading history on shear transfer behavior (aggregate interlock and dowel action). Other variables affecting the shear transfer such as concrete strength, aggregate gradation, specimen geometry, reinforcement amount and size are held constant.

Specimens and Loading

Two sets of specimens reinforced and plain concrete are being tested under 3 cyclic loading histories in addition to monotonic loading under 4 constant axial pressure states (0 f'_c, 0.2f'_c., 0.4 f'_c and 0.6 f'_c). Schematic summary of the experiments are given in table 1. The specimen cross-section and reinforcement is intened to duplicate the outer boundary element of a 1/3 scale rectangular cross-section slender shear wall. The amount of reinforcement of the second group of specimens orthogonal to the crack is 1.47% and the stirrups within the vicinity of the crack is 0.31% (P_y and P_x respectively). The dimensions and the reinforcement of the specimens are given in Figure 1(b).

Both reinforced and unreinforced specimens are subjected to three cyclic loading histories. The first loading history is a constant cycle of low level shear force with amplitude 20% of the ultimate capacity in monotomic loading. The other two load histories represent observed common patterns of seismic loading with load amplitudes reaching 40% of ultimate nominal shear strength capacity under monotonic loading.

Apparatus and Instrumentation

The experimental apparatus is shown in Figure 2. The initial cracking of the specimen is generated by applying axial tension through the axial load actuator. The part of the specimen above the crack interface is fixed to the lateral load frame by two pins and the axial loading mechanism provides the third pin. The two pins of the lateral reaction mechanism are aligned to

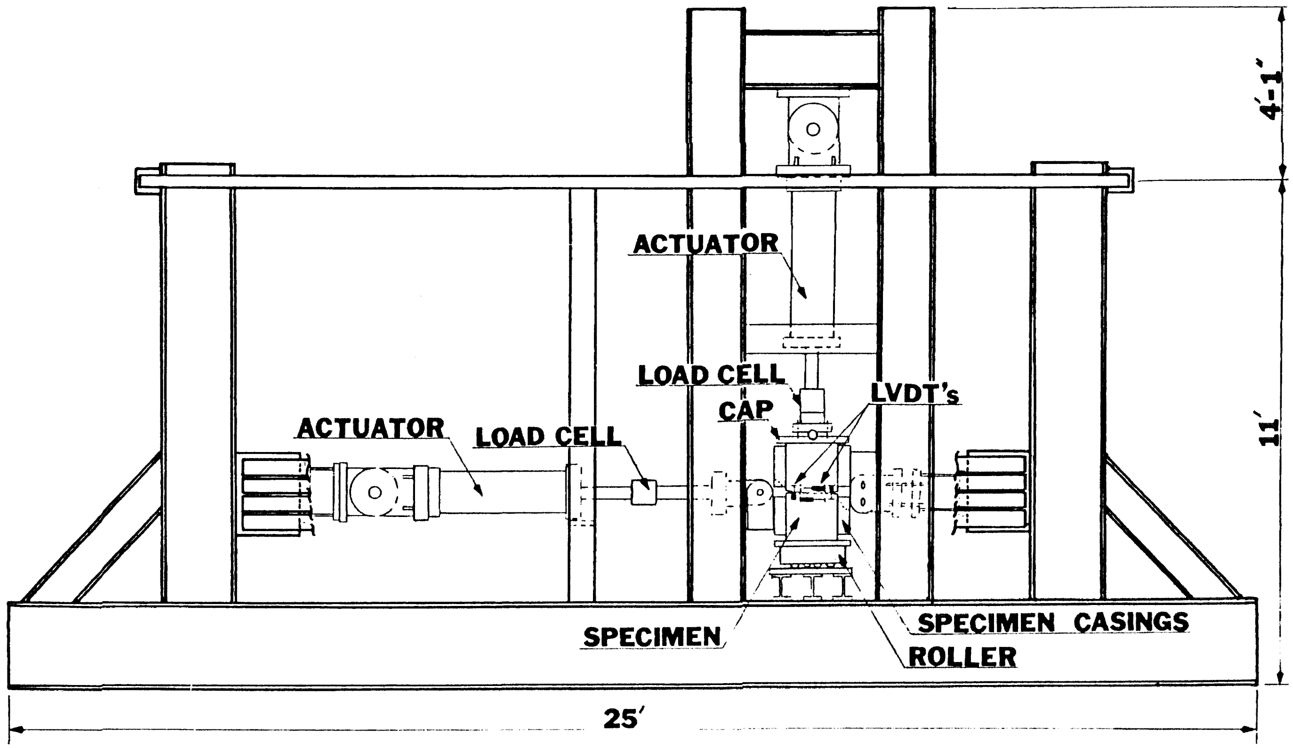


Figure 2. Apparatus and Insturmentation of the Shear Transfer Experiments

generate zero moment on the crack interface and the lateral force components of both pins are monitored to assure zero moment.

The lower portion of the specimen is displaced by the lateral loadings mechanism. The friction force between the specimen base and the load frame are eliminated by placing the specimen on commerically manufactured high capacity roller system.

The experiments are performed in a closed loop fashion through a data acquistion and control processor drived by a desk top computer. The slip and separation along the crack interface is measured using DCDT'S. In addition, axial force is monitored so that constanty is guaranteed.

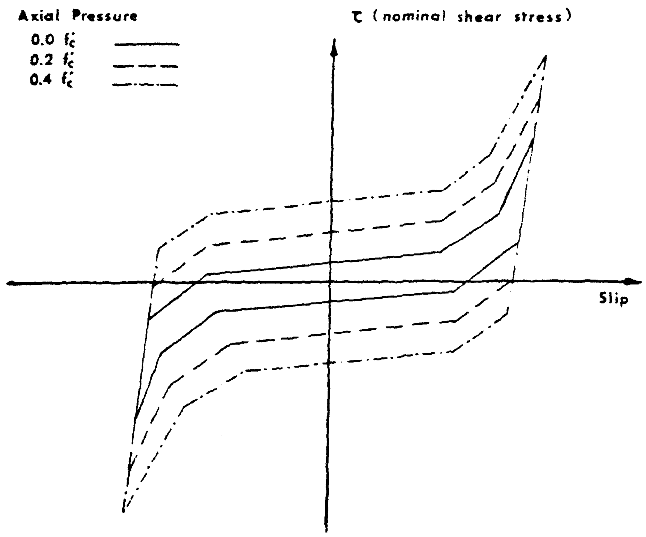


Figure 3. Shear Transfer Behavior Under Different Axial Pressure States

Stiffness Coefficients of Shear Transfer

The nominal shear stress (τ) on the cross-section is defined by dividing the applied shear force to the crack interface area. The relationship between the *nominal* shear stress and shear slip (δ) is directly obtained from the experiments corresponding to each level of axial stress (σ) as shown in Figure 3. Comparisons of the obtained behavior under similar load histories will establish a relation between axial stress and nominal shear stress in the form of:

$$\tau = K.\sigma. \tag{2}$$

Substituting equation 2 into equation 1 the crack opening deformation component can be eliminated and the following relation will be obtained:

$$\tau = K \left(\frac{k_{nn} .\ k_{ss} - k_{sn}^{2}}{k_{nn} .\ K - k_{ss}}\right) \delta \tag{3}$$

The above equation is the basic constitutive relation that can be used in analytical modelling of R/C shear walls (Ref. 4).

CONCLUSION

Contrary to recommended design methods the structures experience nonlinear behavior when subjected to service level earthquake loads. In the case of framed structures coupled with a R/C shear wall the non-linear behavior of the wall is dominated by shear transfer characteristics of the concrete. Considerable degradation occur in shear transer stiffness of the shear wall under low levels of cyclic loading. The load distributions between the shear wall and the moment resisting frame should account for this stiffness degradation.

Further experimental and analytical studies are need to evaluate the behavior of R/C shear walls under low level cyclic loading. In addition to the variables included in this paper, experimental work is needed to evaluate the effects of other variables such as reinforcement amount and size, arrangement of shear reinforcement and bond slip behavior during shear transfer.

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