SEISMIC SHEAR TRANSFER ACROSS CRACKS IN CONCRETE NUCLEAR REACTOR CONTAINMENT VESSELS

by

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SYNOPSIS

Under current methods and criteria for the design of containment shells, large amounts of steel reinforcement are required to accommodate the seismic shearing forces along crack planes formed by internal pressures. The experimental investigation described here is intended to establish the amount of shear which can be transmitted along the crack by interface shear transfer, neglecting the dowel action provided by the reinforcement. Various parameters (aggregate size, amount of reinforcing restraint, crack size, etc.) were investigated in order to establish their effect on the shear capacity and slip characteristics. Results of the study will provide a basis for further investigations including dowel action, and promote development of design and analysis criteria that adequately accounts for this mode of shear transfer.

INTRODUCTION

Large inertia forces must be transmitted across horizontal planes in reinforced concrete nuclear containment vessels. The cracks are assumed to be caused by concurrent or prior pressurization. Shear resistance along the cracks can be developed by components of the axial forces in inclined bars, by shear in the vertical bars (dowel action), and by mechanical interlock of the cracked surfaces (interlock shear transfer).

The present phase of a research program sponsored by the National Science Foundation and carried out at Cornell University has been confined to the interface shear transfer mode. The effects of a number of variables have been studied, as detailed below. Twenty four large precracked concrete blocks were subjected to reversing shear stresses in the range of 100 to 275 psi for up to 25 cycles. The blocks, either 1.5 by 2.0 by 3.0 ft or 1.5 by 2.0 by 1.5 ft, were precracked by wedging and then separated to a preset crack width of 0.01 to 0.03 inches. Further separation of the two halves was restricted by four external rods fastened to the blocks. The amount of shear carried by these rods was only a fraction of one percent of the total shear.

A post-tensioned concrete loading frame was constructed for this study (Fig. 1a). It allows simple restraint of the specimen and easy application of reversing loads with hydraulic equipment. The nominal capacity of the frame is 150 kips shear in either direction.

The standard tests (series A) involved the following data: 18 by 24 in. shearing surface, 0.030 in. preset crack width, medium aggregate hardness, 180 psi cyclic stress, 3000 psi concrete, and four 1.375 in.

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diameter steel restraint rods. Other test series varied from series A; the principal variables included: (a) specimen geometry (depth and shearing area), (b) aggregate size and quality, (c) concrete strength, (d) magnitude of cyclic shear stress, (e) width of preset crack, (f) degree of reinforcing restraint, (g) age of concrete, and (h) construction joint in the plane of the crack. At least two identical specimens were tested for each combination of variables in order to establish repeatability and consistency of test results and to expose any faulty specimens. In the second phase of the program, internal reinforcing bars will be added to the specimen to study the effects of dowel action.

DISCUSSION OF BEHAVIOR

The slip, crack width, and bar forces were recorded incrementally at the first and 15th load cycle and at the peaks of all other cycles. Figure 1 shows typical variations for series A.

a. Components of shear resistance: There are two main modes of action that contribute to the shear resistance of the concrete surfaces: bearing of adjacent pieces of aggregate and mortar, and friction due to the normal restraining forces provided by the reinforcing bars across the crack plane. The effectiveness of bearing action depends greatly upon the initial crack width and on the clamping stiffness of the rebars. The relative magnitude of the two modes also depends on the surface roughness -- greater roughness permits larger bearing forces. Since the initial surface is rougher than after several cycles of loading, the contribution of bearing forces is relatively large initially, whereas the friction forces dominate during later cycles. The increase of bar forces and crack width is smaller in bearing than in friction.

b. Reduction of shear resistance: the examination of the 15th cycle slip (Fig. 1c) shows the reduction of shear resistance as a result of cycling. The first subsequent increment of load (8 kips) usually produced slips greater than six times the slip at the same load during the first cycle.

c. Nonlinear behavior of slip, crack width, and bar forces: considerable crushing takes place during the initial cycles, resulting in a reduced rate of increase in the load-slip, load-crack width, and load-bar force relationships. Furthermore, the reduced contact area and higher contact stresses produce more inelastic straining of the concrete. During later cycles there is a tendency for less crushing and inelastic compaction and an increase in the amount of overriding of the increasingly smoother surfaces. The overriding results in continuously increasing bar forces and hence continual increase in frictional resistance. Each successive load increment must therefore work against an increased friction force which results in a stiffening of the load-slip relationship after the large slips which occur during the first load increments.

d. Shear capacity and surface roughness: a preliminary study has indicated that there is a correlation between the range of total slip for any cycle and the standard deviation of the slopes of the cracked surface profiles from the mean value of zero. Efforts are continuing to relate this relationship to other variables.

MAJOR OBSERVATIONS

The following principal characteristics were observed:

a. the horizontal slip increases in a nearly linear manner with increasing shear load during the first cycle (Fig. 1c), with only a slight decrease in shear resistance occurring at the peak load. This behavior is in contrast to later cycle loadings during which the shear stiffness increased with load.

b. the specimens do not return to the zero slip position upon unloading. The neutral position is reached only during reverse loading.

c. the crack width and bar forces increase at an increasing rate during the initial cycle but at a decreasing rate during later cycles.

d. maximum slip and maximum crack width both increase at a decreasing rate (Figs. 1d and 1f).

EFFECT OF PRIMARY VARIABLES

a. Effect of initial crack width: the shear stiffness increases as the initial crack width decreases. The upper bounds of the expected slip D at cycles 1 and 15, as a function of the initial crack width w_i, for series A are: $D_1 = 1.25\ w_i + 0.012$ inches, and $D_{15} = 2.50\ w_i + 0.08$ inches. At lower crack widths the shear resistance is dominated by crushing and bearing as less overriding occurs.

b. Effect of magnitude of cyclic shear stress: the relationships between cyclic shear stress and the expected slip for cycles 1 and 15 are given conservatively by

cycle 1: $D = 1.67v(10)^{-4}$ in/psi $(0 \leq v \leq 270$ psi$)$

cycle 15: $D = 2.60v(10)^{-4}$ in/psi $(0 \leq v \leq 100$ psi$)$

$D = 3.65v(10)^{-4}$ in/psi $(100 \leq v \leq 270$ psi$)$

The ability of specimens to resist slip is substantially reduced by repeated loading at lower levels. However, it seems that this reduction is insensitive to the lower level of previous loading.

c. Effect of restraint: increased transverse reinforcement reduces slip. The relationship between maximum slip at the first and the 15th cycle of peak loading of 180 psi (series A) is given by

cycle 1: $D = 0.040 - 0.01(k-1.6)$ for $1.6 < k < 3.0$

$= 0.026 - 0.0016(k-3.0)$ for $3.0 < k < 8.0$

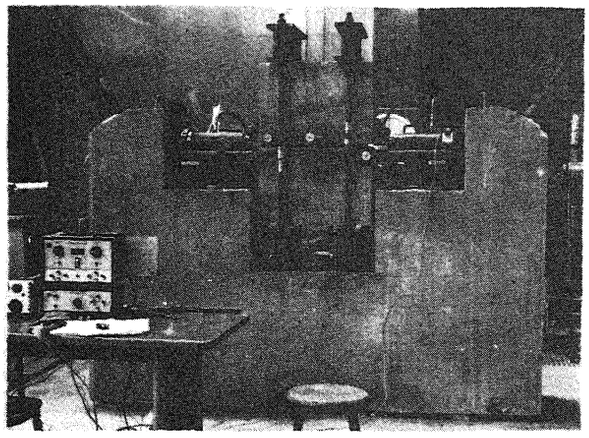
cycle 15: $D = 0.067 - 0.0045\ k$ for $1.6 < k < 8.0$

where k is the vertical clamping stiffness (lbs/in) on a 300 in^2 area.

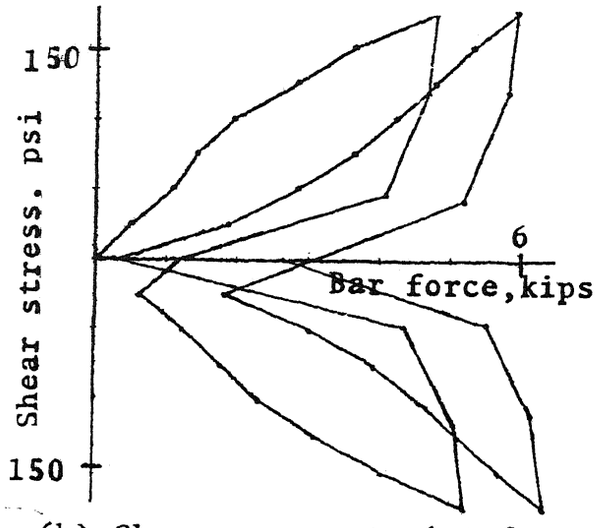
Other variables are also under study. These include the age of concrete, concrete mix, aggregate size and quality, and the existence of a construction joint. Dowel action will be studied later.

IMPLICATIONS FOR DESIGN

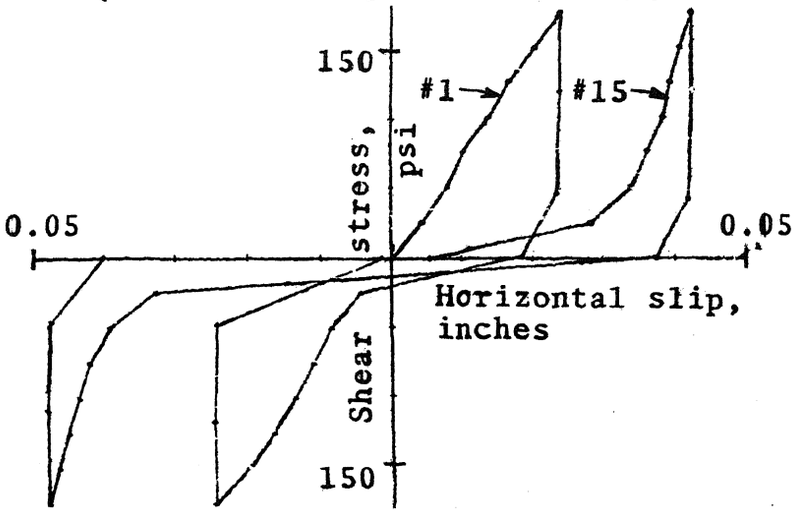
The design of reinforced concrete containment vessels normally does not rely on interface shear transfer to resist seismic shear. Also, dynamic analyses of typical vessels do not account for the variation in stiffness and damping as produced by interface shear phenomena. A better understanding of this behavior will permit more rational design procedures.



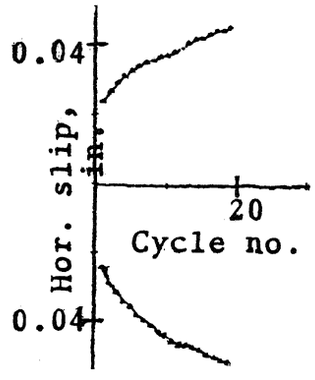
(a) Test set-up



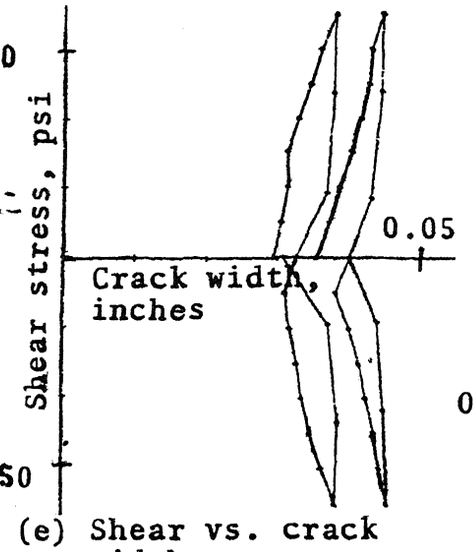
(b) Shear vs. restraint forces



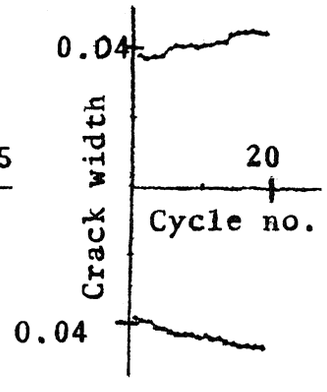
(c) Shear vs. slip



(d) Slip vs. cycle number



(e) Shear vs. crack width



(f) Crack width vs. cycles

FIGURE 1 -- TEST SET-UP AND BEHAVIOR OF SPECIMEN A1