UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D. C. 20555

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MEMORANDUM FOR: Harold R. Denton, Director
Office of Nuclear Reactor Regulation

FROM: Thomas E. Murley, Acting Director
Office of Nuclear Regulatory Research

SUBJECT: RESEARCH INFORMATION LETTER NO.101, "PERIPHERAL SHEARING STRENGTH OF REINFORCED CONCRETE STRUCTURAL ELEMENTS WITH BIAXIAL REINFORCING SUBJECTED TO TENSION"

This Research Information Letter (RIL) describes the results of an experimental study on the static peripheral (punching) shear strength of reinforced concrete elements subjected to biaxial tension applied through the reinforcement (Refs. 1 and 2). The physical situation simulated in the experiments is that of a static force applied normally to the wall of a reinforced concrete containment under internal pressure or other nuclear safety-related concrete structures subject to biaxial tension. The biaxial tension produces a system of orthogonal cracks. The normally applied load necessitates the transfer of punch-type shear stress across these slightly open cracks. Six-inch thick, flat reinforced concrete slabs were used in the experiments. They were not intended to be replica-type models of a typical containment wall, but rather to be representative of the behavior of a containment under the specified load conditions. The inherent punching shear strength of reinforced concrete in combination with biaxial tension was higher than expected, and it was observed to be moderately sensitive to the level of biaxial tension. A critique of the current design formula (Ref. 3, CC-3421.6) is made in light of the results of this study.

1.0 BACKGROUND

The behavior of reinforced concrete in combined biaxial tension and punching shear is not well understood. The current design code (Ref. 3) evolved from conventional practice where source data on punching shear without biaxial tension are available. In nuclear power plant application reinforced concrete is called upon to resist punching shear in combination with biaxial tension, and there are no relevant data available from the conventional practice. High energy lines and equipment like safety relief valves are frequently anchored on the containment wall. For the evaluation of containment integrity, it is frequently necessary to consider large punching loads, for example, at equipment and piping anchor points in conjunction with internal pressure. Design methodology and licensing criteria for the combination of normal loads and biaxial tension in the concrete have evolved from analytical approximations to critical principal stresses and comparisons of these stresses to concrete tensile strength. The experiments described herein are the first known physical tests of actual punching shear strength of biaxially tensioned concrete. They were undertaken to provide a more rational basis for assessing the adequacy and safety of containments and other structures subjected to static punching actions.

2.0 TESTS

2.1 Specimen Configuration and Loading

The specimens were 6-in. thick reinforced concrete slabs, 4-ft. square, reinforced with two layers of No. 4 bars (1/2-in. diameter) spaced 6 in. on center in one direction, and two layers of No. 6 bars (3/4-in. diameter) at 6-in. spacing in the other direction, as shown in figures 1 and 2. A clear cover of 3/4 inch was maintained over the No. 4 bars. This reinforcing pattern corresponds to steel ratios of $\rho = 0.0144$ and 0.0316 in the two directions, respectively. Grade 60 deformed bars and concrete with a 28-day compressive strength f'_c of 3200 to 4500 psi were used. The reinforcing bars extended 3 feet beyond the concrete and were tensioned by hydraulic rams reacting against pipe frames built around the slab in both directions.

Before applying the punching force, the slab reinforcement was tensioned to about 60 to 70% of the yield strength of the bars. This produced a system of orthogonal cracks. The stress level in the reinforcement was then set to a preselected value ranging from 0 to 0.8 f_y, and the punching force was increased gradually until failure resulted. A total of 26 punching strength capacity experiments were conducted. (See Table 1.)

2.2 Test Results

Failure resulted in all tests by the complete punchout of a concrete plug approximately 4 in. square on the top and 6 in. square on the underside of the slab. The punching force produced considerable additional cracking on the bottom face of the slab; much of the bottom cover spalled off. With high biaxial tension, the slabs tended to split horizontally, separating into two layers as the load device penetrated into the specimen. Some permanent deformation of the lower reinforcing bars was also observed.

The displacement of the punched plug of concrete out of the plan of the slab was on the order of 0.1 in. just prior to failure. The load-displacement behavior was generally bilinear with a reduction in stiffness occurring at about three-fourths of the ultimate punching load.

The results are summarized in figure 3, where the punching strength is expressed in terms of a shear stress divided by a concrete tensile strength parameter, f'_c (on the left vertical axis), plotted against the nondimensional level of applied biaxial reinforcement stress, f_s/f_y. The shearing area is defined as the product of the average effective depth, d, of the slab, 4.62 inches times the perimeter, b_o, located at a distance of d/2 from the boundary of the 4-in. square loaded area (b_o = 34.5 in.). Shear strengths in psi are plotted for this same b_o value on the first right side vertical axis.

The current peripheral shear formula (Ref. 3, CC-3421.6):

$$v_u = 4\sqrt{f'_c}\ [\sqrt{1 + (f_m/4\sqrt{f'_c})}\ ] \qquad (1)$$

(here $v_u = v_{ch} = v_{cm}$ as in Ref. 3), which predicts the punching shear strength in the presence of tension, is represented by the graphs in figure 3, for four values of reinforcing ratio = 0.01, 0.015, 0.02, and 0.03; and with constant material properties of f'_c = 3500 psi and f_y = 60,000 psi. It is evident that the graphs representing the code formula (Ref. 3, CC-3421.6) drop down to zero shear strength very quickly in contrast to the actual behavior observed in the experiments.

A more realistic definition of the shearing perimeter, b_o; for this particular set of experiments is 24 in. (4 times the 6-in. maximum side dimension of the punched concrete plug). This corresponds to a perimeter located 0.22d from the boundary of the loaded areas. Introducing this modification, the effective punching shear stress level is increased by the ratio 34.5/24 = 1.44; a corresponding shear stress scale in psi is given on the far right vertical axis in figure 3. These adjusted results for the failure shear stress $v_u = V/b_o d$ on the critical failure paths are represented by the equation

$$\frac{v_u}{\sqrt{f'_c}} = 6.1 - 1.6\ (fs/fy) \qquad (2)$$

for the fixed values of reinforcing ratio used in these experiments. Equation (2) represents a linear relationship (Fig. 3) which provides a satisfactory fit into the groups of experimental point. However, scattering of experimental points is seen in the middle of the figure, which is typical for reinforcing concrete test results when specimens fail by shear (i.e., by actions of principal tensile stresses). Most satisfactory results are obtained at zero biaxial stress when four points are grouped closely together at the left side vertical axis.

The linear Equation (2) differs substantially from code Equation (1), as it is visualized in figure 3.

3.0 CONCLUSIONS AND RECOMMENDATIONS

The summary of the research results is presented in figure 3 in the form of an interaction curve of ultimate strength in punching shear as a function of applied biaxial tension in reinforcement for a fixed steel percentage. Following are some pertinent conclusions that would be of interest to the staff:

° Experimental results, as shown in figure 3, indicated that punching (peripheral) shear strength in tested specimens with zero biaxial tension (i.e., in ordinary thick reinforced concrete plates) is over 50% larger than the design codes indicate (Refs. 3 and 4).

° Tension applied to biaxial reinforcement does not substantially reduce the shear strength capacity of representative reinforced concrete specimens. The punching shear strength at 75% of yield stress in biaxial reinforcing subjected to tension is still above the shear strength assumed in the design formula (Ref. 3, CC-3421.6) for zero biaxial tension; i.e., in ordinary thick reinforced concrete plates (Fig. 3).

° The experiments indicate that the percent of biaxial reinforcement does not influence materially the punching shear strength capacity of the reinforced concrete elements. The design formulas (CC-3421.6) indicate a substantial reduction in the punching shear strength (percentage), which is contrary to the test results.

° The design formula indicates a zero punching shear strength capacity for reinforcing ratio (percentage) from 1 to 3% at tension in reinforcing of 0.40 to 0.12 of the yielding stress, respectively, as shown in figure 3. However, the test results indicate only a moderate reduction of punching shear strength capacity.

° Consequently, the formula (Refs. 3 and 4) should be reconstructed to reflect test data. Parameters entering in the formula should characterize only material properties and the level of tensile stress in reinforcing. The influence of the reinforcing ratio should be deemphasized or eliminated.

The static punching shear strength of orthogonally-reinforced concrete with biaxial tension of the reinforcement is only moderately sensitive to the level of applied biaxial tension. The punching shear strength decreases in an approximately linear manner by about 20% as the biaxial tension increases from 0 to $0.8f_y$. This behavior bears little resemblance to the conservative analytical expression of the design code (Ref. 3, CC-3421.6), Equation (1) and figure 3. A provisional recommendation for revising the code formula, based on Equation (2), may be formulated as follows:

$$\frac{v_u}{\sqrt{f'_c}} = 6.1\phi - 1.6\ (f_s/f_y) \qquad (3)$$

In the formulation of Equation (3), it is recommended that $\phi = 0.85$ be used. Using $\Phi = 0.85$ and zero biaxial tension,

$$\frac{v_u}{\sqrt{f'_c}} = 5.2 \qquad (4)$$

the corresponding line represents a lower bound envelope for the experimental points on figure 3. Further recommendations will be made after the second phase of this study is completed. The second phase will include consideration of such variables as reinforcement ratio, distribution of reinforcement, size of punching loads as compared to concrete slab thickness, shape of the loaded area, position of load relative to reinforcement location, and shear span. The inherent punching shear strength of reinforced concrete in the presence of high biaxial tension, as evidenced from this study, will provide the licensing staff the necessary basis for going beyond the present code limits for operating facilities. For new facilities, the results of this study will aid the licensing staff in developing an interim position with higher limits.

If you have any questions concerning this RIL, please contact Boris S. Browzin of my staff.

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Thomas E. Murley, Acting Director
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Enclosures:
1. Table 1
2. Figures 1 to 3

cc: F. Schroeder, NRR
G. Knighton, NRR

References:

1. J. H. Abrams, "The Punching Shearing Strength of Precracked Reinforced Concrete in Biaxial Tension," Master Thesis, Department of Structural Engineering, Cornell University, 1979.

2. R. N. White, H. Abrams, P. Gergely, "Punching Strength of Biaxial Tensioned Reinforced Concrete," accepted for publication, ASCE Structural Division Specialty Conference: "Civil Engineering and Nuclear Power," Knoxville, Tennessee, September 1980.

3. "ASME Boiler and Pressure Vessel Code," ACI Standard 359-74, Section III, 1977 Edition, Division 2, "Concrete Reactor Vessels and Containments," Article CC-3000 "Design," CC-3421.6 "Peripheral Shear."

4. Building Code Requirements for Reinforced Concrete (ACI 318.77) American Concrete Institute, December 1977.

Table 1

Test Results

Slab Number	Test Number	Concrete Strength (psi)	Biaxial Tension	Punching Strength (kips)
1	0.9A	4100	$0.5f_y$	62.8
	0.9B		$0.5f_y$	60.1
	0.9C		$0.5f_y$	60.2
	0.9D		$0.5f_y$	52.5
2	0.6A	3200	$0.45f_y$	45.1
	0.6B		$0.45f_y$	47.5
	0.6C		$0.45f_y$	40.1
	0.6D		$0.45f_y$	44.9
3	0.6E	3500	$0.57f_y$	44.9
	0.6F		$0.57f_y$	47.6
4	0.0A	4500	$0.00f_y$	66.7
	0.0B		$0.00f_y$	69.7
	0.9E		$0.78f_y$	55.1
	0.9F		$0.78f_y$	57.6
5	0.0C	4100	$0.00f_y$	67.0
	0.2A		$0.20f_y$	65.0
	0.4A		$0.39f_y$	57.5
	0.6G		$0.57f_y$	49.0
6	0.0D	4300	$0.00f_y$	64.1
	0.2B		$0.19f_y$	60.1
	0.4B		$0.38f_y$	55.1
	0.6H		$0.57f_y$	54.7
7	0.2C	3300	$0.19f_y$	52.5
	0.4C		$0.38f_y$	52.4
	0.8A		$0.75f_y$	42.5
	0.8B		$0.79f_y$	43.6

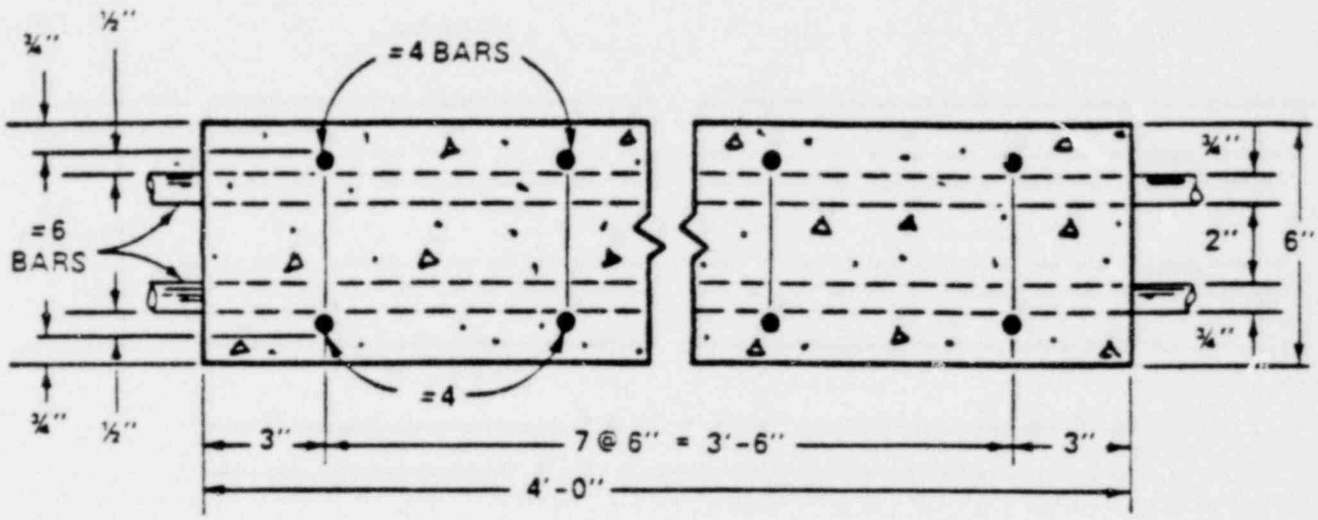


Figure 1 Test Specimen Geometry

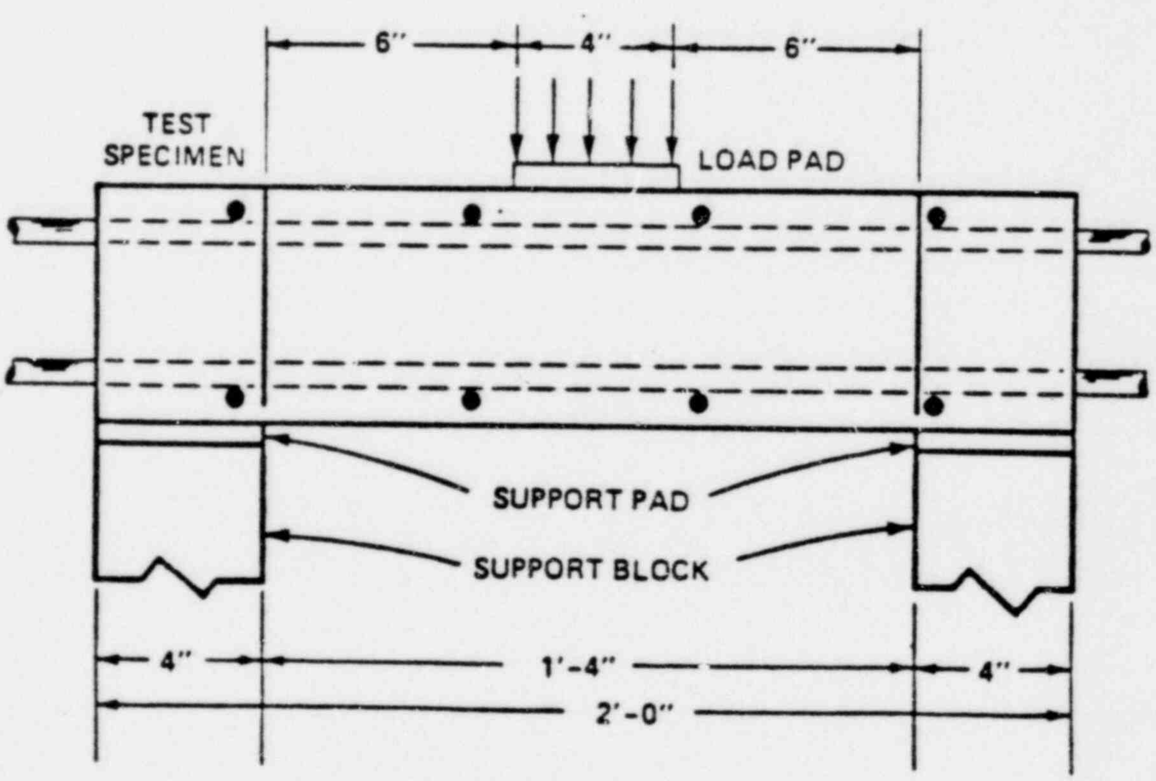
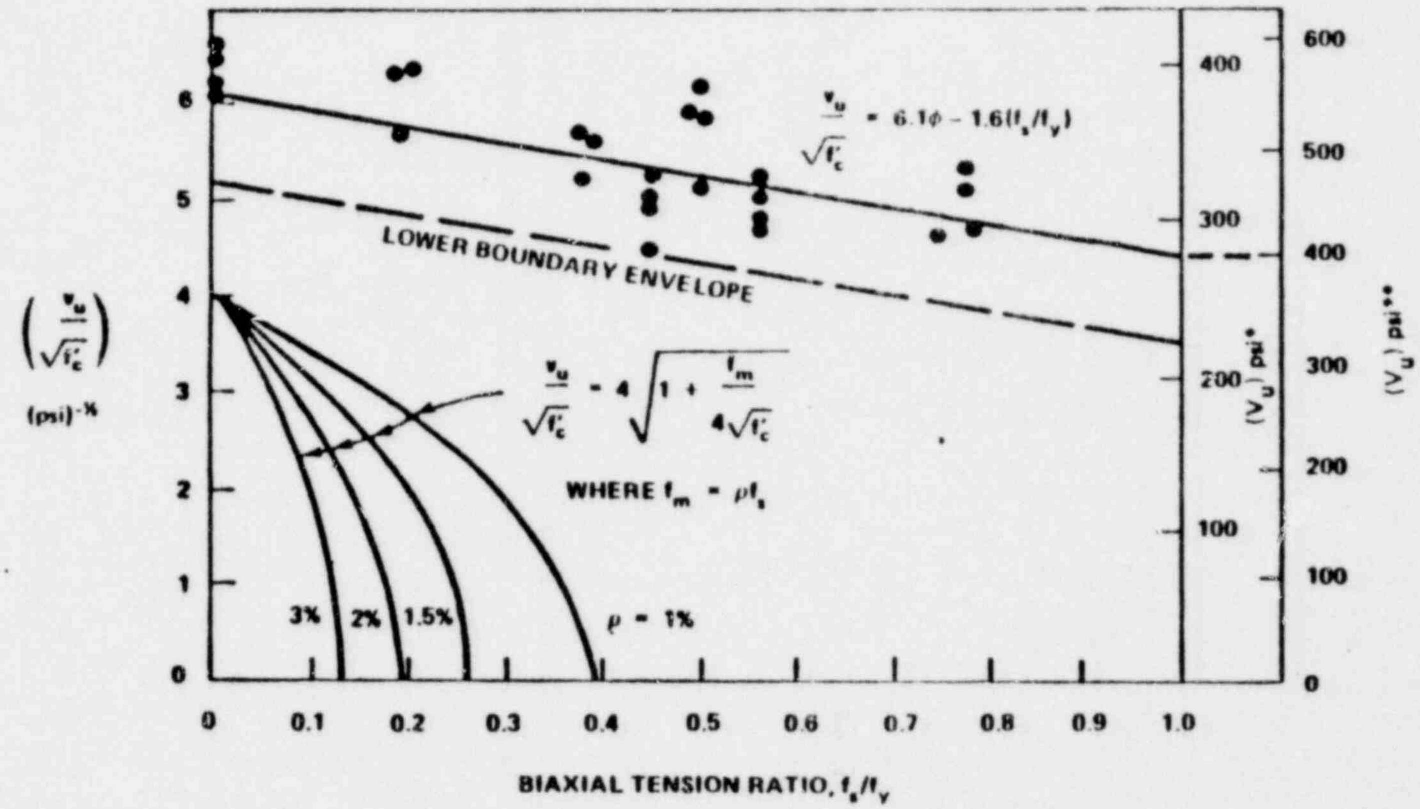


Figure 2 Loading and Support Conditions



*ASSUMED CRITICAL SECTION AT $\frac{d}{2}$ FROM LOAD BOUNDARY, b_o = 34.5 IN.

**ACTUAL CRITICAL SECTION AT 0.22d FROM LOAD BOUNDARY, b_o = 24 IN.

Figure 3 Shear Stress at Punching Failure vs. Biaxial Tension Ratio in Reinforcement