Tension Tests of Concrete Containment Wall Elements

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Abstract

Tension tests of concrete containment wall elements were conducted as part of an Electric Power Research Institute (EPRI) program. The objective of the EPRI testing program is to provide the utility industry with a test-verified analytical method for making realistic estimates of actual capacities of reinforced and prestressed concrete containments under internal overpressurization from postulated degraded core accidents.

The testing program for Phase 1 included eight large-scale specimens representing elements from the wall of a containment. Each specimen was 60-in. (1525-mm) square and 24-in. (610-mm) thick and had full-size reinforcing bars. Six specimens were representative of prototypical reinforced concrete containment designs. The remaining two specimens represented prototypical prestressed containment designs.

Specimen loading included uniaxial loads, biaxial loads, and biaxial loads combined with diagonal loads. Load was applied to specimens statically in increments of appropriate stress levels in the orthogonal and diagonal reinforcement. All specimens were loaded monotonically beyond the yield stress of the reinforcement (68 ksi or 469 MPa) or liner plate (58 ksi or 400 MPa).

Different reinforcement configurations and loading arrangements resulted in data that permit a comparison of the effect of controlled variables on cracking and subsequent concrete/reinforcement interaction in containment elements.

Maximum applied hoop loads were equivalent to a containment pressurization of over 100 psi (0.69 MPa). Specimens were loaded to a maximum hoop strain of approximately 2%. This strain is equivalent to a containment diameter increase of over 3 ft (0.91 m).

Hoop reinforcement tended to act as crack formers under meridional loading. Spacing of through-thickness cracks was approximately 12 in. (305 mm). Crack width at meridional steel stress of 81 ksi (559 MPa) was approximately 0.16 in. (4.1 mm). Cracking due to hoop loading was generally independent of meridional reinforcement locations. Spacing of through-thickness cracks ranged from 18 to 24 in. (457 to 610 mm). Maximum crack width at hoop steel stress of 81 ksi (559 MPa) was approximately 0.35 in. (8.9 mm).

Subtle differences, which were due to variations in reinforcement patterns and load applications among the eight specimens, are being used to benchmark the analytical codes.

Phases 2 and 3 of this program will examine leak rate characteristics and failure mechanisms at penetrations and structural discontinuities.

1. Introduction

Since the Three Mile Island (TMI) incident, accident scenarios with a potential for hydrogen deflagration have become a priority item. As a result, the need to evaluate behavior of nuclear containments under high internal pressures became apparent.

Tension tests of concrete containment wall elements have been conducted as Phase 1 of an Electric Power Research Institute (EPRI) program at Construction Technology Laboratories (CTL). The overall objective of the EPRI program is to provide the utility industry with a test verified analytical method for making realistic estimates of actual capacities and leak rates of reinforced and prestressed concrete containments under internal overpressurization from postulated degraded core accidents. These estimates are needed to perform plant-specific probabilistic risk assessments. Results from tests described herein are being used to confirm analytical models for predicting strength and deformations of containment walls in a separate parallel investigation sponsored by EPRI.

2. Objective

The objective of the CTL testing program (Phase 1) was to determine strength and deformation characteristics of steel and concrete specimens representing wall elements of concrete containments, as illustrated in Fig. 1. Tests were conducted using selected combinations of uniaxial and biaxial forces. Biaxial forces modeled in this test program are caused primarily by internal pressure within the containment.

3. Test Program

The test program to date included eight large-scale specimens representing elements from the wall of a concrete nuclear containment. Each specimen was 60-in. (1525-mm) square, 24-in. (610-mm) thick, and had full-size reinforcing bars. Table I lists specimen design

Table I
SPECIMEN REINFORCEMENT AND DESIGN VARIABLES

Specimen Reinforcement and Design Requirements	Specimen Name							
	UA1	UA2	UA3	BA1	BA2	BA3	PC1	LP1
Hoop Reinf. (No. 18) (Loaded) $A_S/A_G = 0.022^*$	X	X	X	X	X	X		
Meridional Reinf. (No. 14) (Unloaded) $A_S/A_G = 0.013$			X					
Meridional Reinf. (No. 14) (Loaded)				X	X	X		
Diagonal Reinf. (No. 10) (Unloaded)			X		X			
Diagonal Reinf. (No. 10) (Loaded)						X		
Minimum Reinforcement (No. 7) $A_S/A_G = 0.0042$							X	
Preformed Cracks		X						
Liner Plate, 1/4 in. (6.4 mm)								X
Tendon Ducts							X	X

* A_S/A_G = Ratio of area of reinforcement to gross cross-sectional area of concrete.

variables. Specimens UA1 through BA3 represented prototypical reinforced concrete containment designs. Reinforcement details included hoop, meridional, and diagonal bars. Reinforcement details for Specimens UA3, BA2, and BA3 are shown in Fig. 2.

The remaining two specimens represented prototypical prestressed containment designs. Tendon ducts were simulated in the latter two specimens using thin walled tubing. Specimen PC1 contained a low percentage of reinforcement representative of that used in prestressed containments to control stresses due to drying shrinkage and temperature differentials in the concrete wall. Orthogonal reinforcement was located near both faces of the test specimen. Specimen LP1 had liner plates anchored to both faces of concrete. Although not prototypical, this arrangement provided a symmetric specimen. Symmetry eliminated the need for the complex loading fixture that would be required with a prototypical liner on one side only. Liner anchorage consisted of angles welded to the liner plate.

Objective of testing Specimens UA1 through BA3 was to investigate effects of different reinforcement and loading configurations on behavior of reinforced concrete containment wall elements. Addition of variables to each succeeding specimen in the test sequence provided a basis for comparison. Hoop reinforcement with applied loads was the only common feature for these first six specimens.

Comparison of the cracking behavior and strain distribution between Specimen UA1 and UA2 was to indicate any effects preformed cracks had on the adjacent uncracked area. The effect of reinforcing and loading conditions on specimen strain distribution and surface cracking was investigated with Specimens UA3, BA1, BA2, and BA3. Testing of Specimen PC1 was to indicate if nominal hoop and meridional reinforcement found in prestressed containments is sufficient to crack the full concrete section. Interaction between liner with anchorage and concrete was evaluated with Specimen LP1.

4. Testing Apparatus

Specimen loading included uniaxial loads, biaxial loads, and biaxial loads combined with diagonal loads. Load was applied to specimens statically in increments of appropriate stress levels in the orthogonal and diagonal reinforcement. For biaxial loading, the ratio of hoop to meridional load was approximately 2 to 1. This ratio modeled the forces in a typical containment structural element away from areas with structural discontinuities. All specimens were loaded monotonically beyond yield stress of reinforcement (68 ksi or 469 MPa) or liner plate (58 ksi or 400 MPa). This was accomplished by pulling on the reinforcement and liner with hydraulic rams reacting against a concrete reaction frame. The reaction frame was constructed by CTL for the U.S. Nuclear Regulatory Commission in a previous program where membrane shear behavior during simulated earthquake loading was investigated. The test setup is shown in Fig. 3.

5. Instrumentation

Specimen behavior was measured using external and internal instrumentation. Loads were monitored by calibrated load cells. Overall specimen deformations were measured using linear potentiometers. Specially designed gages measured changes in crack width. Internal instrumentation consisted of electrical resistance strain gages attached to reinforcing bars to measure steel strains. Strain gages were also attached to small-diameter deformed wire in an attempt to measure concrete strains. All measurements were recorded by a digital data

acquisition system that stored the data in a desktop computer. External instrumentation and crack patterns for Specimen BA3 are shown in Fig. 4.

6. Results

Tests were ended when limits of the loading equipment were reached rather than at maximum specimen strength or strain. The following comments are based on test results from Specimens UA1 through BA3. Where extrapolations are made to a prototypical containment vessel, the vessel has a 150-ft (45.7 m) diameter and a 4-ft (1.22-m) wall thickness.

- (a) Maximum applied hoop loads were equivalent to a containment pressurization of over 100 psi (0.69 MPa). Overall specimen hoop strain at maximum load was on the order of 2%. This strain is equivalent to a containment diameter increase of over 3 ft (0.91 m).
- (b) Applied hoop loads at specimen yield were equivalent to a containment pressurization of approximately 80 psi (0.55 MPa). Overall specimen hoop strain at yield load was approximately 0.3%. This strain is equivalent to a containment diameter increase of approximately 0.42 ft (0.13 m).
- (c) Hoop reinforcement tended to act as crack formers under meridional loading. Spacing of through-thickness cracks was approximately 12 in. (305 mm). Crack width at meridional steel stress of 81 ksi (559 MPa) was approximately 0.16 in. (4.1 mm).
- (d) Cracking due to hoop loading was generally independent of meridional reinforcement locations. Spacing of through-thickness cracks ranged from 18 to 24 in. (457 to 610 mm). Maximum crack width at hoop steel stress of 81 ksi (559 MPa) was approximately 0.35 in. (8.9 mm).

In Specimen PC1, nominal reinforcement was sufficient to induce cracking at reinforcement locations in both hoop and meridional directions. Spacing of through-thickness cracks due to hoop load was approximately 12 in. (305 mm) and spacing of through-thickness cracks due to meridional load was approximately 24 in. (610 mm).

Specimen LPI had through-thickness cracks at all angle anchorages to the liner plate.

Hoop steel stresses versus overall hoop strains for Specimens BA1, BA2, and BA3 are shown in Fig. 5. These typical load versus strain curves show concrete cracking at hoop steel stress of approximately 9.4 ksi (64.8 MPa).

Subtle differences in specimen behavior, which were due to variations in reinforcement patterns and load applications among the eight specimens, are being used to benchmark the analytical codes. In Fig. 5, the BA2 plot indicates a stiffer specimen when compared to the plots for BA1 and BA3. This was due to the effect of unloaded diagonal reinforcement in Specimen BA2. On the other hand, data from Specimen BA1 with no diagonal reinforcement agrees well, as would be expected, with data from Specimen BA3 with loaded diagonal reinforcement. Consistent variation from specimen to specimen has indicated a relatively low "error bar" in the test program.

7. Subsequent Testing

Additional tests in Phase 1 will examine the behavior of liner plates subjected to biaxial tension. Plain and welded liner plates with angle anchorages will be tested.

Phase 2 in the EPRI program will investigate the leak rate characteristics and failure mechanisms of prototypical containment walls with and without penetrations. Tests will be performed on full-scale specimens for use in qualifying analytical methods.

Phase 3 will examine the response of containment structures at discontinuities such as wall/base mat intersection and at the spring line or ring beam. Tests will be performed on fully cylindrical or partially cylindrical models.

8. Acknowledgment

The project team would like to thank Adolf Walser and Dr. Joseph Ucciferro for their assistance in the areas of prestressed and reinforced concrete containment designs. The project team would also like to thank Dr. G. E. Sliter of EPRI for overall guidance and technical input which led to successful completion of this program. Tests in this program were performed in a concrete reaction frame built for a previous testing program sponsored by the Nuclear Regulatory Commission. Tests were performed in the Structural Laboratory of Construction Technology Laboratories under the direction of Dr. H. G. Russell, Director, Structural Development Department.

Fig. 1 Biaxial Tension Due to Internal Pressurization

Fig. 2 Reinforcement Details of Specimens UA3, BA2, and BA3

Fig. 3 Test Setup

Fig. 4 Instrumentation and Crack Patterns
for Specimen BA3

Fig. 5 Load versus Strain for Specimens BA1, BA2, and BA3