

Experimental Study on Air Leakage Characteristics of PCCV

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1. Introduction

Prestressed Concrete Containment Vessels (PCCV) in nuclear power plants serve as the ultimate physical barrier, preventing the release of radioactive materials into the environment during severe accidents. These structures are fundamentally composed of prestressed reinforced concrete (PSC) walls. Concurrently, a steel containment liner plate (CLP) is installed on the innermost surface of the containment building to act as the primary leak-tight boundary.

The structural integrity of a PCCV is directly correlated with its leakage rate; previous studies have extensively documented that even minor structural cracks or localized corrosion can cascade into critical containment failures. However, the experimental specimens employed in these preceding studies often fail to adequately represent the substantial thickness of actual containment walls [1-3]. Due to inherent experimental constraints, structural configurations are frequently scaled down or simplified, thereby limiting the accurate reflection of the authentic structural and mechanical characteristics of full-scale PCCVs.

Therefore, building upon a previous pilot test conducted on an RC structural wall devoid of inclusions, this study investigates the tension-induced cracking and leakage characteristics using a full-scale specimen representative of a mid-height PCCV wall, intricately incorporating actual internal embedments. This research encompasses comprehensive measurements of the leakage rates in relation to concrete damage, providing a detailed comparative analysis of the distinct structural responses and permeability.

2. Experimental Program

2.1. Specimen Design

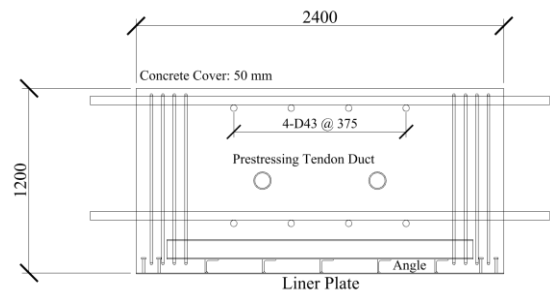
To represent a unit element of the mid-height wall in a containment building, the specimen was fabricated as a reinforced concrete (RC) block with an embedded CLP. The dimensions of the specimen were 2,400 mm in length, 900 mm in height, and 1,200 mm in thickness. To prevent eccentric loading during the test, the specimen was rotated such that its thickness acted as the vertical height.

ASTM Grade 60 No. 18 bars were utilized for the reinforcement. These bars were arranged in the longitudinal direction to represent the hoop reinforcement of the PCCV placed in two rows with a

spacing of 300 mm. Perpendicular to these hoop bars, No. 14 bars were arranged in groups of four at 375 mm intervals, representing the meridional reinforcement of the PCCV. The reinforcing mesh positioned in the upper layer of the cross-section simulates the outward layer of the PCCV, with a concrete cover of 50 mm from the hoop bars. The lower reinforcing mesh represents the inward layer adjacent to the CLP, featuring a 300 mm cover from the meridional bars. To prevent concrete spalling induced by stress concentration at both ends of the specimen during loading, No. 5 hoops were additionally installed at 75 mm intervals.

Prestressing tendon ducts with an outer diameter of 114 mm were embedded in both the hoop and meridional directions. The hoop-direction duct was aligned 300 mm below the top surface of the specimen, positioned beneath the left and right reinforcing bars. The meridional ducts were placed in single rows, symmetrically offset by 375 mm from the centerline of the PCCV wall section. Since no prestress was applied in this study, only the empty ducts were embedded without tendons.

A 6 mm-thick liner plate was attached to the bottom of the specimen. This plate consisted of two 1,200 x 900 mm steel plates butt-welded in the longitudinal direction, leaving a 150 mm unwelded segment (75 mm upward and downward from the center) to simulate liner plate tearing [4]. To prevent the detachment of the liner plate from the concrete, KS D 3502 90×90 angles were welded at 375 mm intervals. Furthermore, KS D 3502 125×65 channels were placed perpendicularly to the angles and welded along all contact surfaces to effectively prevent angle slippage.



(a) Front elevation

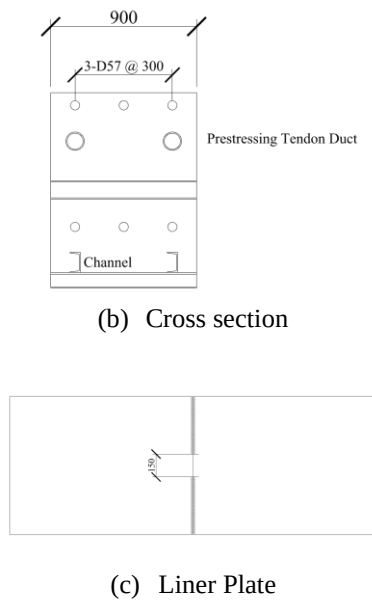


Fig. 1. Specimen fabrication details.

2.2. Test Setup

To rigorously analyze the crack and leakage characteristics of reinforced concrete walls subjected to direct tension, a longitudinal uniaxial tensile load was applied to the externally protruding hoop bars to induce through-thickness cracks in the specimen. The target load was set to 6,000 kN, and the loading was executed under displacement control using two hydraulic actuators, each with a capacity of 5,000 kN.

Three types of instrumentation were employed to monitor the structural deformation. Strain gages were attached at five locations at 400 mm intervals within the region of interest (ROI) on each hoop bar. Four string-type displacement transducers were installed at both ends of the ROI on the front and rear surfaces of the specimen to measure localized deformation. Furthermore, Fiber Optic Sensors (FOS) were embedded within the concrete to detect cracking and measure tensile strain. The FOS layout consisted of a 14×3 grid, with sensors strategically embedded near the internal inclusions and at intermediate locations.

2.3. Leakage Test Protocol

A leakage test was carefully designed to evaluate the air flow rate through the cracks formed in the damaged specimen post-loading. A steel chamber measuring 1,600 mm in length and 650 mm in width was mounted on the top surface of the specimen. This chamber interfaced with the concrete via a polyurethane sealant. To prevent the sealant from tearing under internal pressure, a 10 mm-thick rubber liner was interposed between the chamber and the concrete surface prior to sealing. Once the sealant was fully cured, airtight tape was applied from the chamber flange to the bottom of

the specimen. For protruding geometries where the tape could not adhere properly, non-acetic silicone caulking was applied to ensure complete hermeticity.

A pipe at the top of the chamber was connected to a specifically designed negative pressure induction system. The pressure supplied from an air compressor to a mechanical ejector generated negative pressure in a vacuum tank via the Venturi effect. A regulator connected between this tank and the chamber controlled the flow rate, extracting air to lower the chamber's internal pressure. Consequently, ambient air permeated through the concrete cracks. To maintain a constant target pressure, the regulator was continuously adjusted. Once a steady state was achieved—defined as maintaining the same pressure for over 60 seconds—the flow rate was recorded from the flow meter. To capture the data on a logarithmic scale, the pressure increments were configured into 8 steps ranging from 0.1 kPa to 20 kPa, followed by an additional final step at the maximum regulator opening.

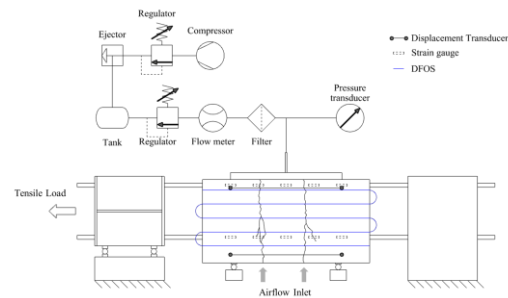


Fig. 2. Overall test setup for structure and leakage.

3. Results and Discussion

3.1. Force – Deformation Relation

The maximum applied tensile force reached approximately 4,700 kN. When the load attained 1,550 kN, the negative pressure initially applied to the chamber gradually recovered to zero. This phenomenon was directly attributed to the onset of airflow resulting from the formation of a through-thickness crack; hence, this point was recorded as the cracking initiation point. This observation was further corroborated by acoustic emissions detected at the exact same moment in the video recording capturing the bottom of the specimen.

Based on this initiation point, loading was temporarily paused, and leakage tests were conducted whenever the average displacement recorded by the displacement transducers exhibited a sudden shift (accounting for inherent signal noise). At the final loading step, the average displacement of the specimen was 1.075 mm. The experiment was officially terminated after a total of eight loading steps due to subsequent load degradation.

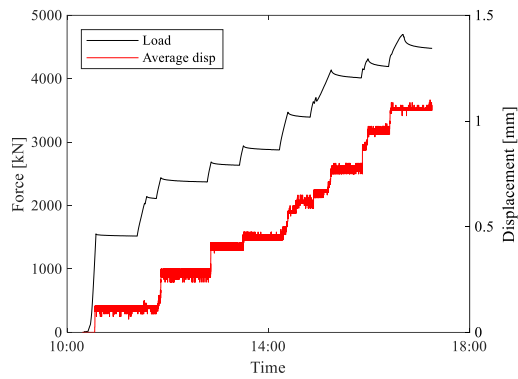


Fig. 3. Time series data of force and displacement

3.2. Pressure – Flowrate Relation

Prior to crack initiation, a negative pressure of up to 42 kPa was applied to verify the structural airtightness of the setup. Following crack generation, the negative pressure could no longer reach 40 kPa, and the maximum achievable vacuum pressure at the full opening of the regulator decreased progressively as the crack widened across the sequential steps. This strongly confirms that no extraneous air ingress occurred from locations other than the specimen's designated crack surface.

In the initial phase of pressure formation, localized turbulence emerged due to the geometric tortuosity characteristic of concrete cracks, which consequently induced a high initial pressure differential. However, as the airflow stabilized into a unidirectional path, the turbulent effects naturally diminished, allowing the system to stabilize and maintain a constant pressure differential. Moving beyond this qualitative observation, a rigorous quantitative analysis correlating the structural response with the distinct leakage characteristics of the PCCV is imperative for a comprehensive evaluation.

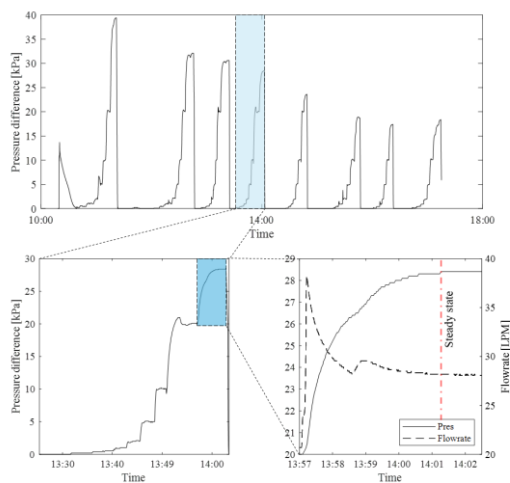


Fig. 4. Time-history of the pressure difference and flow rate illustrating the definition of steady state.

4. Conclusions

This experimental study focused on characterizing the permeability of tension-induced cracks using a full-scale PCCV specimen, conducted as an extension of a previously performed pilot test. Unlike the preliminary pilot test, which utilized a pure RC wall specimen devoid of internal inclusions, the specimen in this study was meticulously designed with an internal embedment configuration identical to that of an actively operating nuclear containment building wall. Consequently, quantifying the precise impact of these complex internal embedments on the overall leakage rate of the PCCV wall remains a critical objective for future research.

A primary takeaway from this investigation is that structural defects occurring in the CLP—which is fundamentally installed as a barrier to prevent the release of radioactive materials—can directly facilitate significant leakage. Furthermore, the findings indicate that once continuous airflow pathways, such as structural cracks or internal voids, are established within the concrete, the tensile forces applied to the wall can substantially amplify this permeability. Therefore, rigorous structural health monitoring and proactive defect prevention strategies for operating nuclear power plants are paramount to mitigating potential risks and ensuring containment integrity in the event of an accident.

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