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Original Article

CONTAINMENT PERFORMANCE EVALUATION OF PRESTRESSED CONCRETE CONTAINMENT VESSELS WITH FIBER REINFORCEMENT

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ABSTRACT

Background: Fibers in concrete resist the growth of cracks and enhance the postcracking behavior of structures. The addition of fibers into a conventional reinforced concrete can improve the structural and functional performance of safety-related concrete structures in nuclear power plants.

Methods: The influence of fibers on the ultimate internal pressure capacity of a prestressed concrete containment vessel (PCCV) was investigated through a comparison of the ultimate pressure capacities between conventional and fiber-reinforced PCCVs. Steel and polyamide fibers were used. The tension behaviors of conventional concrete and fiber-reinforced concrete specimens were investigated through uniaxial tension tests and their tension-stiffening models were obtained.

Results: For a PCCV reinforced with 1% volume hooked-end steel fiber, the ultimate pressure capacity increased by approximately 12% in comparison with that for a conventional PCCV. For a PCCV reinforced with 1.5% volume polyamide fiber, an increase of approximately 3% was estimated for the ultimate pressure capacity.

Conclusion: The ultimate pressure capacity can be greatly improved by introducing steel and polyamide fibers in a conventional reinforced concrete. Steel fibers are more effective at enhancing the containment performance of a PCCV than polyamide fibers. The fiber reinforcement was shown to be more effective at a high pressure loading and a low prestress level.

1. Introduction

The defense-in-depth philosophy uses a series of safety barriers in the design of light-water reactors to prevent the release of radioactive materials from the reactor core into the environment. The three main barriers are the zirconium fuel cladding containing fuel pellets, the steel reactor vessel, and the steel or concrete containment structure. The containment structure, which is the final physical barrier, must be leak proof to contain radioactive materials during a

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severe accident. When subjected to severe accident conditions, the deterministic performance criteria for steel containments are stated in SECY-90-016 [1] as follows: “The containment should maintain its role as a reliable leak-tight barrier by ensuring that containment stresses do not exceed ASME Service Level C limits for a minimum period of 24 hours following the onset of core damage and that following this 24-hour period the containment should continue to provide a barrier against the uncontrolled release of fission products.” This criterion is not applicable to concrete containments, but is useful to develop equivalent deterministic acceptance criteria for both reinforced and prestressed concrete containments.

Based on the containment depressurization times, the containment performance is characterized by three possible categories of failures: leak, rupture, and catastrophic rupture. The failure criteria are defined in NUREG-1150 [2]. A “leak” is defined as a containment breach that would arrest a gradual pressure buildup but would not result in containment depressurization in < 2 hours, whereas a “rupture” is defined as a containment breach that would depressurize the containment within 2 hours. A “catastrophic rupture” is defined as the loss of a substantial portion of the containment boundary. The leak size required to meet the leak criterion is estimated to be between 0.028 m^2 and 0.046 m^2, and the hole size needed to meet the rupture criterion is estimated to be approximately $\geq$ 0.093 m^2 [2–5]. When the total crack opening in the containment exceeds 0.028 m^2, the radioactive materials inside the containment will be released into the environment. The leak rate is dependent on the number of cracks, the height and width of the cracks, and the active flow paths.

Cracking is unavoidable in concrete because of its inherently low tensile strength and low strain capacity at a fracture. To overcome these shortcomings in conventional reinforced concrete (RC), the concrete is reinforced by steel bars that can carry the tensile stress after cracking of the concrete. For the same purpose, in recent years, fibers have occasionally been added to provide tensile strength in a cement mixture and control the cracking. Fiber-reinforced concrete (FRC) includes thousands of small fibers that are distributed randomly in the concrete. FRC fails in tension only when the fibers break or are pulled out of the cement matrix. Through the bridging action at the cracks, fibers resist the growth of cracks in concrete. As a result, fibers increase the tensile toughness of concrete and enhance the postcracking behavior of concrete structures. Two types of fibers are commonly available for concrete: steel and synthetic fibers. Steel fibers are mainly used in structural applications such as industrial pavements, precast structural elements, and tunnel linings. Synthetic fibers are used in industrial pavements to reduce the cracking induced by shrinkage [6].

A number of studies have been conducted on the tension and postcracking behaviors of FRC. Shah and Rangan [7] found that fibers considerably increase the resistance of concrete to crack propagation. They observed that the significant reinforcing effect of fibers is derived after the cracks are initiated in the matrix, and the postcracking resistance of fibers is considerably influenced by their aspect ratio (bond strength), orientation with respect to the cracking direction, and their stress–strain relationship. Abrishami and Mitchell [8] observed that the normal and high-strength RC specimens suffered splitting cracks and lost a significant amount of tension stiffening after cracking as well as experiencing significant deformation, while the presence of steel fibers controlled the splitting cracks and led to significant increases in the tension stiffening of both RC specimens. Bischoff [9] found that tension stiffening in FRC is a combination of the behavior between the cracks and at the cracks, and adding steel fibers to the concrete improves the tension stiffening in RC because the FRC is able to carry tensile forces at the cracks. Deluce and Vecchio [10] also found that the cracking behavior of steel FRC (SFRC) specimens was significantly altered by the presence of a steel reinforcing bar, and that the crack spacing and crack width were influenced by the reinforcement ratio and bar diameter of the conventional reinforcing bar, as well as by the volume fraction and aspect ratio of the steel fiber.

The containment performance of a prestressed concrete containment vessel (PCCV) will be improved through a significant decrease of the crack open area and the prevention of through-wall cracks. Fibers can be successfully used for improving the containment performance of the PCCVs by reducing the cracks in the containment concrete. In this study, the effects of steel and polyamide fiber reinforcement on the ultimate pressure capacity of a PCCV are evaluated.

2. Cracking behavior in FRC

2.1. *Cracking mechanism in FRC*

The cracking process in FRC can be identified in four distinct zones, as shown in Fig. 1: (1) a zone of microcracking; (2) a zone of microcrack growth; (3) a bridging zone, where the stress is transferred by a fiber pullout and aggregate bridging; and (4) a traction-free zone, which occurs for relatively large crack openings [11]. The cracking behavior depends on the characteristics of the fibers, such as the fiber types, lengths, cross-sectional geometry, surface treatment, and volume fractions. For a strain-softening specimen, a localized single crack governs the postpeak behavior and once the matrix cracks the stress will start to decrease. For a pseudostrain-hardening specimen, called “high-performance FRC (HPFRC),” the postcracking strength is larger than the cracking strength, or elastic–plastic response. HPFRC, a cement composite comprising a cement-based matrix and short fibers, is highly ductile and thus exhibits dense and multiple fine cracks.

2.2. *Cracking in FRC containing reinforcing bars*

In an RC member, the concrete between adjacent cracks carries tensile stresses and thus provides additional stiffness under tension. This tension-stiffening effect is provided by the bond force transfer between reinforcing bars and the surrounding concrete. The addition of fibers into plain concrete enhances the bond performance and improves the tension