Evaluation of Ultimate Pressure Capacity of a Prestressed Concrete Containment Building with Steel or Polyamide Fiber Reinforcement

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1. Introduction

Plain concrete has a low tensile strength and a low strain capacity at fracture under tension since it is an inherently brittle material. Fiber reinforced concrete (FRC) includes thousands of small fibers that are distributed randomly in the concrete. Fibers resist the growth of cracks in concrete through their bridging at the cracks. Therefore, FRC fails in tension only when the fibers break or are pulled out of the cement matrix. For this reason, the addition of fibers in concrete mixing increases the tensile toughness of concrete and enhances the post-cracking behavior.

A prevention of through-wall cracks and an increase of the post-cracking ductility will improve the ultimate internal pressure capacity of a prestressed concrete containment building (PCCB). In this study, the effects of steel or polyamide fiber reinforcement on the ultimate pressure capacity of a PCCB are evaluated.

2. Tension Responses of Fiber Concrete Members

The tension responses of concrete members constructed using steel fiber reinforced concrete (SFRC) and polyamide fiber reinforced concrete (PFRC) were investigated by axial tension tests.

2.1 Concrete Mix Proportions

For the test specimens, concrete mixes with a compressive strength of 42 MPa are given in Table I for plain and fiber concretes. For SFRC, a 1.0% volume fraction of hooked-end steel fibers were added. The steel fibers had a length of 30 mm and a diameter of 0.5 mm, giving an aspect ratio of 60. The tensile strength of the steel fibers was 1,100 MPa. For PFRC, a 1.5% volume fraction of polyamide fibers were used. The polyamide fibers had a length of 30.28 mm and a diameter of 2.31 mm. The tensile strength of the polyamide fibers was 650 MPa. All of the reinforcing bars had a nominal yield strength of 400 MPa.

2.2 Test Setup

All of the specimens for an axial tension test had a cross section of 270 mm by 270 mm, and a length of 3,000 mm. A single D41 steel bar was provided in each specimen. The load was applied to the steel reinforcing bar through a set of tension grips at the top and bottom, and therefore the applied load transferred from the steel reinforcing bar to the concrete section. Two linear voltage differential transducers (LVDTs) were placed between steel plates at both ends of the concrete to measure the total elongation of the concrete specimen.

Table I: Mix Details of the Concrete Used in Specimens

Mix proportions	Plain concrete	SFRC	PFRC
Cement (kg/m^3)	325.50	325.50	376.00
Water (kg/m^3)	162.75	162.75	188.00
Coarse aggregate (kg/m^3)	938.77	938.77	722.00
Sand (kg/m^3)	748.89	748.89	883.00
Coarse aggregate size (mm)	19	19	20
Fly ash (kg/m^3)	81.38	81.38	94.00
Water-reducing agent (kg/m^3)	2.60	3.66	-
Air-entraining agent (%)	0.15	0.15	0.2
Superplasticizer (%)	-	-	2.0
Viscosity agent (%)	-	-	0.15
Water/cement ratio (%)	40	40	40
Fibers (%)	-	1.0	1.5

2.3 Tension Responses

Fig. 1 shows the tension responses of the specimens. A slight increase in the initial stiffness and cracking load is observed in SFRC specimen. After cracking, both of the FRC specimens show more tension stiffening than the RC specimen. The significant post-cracking behavior is observed in the SFRC specimen. The FRC specimens have resistance after yielding of the reinforcing bar.

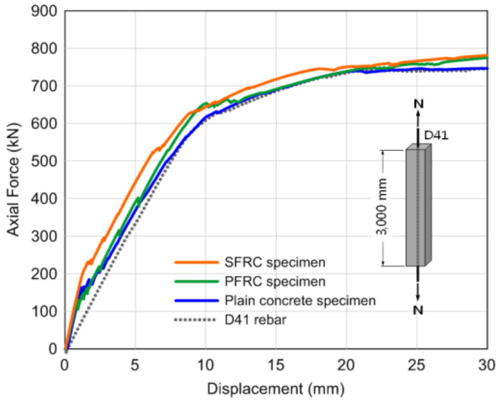

Fig. 1. Axial force versus displacement responses.

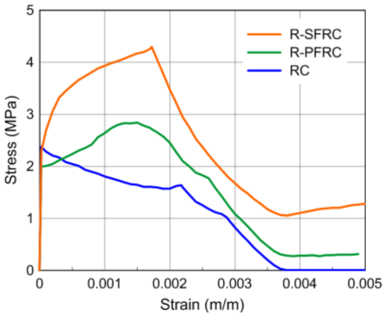

Fig. 2. Tension stiffening in different concretes.

3. Evaluation of Ultimate Pressure Capacity

3.1 Tension Stiffening Model

Based on the tension responses of the specimens, the tension stiffening behavior of three different types of concrete is derived, as shown in Fig. 2. After yielding of the reinforcing bar, tension stiffening in the conventional reinforced concrete (RC) members completely vanishes, but those in the reinforced-SFRC (R-SFRC) and reinforced-PFRC (R-PFRC) members remain because of a function of the fiber bridging.

3.2 Failure Criteria

To evaluate the ultimate pressure capacity of conventional PCCBs, a strain-based failure criterion of 0.8 percent is recommended using the US NRC Regulatory Guide 1.216 [1]. However, the strain limits for PCCBs constructed using R-SFRC or R-PFRC are not presented. In this study, failure criteria for those PCCBs are assumed. Plain concrete has a very low tensile strain capacity, while FRC has a high-tensile strain capacity, as shown in Fig. 3. This indicates that the average crack width is very small in FRC and high strain limits can be applicable to PCCBs constructed using FRC. Based on Figs. 2 and 3, conservatively, the strain limits for PCCBs constructed using R-SFRC and R-PFRC are assumed as 1.5% and 0.8%, respectively.

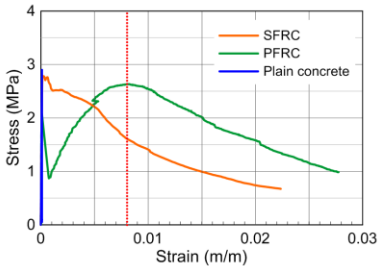

Fig. 3. Direct tensile stresses for different concretes.

3.3 Ultimate Pressure Capacity

The ultimate pressure capacity is evaluated for a PCCB of OPR-1000 type nuclear power plants. Even though the PCCB has been built using a conventional RC, we assumed that it is constructed using the R-SFRC and R-PFRC for comparison purposes only. The general-purpose finite element analysis program, ABAQUS [2], was used for internal pressure analyses. The analysis results are shown in Fig. 4 and Table II.

The ultimate pressure capacities for $\text{PCCB}_{\text{R-SFRC,1.0\%}}$ and $\text{PCCB}_{\text{R-PFRC,1.5\%}}$ were approximately 17% and 10% higher than that for a conventional PCCB, respectively.

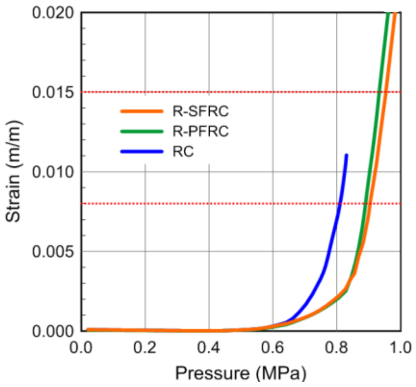

Fig. 4. Strain versus internal pressure for different PCCBs.

Table II: Ultimate Pressure Capacities for PCCBs

Type	Design pressure P_d (MPa)	Ultimate pressure P_u (MPa)	P_u/P_d
PCCB_{RC}	0.40	0.81	2.03
$\text{PCCB}_{\text{R-SFRC,1.0\%}}$	0.40	0.95	2.38
$\text{PCCB}_{\text{R-PFRC,1.5\%}}$	0.40	0.89	2.23

4. Conclusions

The effects of steel and polyamide fibers on the ultimate pressure capacity of a PCCB were investigated using the tension responses for uniaxial test specimens. It was revealed that the ultimate pressure capacity can be greatly improved by introducing steel and polyamide fibers in a conventional RC. When R-SFRC contains hooked steel fibers in a volume fraction of 1.0%, the ultimate pressure capacity of a PCCB can be improved by 17%. When R-PFRC contains polyamide fibers in a volume fraction of 1.5%, the ultimate pressure capacity of a PCCB can be enhanced by 10%. Further studies are needed to determine the strain limits acceptable for PCCBs reinforced with fibers.

Acknowledgement

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REFERENCES

[1] US NRC Regulatory Guide 1.216, Containment Structural Integrity Evaluation for Internal Pressure Loadings above Design-Basis Pressure, U.S. Nuclear Regulatory Commission, Washington, DC, USA, 2010.

[2] ABAQUS, ABAQUS/Standard 6.8 – User's Manual, Hibbitt, Karlsson & Sorensen, Inc., 2008.