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EVALUATION OF ULTIMATE PRESSURE AND SEISMIC CAPACITIES OF A PRESTRESSED CONCRETE CONTAINMENT VESSEL REINFORCED WITH STEEL FIBERS

Young-Sun Choun[1], Daegi Hahm[2], and Junhee Park[3]

[1] Principal Researcher, Integrated Safety Assessment Division, Korea Atomic Energy Research Institute, Daejeon, Republic of Korea (sunchun@kaeri.re.kr)
[2] Senior Researcher, Integrated Safety Assessment Division, Korea Atomic Energy Research Institute, Daejeon, Republic of Korea
[3] Postdoctoral Researcher, Integrated Safety Assessment Division, Korea Atomic Energy Research Institute, Daejeon, Republic of Korea

ABSTRACT

Steel fibers have been used for a cement mixture to improve the material properties such as toughness, ductility, and tensile strength, and to enhance the cracking and deformation characteristics. Therefore, the addition of steel fibers into a conventional reinforced concrete can enhance the structural and functional performance of safety-related concrete structures in nuclear power plants. The effects of steel fibers on the ultimate internal pressure and seismic resisting capacities of a prestressed concrete containment vessel are investigated. The material properties of steel fiber reinforced concrete are briefly discussed, and the tension and cyclic behaviors of structural members and walls are investigated. For a prestressed concrete containment vessel reinforced with a 1% volume hooked steel fiber, increases of approximately 12% and 64% were estimated for the ultimate pressure capacity and maximum lateral displacement, respectively.

INTRODUCTION

Steel fiber reinforced concrete (SFRC) is a composite material made of plain concrete and discontinuous discrete steel fibers. SFRC fails in tension only when the steel fiber breaks or is pulled out of the cement matrix. Thus, steel fibers can provide additional strength in plain concrete. Plain concrete has a low tensile strength and a low strain capacity at fracture, whereas SFRC has a significant improvement in tensile strength and strain capacity. Because of this advantage, steel fibers have been used mainly to improve the behavior of structural members for serviceability issues (De Montaignac et al. (2012)). Nowadays, SFRC is mostly applied in the field of industrial floor and tunnel constructions, and is also suggested for a partial stirrup or punching reinforcement in reinforced concrete (RC) beams and plates, respectively, or even a complete substitution of conventional steel reinforcements in flat slab construction (Michels et al. (2013)).

The addition of steel fibers into a cement mixture or plain concrete improves the material properties such as flexural toughness, impact resistance, and flexural fatigue endurance, and increases the structural performance of concrete structures. The use of steel fibers in RC beams provides more uniformly distributed and smaller cracks in the bending portion. Also, steel fibers improve the shear strength of plain concrete in beams. With sufficient amount of steel fibers the failure mode can be changed from shear failure to bending failure. In conventional RC members, the addition of steel fibers provides not only an increase of shear capacity but also a substantial post-peak resistance and ductility (Balázs, G. L. and Kovács, I. (2004)). A higher fiber dosage involves a higher post-cracking strength (Michels et al. (2013)). Eventually, steel fibers can be effectively used where high impact resistance is required because they provide large ductility and energy absorption capacity. RC members generally show a more rapid deterioration in shear resisting mechanisms under a reversed cyclic load compared to elements subjected to monotonic or cyclic loading in only one direction (Parra-Montesinos et al. (2004)). The use of high-performance fiber-reinforced cement composites provides excellent damage tolerance under large displacement reversals compared with regular concrete (Canbolat et al. (2005)).

A large number of previous experimental investigations indicate that the use of steel fibers in concrete can enhance the structural and functional performance of prestressed concrete containment vessels (PCCVs) in nuclear power plants. A prevention of through-wall cracks and an increase of the post-cracking ductility will improve the ultimate internal pressure capacity, and a high shear resistance under cyclic loadings will increase the seismic resisting capacity. In this study, the ultimate pressure and seismic capacities of a PCCV constructed with reinforced-SFRC (R-SFRC) are evaluated based on experimental results. For an understanding of the material properties of SFRC, the effects of steel fibers on concrete properties are briefly discussed. Experimental programs for investigating the tension responses and shear behaviors of R-SFRC members are addressed. Also, the responses of R-SFRC members are compared with those of RC members.

MATERIAL PROPERTIES OF SFRC

The mechanical properties of SFRC are influenced by the type of fiber, aspect ratio (length-to-diameter ratio), the amount of fiber, the strength of the matrix, the size and shape of the specimen, and the size of the aggregate. Fibers influence the mechanical properties of concrete in all failure modes, especially those that induce fatigue and tensile stress, e.g., direct tension, bending, impact, and shear. The strengthening mechanism of fibers involves the transfer of stress. Stress is shared by the fiber and matrix in tension until the matrix cracks, and then the total stress is progressively transferred to the fibers (ACI (1988)). In general, steel fibers improve the ductility of concrete, but their effectiveness varies in compression, tension, shear, torsion, and flexure (ACI (2001)). The following is a brief summary of the mechanical properties of SFRC (ACI (1988), ACI (2001)).

Compression

The effect of steel fibers on compressive strength of concrete varies. The ultimate strength of concrete is slightly affected by the presence of fibers. Increases in the compressive strength of SFRC are about 0% to 15% for up to 1.5% by the volume of fibers. The improved toughness in compression imparted by fibers is useful in preventing a sudden and explosive failure under static loading, and in absorbing energy under dynamic loading.

Direct Tension

The strength of an SFRC in direct tension is generally of the same order as that of plain concrete. However, its toughness can be one to two orders of magnitude higher, primarily because of the large frictional and fiber bending energy developed during fiber pullout on either side of a crack, and because of a deformation at multiple cracks when they occur. The tensile strength of SFRC increases on the order of 30% to 40% for the addition of 1.5% by the volume of fibers. Increases in the tensile strength depend greatly on the distribution of fibers, i.e., large increases for fibers uniformly oriented in the direction of the tensile stress, while slight increases for randomly distributed fibers.

Shear and Torsion

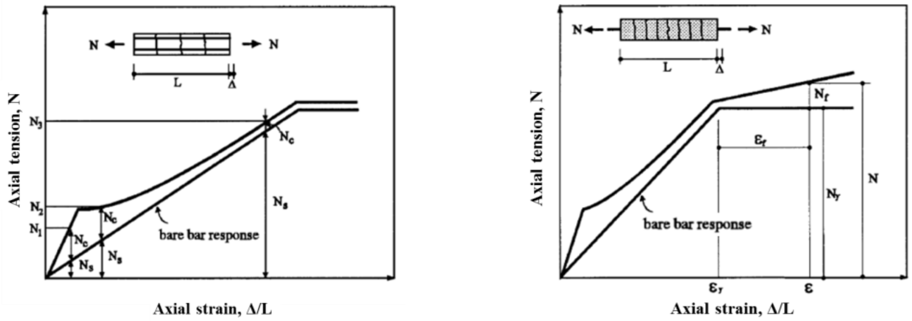
Steel fibers generally increase the shear and torsional strength of concrete. Under pure shear, the strength of SFRC increases from 0 to 30% for 1.0% by the volume of fibers. The inclusion of steel fibers in RC beams results in a substantial increase in the shear strengths. When a 1.0% volume fraction of fibers was used, an increase of up to 170% was observed in the ultimate shear strength (Narayanan and Darwish (1987)).

Flexure

Increases in the flexural strength of SFRC are substantially greater than in tension or compression. The flexural strength of SFRC was shown to be about 50 to 70% more than that of the unreinforced concrete matrix in a normal third-point bending test. The use of higher fiber volume fractions will produce greater increases up to 150%, whereas at a lower fiber volume, a significant increase in flexural strength may not be realized.

TENSION STIFFENING IN R-SFRC MEMBERS

The main advantage of using steel fibers in concrete is to enhance the post-cracking response. After cracking, the concrete between the cracks carries tension in a reinforced concrete member subjected to tension. This stiffening effect after cracking (referred as "tension stiffening") can significantly increase in the SFRC because fibers can carry tensile force at the cracks. The increased tension stiffening leads to reduced crack widths and crack spacing (Abrishami and Mitchell (1997), Bischoff (2003)). .



(a) RC member (b) R-SFRC member

Figure 1. Typical responses of RC and R-SFRC members in tension (Abrishami and Mitchell (1997)).

Figure 1 shows typical tension responses of RC and R-SFRC members, and the response of a bare bar. The axial tension is carried by the steel reinforcement and concrete in a RC member, and by the steel reinforcement, the concrete, and the fibers in an R-SFRC member. Beyond cracking the tension in the concrete, N_c, reduces but stiffens the response. After yielding of the reinforcing bar, a large strain occurs at the crack location. Hence, the reinforcement must carry all the tension at the crack location for the RC member, while the steel fibers participate in carrying the load across the cracks for the SFRC member. The steel fibers in SFRC enable tension stiffening after yielding of the bar.

Because the reinforcing steel bars, which are used for the construction of a PCCV in NPPs, have larger diameters, the tension responses and tension stiffening models used in this study were obtained from experimental results.

Tension Specimens

All of the specimens 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 a both ends of the concrete to measure the total elongation of the concrete specimen.

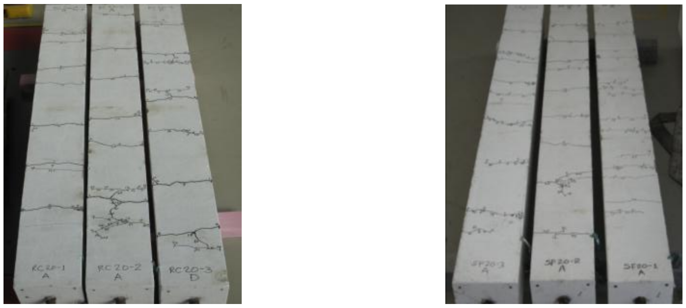
Concrete mixes with compressive strength of 42 MPa are given in Table 1 for the plain and fiber concretes. The compressive strength values at the time of testing were approximately 40.23 MPa in plain concrete and 44.67 MPa in fiber concrete. For the fiber concrete, a 1.0% volume fraction of hooked-end steel fibers were added. The 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 fibers was 1,100 MPa. All of the reinforcing bars had a nominal yield strength of 400 MPa.

Table 1: Mix details of the concrete used in specimens.

Mix proportions (kg/m^3)	Plain concrete	Fiber concrete
Cement	325.50	325.50
Water	162.75	162.75
Coarse aggregate (19 mm)	938.77	938.77
Sand	748.89	748.89
Fly ash	81.38	81.38
Steel fibers	-	79
Water-reducing agent	2.60	3.66
Air-entraining agent	0.15	0.15

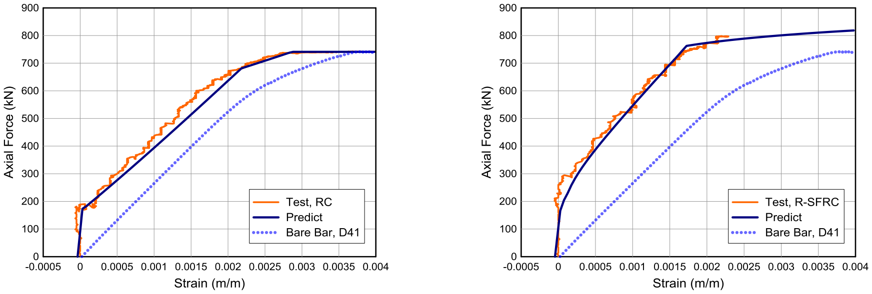
Tension Responses

Figure 2 shows crack patterns in RC and R-SFRC specimens after axial tension test. In all of the R-SFRC specimens, the transverse cracks were smaller and more closely spaced than the RC specimens, and no splitting cracks occurred. Figure 3 shows tension responses of RC and R-SFRC specimens and their prediction models used for numerical analyses. Also shown in this figure is the response of a bare bar.



(a) RC specimens (b) R-SFRC specimens

Figure 2. Crack patterns in tension specimens constructed with RC and R-SFRC.



(a) RC specimen (b) R-SFRC specimen

Figure 3. Tension responses and predict models for RC and R-SFRC specimens.

As can be seen, a slight increase in initial stiffness and cracking load is observed in an R-SFRC specimen. After cracking, the R-SFRC specimen shows more tension stiffening than the RC specimen because the reinforcing bar must carry all of the tension at the crack location in the RC specimen while the rebar and fibers share the tension in the R-SFRC specimen. It is also shown that the response of the RC specimen follows that of the bare bar after yielding of the rebar, whereas the R-SFRC specimen can carry loads greater than the yield load of the bare bar.

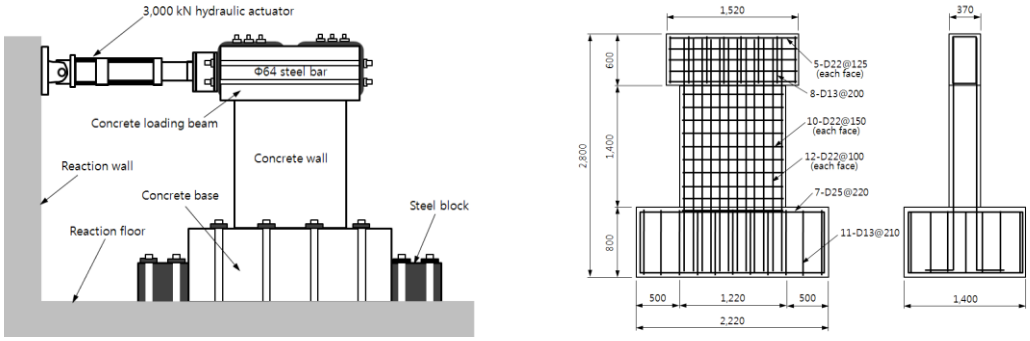
SHEAR BEHAVIOR OF AN R-SFRC STRUCTURAL WALL

The use of steel fibers in high-performance cement composites increases the displacement capacity of low-rise structural walls (Parra-Montesinos et al. (2004)). If steel fibers in conventional concrete have an equivalent effect in shear response, it is likely that a minor damage would occur after a large earthquake in R-SFRC walls. In this study, an experimental investigation on the shear behavior of R-SFRC structural walls under a reversed cyclic loading was conducted.

Test Setup and Wall Specimens

Figure 4(a) shows the test setup for the cyclic tests of structural walls. Lateral displacements were applied through a 3,000 kN hydraulic actuator connected to the loading beam of a specimen at one end and a strong reaction wall at the other end. The specimen consists of a loading beam, wall, and base. Figure 4(b) shows the dimensions and reinforcement details of the wall specimens. The height-to-width ratio of the wall is 1.15. Two RC materials were used for the specimens: 1) normal RC with a compressive strength of 42 MPa, 2) SFRC having a compressive strength of 42 MPa and containing a 1.0% volume hooked steel fiber with a diameter of 0.5 mm, length of 30 mm, and tensile strength of 1,100 MPa. Mix details of concrete are shown in Table 1. All of the reinforcing bars had a nominal yield strength of 400 MPa.

The wall specimens were subjected to a displacement loading history of the reversed cycle tests as shown in Figure 5. Two cycles were applied to each drift up to 3.5% for investigating the degradation in strength and stiffness during repeated cycles.



(a) Test setup (b) Specimen details

Figure 4. Test setup and details of shear wall specimens.

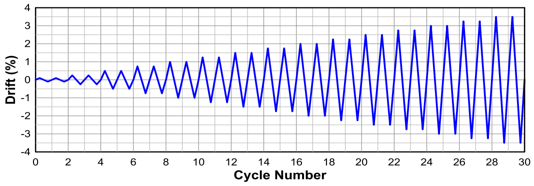


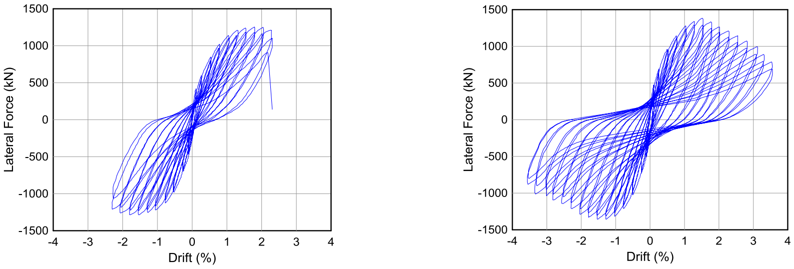
Figure 5. Displacement loading history for reversed cyclic tests.

Drift Hysteresis Responses

Figure 6 shows the cracking patterns at drift levels of failure: a 2.25% draft in a RC specimen, and a 3.5% drift in an R-SFRC specimen. As can be seen, the failure mechanism in the RC and R-SFRC specimens was totally different. The RC specimen exhibited a mixed failure mode of diagonal tension and diagonal compression, whereas the R-SFRC specimen exhibited a sling shear failure mode. The lateral force versus drift response of the two specimens is shown in Figure 7. The R-SFRC specimen, which contains steel fibers at a 1.0% volume fraction, has a larger lateral force, draft capacity, and energy dissipation than the RC specimen. It was revealed that the addition of steel fibers in a RC wall can enhance its shear resisting capacity significantly.

(a) RC specimen at 2.25% drift (b) R-SFRC specimen at 3.5% drift

Figure 6. Cracking pattern at failure drift level in RC and R-SFRC specimens.



(a) RC specimen (b) R-SFRC specimen

Figure 7. Lateral force versus drift response of RC and R-SFRC specimens.

EVALUATION OF ULTIMATE PRESSURE AND SEISMIC CAPACITIES

Ultimate Pressure Capacity

The ultimate pressure capacity is evaluated for the KSNP (Korean Standard Nuclear Power Plant) type PCCV. Even though the KSNP type PCCV has been built using a conventional RC, in this study, we assumed that it is constructed using the R-SFRC for comparison purposes only. The proposed tension stiffening models for the RC and R-SFRC members are given in Figure 3. The analytical model of the PCCV is developed using the general-purpose FE analysis program, ABAQUS (2008). The behavior of concrete after experiencing damage is modeled using the concrete damaged plasticity model, which is a continuum, plasticity-based, damage model for concrete. For the modeling of the PCCV structure, the solid element, which is able to describe embedded tendons discretely using truss elements, is used. The 3-dimensional model of the PCCV includes large penetrations such as an equipment hatch and an airlock. Tendons are modeled discretely using truss elements. To simplify the modeling and analysis procedure, the slippage of a tendon within the tendon sheath is neglected so that the bond effect between the concrete and tendon steel is not considered in this study. The reinforcing bars are modeled using the embedded surface elements considering its reinforcement ratio. A strain-based failure criterion specified in US NRC Regulatory Guide 1.216 (2010) was used to evaluate the ultimate pressure capacity. Table 2 shows the estimated ultimate pressure capacities for the two PCCVs constructed by different concrete. The ultimate pressure capacity for a PCCV constructed with steel fibers at a 1.0% volume fraction ($\mathrm{PCCV}_{\text{R-SFRC,1.0\%}}$) was approximately 12% higher than that for a conventional PCCV ($\mathrm{PCCV}_{\mathrm{RC}}$).

Table 2: Ultimate pressure capacities for PCCVs.

Type	Design pressure P_d (MPa)	Ultimate pressure P_u (MPa)	P_u/P_d
$\mathrm{PCCV}_{\mathrm{RC}}$	0.40	0.81	2.03
$\mathrm{PCCV}_{\text{R-SFRC,1.0\%}}$	0.40	0.91	2.28

Seismic Resisting Capacity

For a seismic analysis, the PCCV was represented by a lumped-mass stick model, which has a different eccentricity between the mass center and rigidity center at each level of lumped masses. The mass of the model includes all of the mass of the walls, slabs, and heavy equipment. OpenSees (2006) was used for obtaining the structural response under a cyclic load. As a material model, the Hysteretic model of OpenSees was used to simulate a degradation of the strength and stiffness. For developing the envelope curve of the Hysteretic model, the ultimate tangential shear strength for PCCV was determined by an equation presented by Ogaki et al. (1981). The pinch factors for the Hysteretic model were derived based on the hysteretic response of walls under a reversal cyclic load, as shown in Figure 7. For the element modeling, the nonlinearBeamColumn element was selected from the OpenSees elements library, which adopts five Gaussian points for numerical integration.

Table 3 shows the response of PCCV models by the cyclic analysis. The maximum shear strength and lateral displacement for a $\mathrm{PCCV}_{\text{R-SFRC,1.0\%}}$ were approximately 8% and 64% greater than those for a $\mathrm{PCCV}_{\mathrm{RC}}$, respectively. The energy dissipation capacity was approximately 347% larger in a $\mathrm{PCCV}_{\text{R-SFRC}}$. For a $\mathrm{PCCV}_{\text{R-SFRC}}$, the increase is slight in the maximum shear strength, but significantly large in the maximum lateral displacement and energy dissipation capacity.

Table 3: Maximum resisting capacity of PCCVs for a lateral force.

Type	Maximum shear strength (MN)	Maximum lateral displacement (mm)	Energy dissipation capacity (MN-mm)
$\mathrm{PCCV}_{\mathrm{RC}}$	1,052	568	2,064,648
$\mathrm{PCCV}_{\text{R-SFRC,1.0\%}}$	1,137	932	9,228,603

CONCLUSION

The addition of fibers into a conventional concrete can improve its toughness and ductility, and enhance the cracking and deformation characteristics of the structures. The effects of steel fibers on the ultimate pressure and seismic resisting capacities of a PCCV are investigated. For a PCCV constructed by R-SFRC, tension stiffening and shear hysteresis models are developed based on the results from direct tension and reversed cyclic load tests for the R-SFRC structural members and walls.

In the R-SFRC members under a direct tension, the transverse cracks are smaller and more closely spaced than in the RC members. More tension stiffening is obtained in the R-SFRC members after cracking of concrete. Also, they can carry loads greater than the yield load of the bare bar. Under a reversed cyclic load, the failure of an R-SFRC wall is governed by a sling shear, whereas the failure of a RC specimen is governed by a diagonal tension and a diagonal compression. A large shear strength, draft capacity, and energy dissipation are obtained in an R-SFRC wall.

It is revealed that both of the ultimate pressure capacity and the seismic resisting capacity of a PCCV can be greatly enhanced by introducing steel fibers in a conventional RC. Estimation results indicate that the ultimate pressure capacity and maximum lateral displacement of a PCCV can be improved by 12% and 64%, respectively, if a conventional RC contains hooked steel fibers in a volume fraction of 1.0%.

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