Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 9-10, 2024

Analysis of scaled down model of RCCV and PCCV under internal ANFO explosion

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***Keywords:** i*nternal blast, reinforced concrete, RCCV, PCCV, stiffness, blast safety

1. Introduction

Concrete is a common construction material used in both military and infrastructures. Those of structures should be designed to resist extreme accidents such as bomb attack, aircraft collision, and car crash. Also, rapid industrial development and urbanization, not only containment vessels or infrastructures but civilian structures such as government buildings, commercial centers, residential apartments, and industrial facilities can be a target for terrorist attacks. These terrorist attacks can cause significant structural damage, casualty and economic loss.

Conventional reinforced concrete (RC) column, beam and slab, as major load carrying components, are often damaged when subjected to extreme accidents such as bomb attack, aircraft collision, and car crash, which might lead to partial or whole collapse of building and infrastructures.

To overcome natural weakness of RC concrete structure in tension and the growth of cracks, prestressed technique is employed in both military constructions and infrastructures. Prestressed concrete (PSC) may increase structural stiffness and crack-control performance [1-3].

As extreme loading accidents such as explosion and collision have frequently occurred all over the world, the need for blast and impact protection design of RC and PSC structures against explosion and collision accidents is increasing. Early research about blast effect on structures began in the United States after World War Ⅱ. Blast load on structures research is still ongoing and now includes the issue of design and retrofit of infrastructures [4] (Landry, 2003). However, most studies have analyzed the behaviour of outer walls of military structures and infrastructures according to blast and impact loads. In addition, the structural design of the existing infrastructures such as RC containment vessel (RCCV), PSC containment vessel (PCCV) and LNG tanks for internal explosion accidents was not presented.

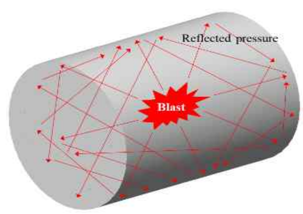
Therefore, in this study, a scaled down model of a RCCV and PCCV was designed and fabricated for internal ANFO blast test. Then, the test data are obtained to be used for RCCV and PCCV model calibration for internal blast structural simulation. With the calibrated model, numerical simulations of scaled down model of RCCV and PCCV to blast loadings are carried out by considering varied prestressing levels, different concrete compressive strengths and charge of ANFO blast weights. The results of mid-span maximum deflection, maximum deflection at the maximum location where the blast pressure is applied, and crack pattern of scaled down models of RCCV and PCCV were used to calculate structural stiffness and allowable maximum blast pressure.

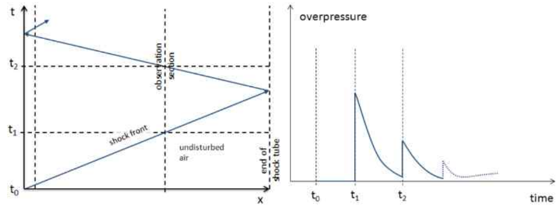
2. Test Method and Details

In this section, author would like to present the basic idea of RC concrete specimen for internal blast. The author would like to present experimental data on the internal blast method and scaled down models of RCCV and PCCV under internal ANFO blast loads as results.

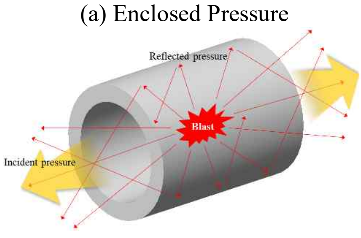
2.1 Concept of Internal Blast Loading

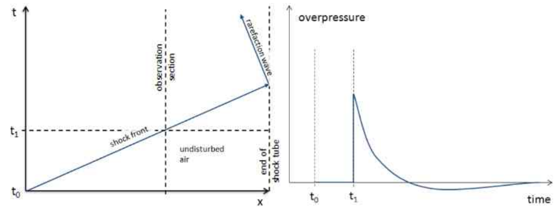
As shown in Fig. 1(a), if an internal blast occurs in a fully enclosed RCCV, data acquisition is nearly impossible, due to reflecting blast pressures inside the structure destroying the pressure gauges and strain sensors attached to the inner surface. Therefore, in this study, the internal blast was detonated inside of a semi-open specimen as shown in Fig. 1(b). The opening allowed a partial release of the internal blast pressure to control the pressure magnitude to be able to obtain pressure data. The blast pressures which were released to the left and right open ends of the specimen were measured by incident pressuremeters placed at a certain distance from the opening while the reflected pressure inside of the specimen was measured by a reflected pressuremeter attached to the inner section.





(a) Enclosed Pressure





(b) Semi-Open Pressure

Fig. 1 Schematic drawing of internal blast pressure propagation

2.2 Internal Blast Loading Scenario

An internal blast scenario of a charge explosion due to unidentified explosive installation or mechanical device failure inside the containment vessel structure was used for this study. The average blast pressure (P_r) and average unit impulse ($i_r/W^{1/3}$) were calculated based on TM5-1300 (UFC 3-340-02) [5]. The explosive pressure load was estimated from the data obtained from the experiment. Because the pressure was bouncing multiple times in the enclosed space, pressure considered in the analysis is based on only the pure initial blast pressure reaching the inner surface. In this study, ANFO explosive that discharges only pure blast pressure was used as blast charge in the test.

2.3 Test specimen details

Test specimens were modeled and designed based on a target structure of RCCV of Kori 1 and 2 NPP and PCCV of APR-1400 (Korea Standard Nuclear Reactor (KSNR) with a 1.4 million KWe generation capacity. The RCCV was designed as a RC structure with a service life of 40 years and APR-1400 PCCV is designed as a post-tensioned PSC structure with a service life of 60 years (Dameron et al, 1989, Dunham et al., 1985, Amin et al., 1993).

The actual RCCV and PCCV consisted of a tubular wall and an elliptical dome. The primary design feature of the PCCV is the arrangement of bi-directional PS tendons in vertical and meridional directions in the wall and triple-directional PS tendons in the dome. The outer wall has three buttresses to anchor the unbonded tendons for partial overlapping at 240°. The hoop and vertical tendons should be located between the outer and inner rebars of the wall and the vertical tendons should be arranged so that they pass through the center of the wall. It is structurally advantageous to place the hoop tendons closer to the exterior than the vertical tendons and outermost surface of the wall.

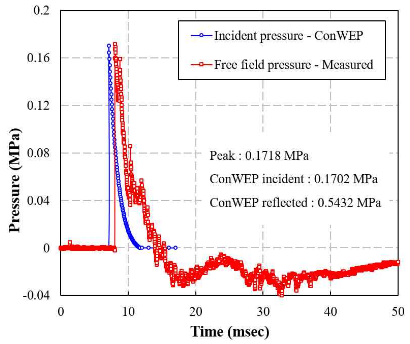
For the RCCV wall, the reinforcement ratio was 0.024 and design concrete compressive strength was 41.37 MPa. For the PCCV wall, the reinforcement ratio and design concrete compressive strength were same as RCCV wall, tendon ratio is 0.0107, which gives a 10% higher PS force than conventional PCCV. Outer and inner diameter of the RC and PSC tubular specimens was 2,700 mm and 2,000 mm, respectively, as shown in Fig. 2. The wall thickness was 350 mm and the longitudinal tube length was 3,600 mm. The tube thickness was designed with a required minimum concrete cover thickness of 50 mm. Four RC specimens were blast tested using ANFO charge of 15.88, 20.41, 22.68, and 24.95 kg, which were titled as RC35, RC45, RC50, and RC55, respectively. Also, five PSC specimens were blast tested using ANFO charge of 22.68, 24.95, 27.22, 29.48, and 31.75 kg, which were titled as PSC50, PSC55, PSC60, PSC65, and PSC70, respectively.

3. Internal Blast Analysis results

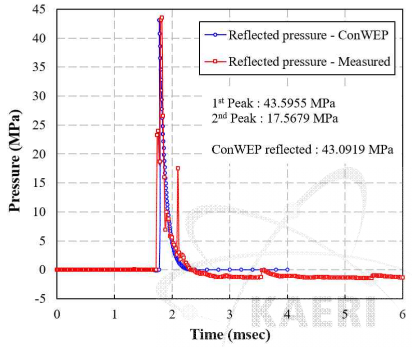
Free field pressure, deflection, strain, and environmental condition data for RC35, RC45, RC50, and RC55 are tabulated in Table. 1. As shown in the table, when the blast charge weight increased, the magnitude of all of the data increased. For example, when the weight of explosive charge increased from 15.88 kg to 24.95 kg, the peak incident pressure and deflection stabilization time duration increased from 0.1718 to 0.3394 MPa and from 5.856 to 5.981 msec, respectively.

3.1.1. Incident and Reflected Blast Pressure

Fig. 4 shows the free-field incident and internally reflected pressure in relation to the time of the ANFO 15.88 kg charge detonation measured from the pressuremeter at a distance of 7,000 mm from the mid-span. For RC35, the measured peak measured pressure was 0.1718 MPa and the impulse was 0.3601 MPa-msec. ConWEP calculated incident peak pressure was 0.1702 MPa and the impulse magnitude was 0.1718 MPa-msec The trend of ConWEP calculated incident pressure was similar to the test pressure. However, ConWEP calculated impulse pressure was 109.60% lower than RC35 test data. As shown in Fig. 4(b), the measured reflected pressure of RC35 was approximately 2 MPa higher than ConWEP calculation. The difference between the measured and calculated results is likely due to ConWEP being an external blast pressure calculating program, which is unable to consider internal reflections and interactions of various types of the internal blast pressures.



(a) Incident pressure



(b) Reflected pressure

Fig. 4 Blast pressure results of RC35

3.1.2. Time-Deflection Relations

For RC50, the maximum and residual deflection at the mid-span was 15.27 and 6.62 mm, respectively. In RC50, the deflection behavior was a cyclic type due to repeated application of reflected pressures to the interior surface of the specimen. As shown in Fig. 5, plastic deflection occurred in RC50 due to the damage of the wall from the initial direct blast pressure.

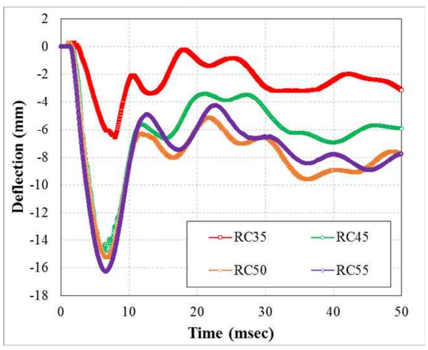
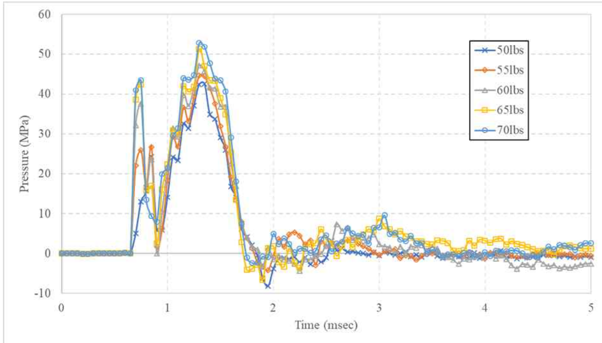


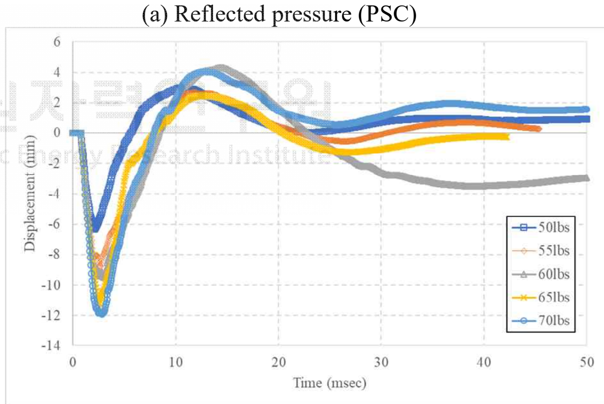
Fig. 5 Time-deflection curves of specimens (RC)

The results indicated that RC35 had a much smaller residual deflection than the other specimens. Based on the residual deflection results, it is safe to assume that RC35 behaved primarily in an elastic manner with minor plastic deflection, while other specimens were catastrophically damaged by the blast, resulting in large residual deflections.

Also, in Fig. As shown in Figure 6, the size of the reflected pressure acting on the wall of the structure and the size of the deflection at the LVDT installation location gradually increased as the explosion amount increased.



(a) Reflected pressure (PSC)



(b) Time-deflection curves of specimens (PSC)

Fig. 6 Blast pressure results of PSC specimen

3.2 Structural Stiffness Analysis According to Explosive Charge Weight

As shown in Fig. 5, the maximum deflection was much larger in RC45 than RC35. It is safe to conclude that the specimen subjected to an internal blast charge weight exceeding 15.88 kg caused a structural tensile failure, in which the specimen could not resist the load and induced plastic deformation.

Based on the observation, the following equations can be derived. The correction factor ($\gamma=\frac{1}{\alpha}$) of an internal blast compared to an external blast can be expressed by Equation (1) through a maximum internal blast force (F_{max}), a wall stiffness (K) of the tube structure, and a wall deflection (U_{max}).

(1) $$F_{max} = \alpha(K \cdot U_{max})$$

where $K=K_{el}+K_{pl}$ and $U_{max}=U_{el}+U_{pl}$ with the subscript el and pl denoting elastic and plastic, respectively. It is important to note that γ value has to be greater than 1.0, since an internal blast creates larger pressure magnitude due to the reflection effect of enclosed space compared to an external blast. The maximum applied force and deflection is compared for both elastic and plastic behaviors. As shown in Fig. 6, it is assumed that the majority of the internal blast pressure was applied primarily to the left and right of the mid-span equaling a distance of $2r_{internal}$, equivalent to 2,000 mm for this test. If K and U_{max} are substituted into Equation (1), then the equation becomes as follows.

$$(2)\ \gamma F_{max} = (K_{el} \cdot U_{el} + K_{pl} \cdot U_{pl})$$

The correction factor for the pressure γ of the internal blast loading can be calculated by calculating α by inputting the initial peak pressure values into Equation (2) with the values of K_{el}, K_{pl}, U_{el}, and U_{pl} to obtain γ value. Then, γ is multiplied to P_{max} to reflect the increase in the failure load data of the RC tubular specimens. The correction factor of γ_{35}, γ_{45}, γ_{50}, and γ_{55} are approximately 2.00, 1.37, 1.33 and 1.22, respectively. It has been verified that the structural resistance of RC tubular structure to internal blast loading has a bi-linear behavior with an initial elastic behavior followed by a plastic behavior. Also, by implementing the internal blast correction factor γ, the plastic stiffness showed almost horizontal plastic behavior.

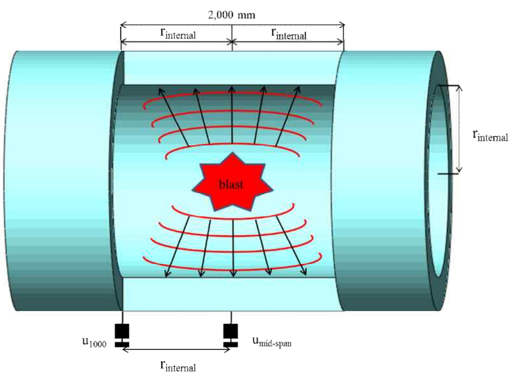


Fig.7 Internal blast analysis model

Normally, it is nearly impossible to calculate or measure the structural stiffness coefficients for RC members under blast loading. However, in this study, because the pressure and deflection of the RC tubular specimens were measured from the test, K_{el} and K_{pl} could be obtained from the regression plot of F versus U test data as shown in Fig. 7. From the Fig. 7 , a drastic and distinct change of slope of the curve is observed. Between RC35 and RC55, the stiffness changed due to residual plastic deflection.

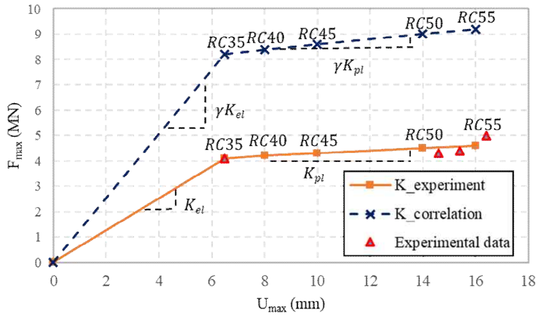


Fig. 8 Comparison of experiment and correlation K value according to specimen

4. Conclusions

In this study, the internal blast resistance capacity and stiffness of RC tubular structure were evaluated by fabricating a scaled-down model of a RCCV and conducting an experiment. The effect of the charge weight depend internal blast pressure on damage to the RC specimen was evaluated by varying the explosive charge weight from 15.88 kg to 24.95 kg. The following conclusions can be drawn from the study.

(1) A RC tubular structure was fabricated by scaling down a RCCV structure to apply internal blast loading scenario. Using the scaled down specimen, the internal ANFO explosive charge weight of 15.88, 20.41, 22.68, and 24.95 kg was applied to the test. The blast test data of pressure, deflection, strain, and crack pattern were obtained. In addition, a system for precise data acquisition was proposed

(2) Specimens of RC35, RC45, RC50, and RC55 according to the amounts of explosive charge weight were designed and tested. Maximum deflection of RC35, RC45, RC50, and RC55 specimen were 6.57, 14.67, 15.27, and 16.25 mm, respectively. Also, residual deflection data were obtained according to the explosive charge weight. The test data were used to calculate elastic and plastic structural of stiffness of the specimen center internal blast load, which gave the result of 0.65, and 0.05 N/mm, respectively. Since the test specimen and the real scale RCCV used exactly the same material for construction, rebar ratio and cross-sectional design, specimen and RCCV have to be same.

(3) The pressuremeter data suggest that there were multiple peaks in behaviour of the RC tubular structure from an internal blast loading. Therefore, a more in-depth evaluation of the time dependent pressure behavior from internal blast loading in real-scale RCCV structures is needed in the future.

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