Structural Stiffness Analysis of Scaled-down Reinforced Concrete Containment Vessels under Internal Blast Loading

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1. Introduction

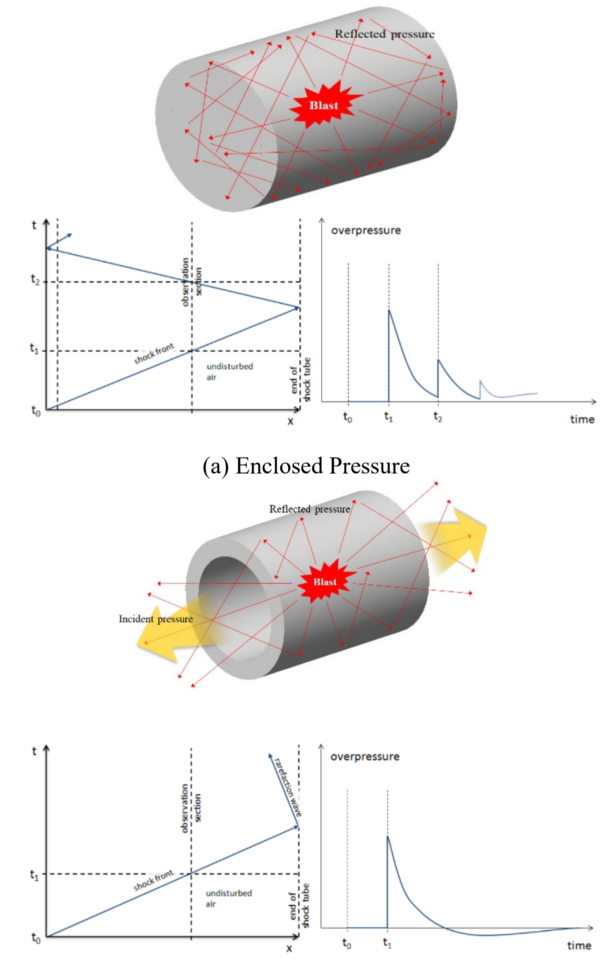
Reinforced concrete (RC) is a most widely used structure type for construction of buildings and infrastructure. When an extreme load such as blast and impact is applied to a RC structure, its resistance depends greatly on its stiffness and load bearing capacity. The degree of structural damage is significantly more severe when a blast occurs inside than outside of a structure. Also, during an internal blast test, internal blast pressure measurement is nearly impossible since pressure gauges installed inside the enclosed space are damaged by the reflected blast pressures. For this reason, there is very limited number of test data available on internal blast characteristic and its structural effect. [1-3] However, existing designs for RC structures such as reinforced concrete containment vessels (RCCVs) do not include design features to protect the structure for internal blast. [4-6] The only meaningful study to date on internal loading of RCCV was performed at Sandia National Laboratory (SNL) in the U.S., in which experiments are conducted on 1/4 and 1/3 scale steel containment vessel and PCCV, respectively, by applying slow internal pressure buildup loading. [7] Therefore, the internal blast resistance capacity of RC structures is evaluated by performing internal blast tests on RC tubular structures. The main objective of the study was to observe and document the basic structural behavior data obtained from internal blast loading tests. In this study, a scaled down model of a RCCV was designed and fabricated for internal blast test. Then, the test data are obtained to be used for RCCV model calibration for internal blast structural stiffness

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 RC tubular specimen 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). [3] 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 Internal Blast Loading Test Set-up

Test specimens were modeled and designed based on a target structure of RCCV of Kori 1 and 2 Nuclear Power Plant (NPP). For the RCCV wall, the reinforcement ratio was 0.024 and design concrete compressive strength was 41.37 MPa. The tubular specimens without the dome and lining plate were fabricated by scaling down the wall thickness while applying the same reinforcement ratio and target concrete compressive strength as the original structure.

In this study, the test specimens were fabricated for the internal blast test except that a scaled down RC tubular structure with two open ends. Four RC specimens were blast tested using ANFO explosive charge of 15.88, 20.41, 22.68, and 24.95 kg, which were titled as RC35, RC45, RC50, and RC55, respectively.

Outer and inner diameter of the RC 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. A RCCV is normally designed to have a 6 mm thick steel liner plate to prevent radiation leakage in case of malfunction of a nuclear reactor. However, in this study, the liner plate was not incorporated to the specimen to focus solely on concrete behavior under internal blast loading. As shown in Fig. 2, D13 Rebar were arranged in a grid configuration with a spacing of 100 mm and a unit weight of 1,101 kg/m.

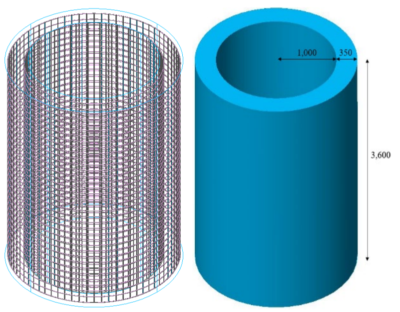


Fig. 2 Rebar and specimen details (unit: mm)

As shown in Fig. 3, a frame structure with a clearance of 1,000 mm from the ground surface was used to support the specimen. The tubular specimen with a weight of 2,600 kg was mounted on the support frame and tightened at both ends using 100 mm sling wire, chain block, and fastening buckle to maintain full contact between the specimen and the support frame throughout the test.

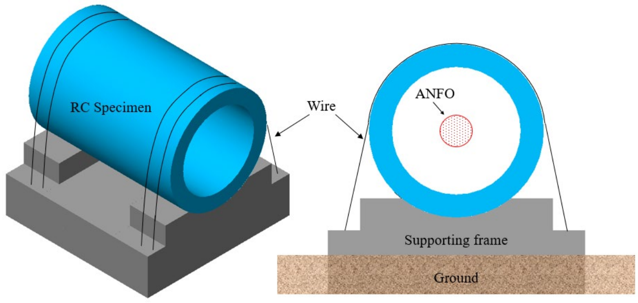


Fig. 3 Details of supporting frame

3. Test Result Discussion and Analysis

3.1 Internal Blast Loading Test Results

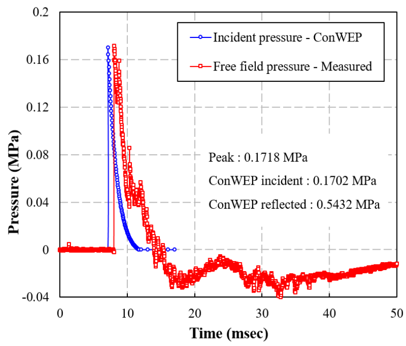
Free field pressure, deflection, strain, and environmental condition data for RC35, RC45, RC50, and RC55 are tabulated in Table. 1. As shown in the table, when the blast charge weight increased, the magnitude of all of the data increased. For example, when the weight of explosive charge increased from 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.

Table 1. Summary of RC specimen test results

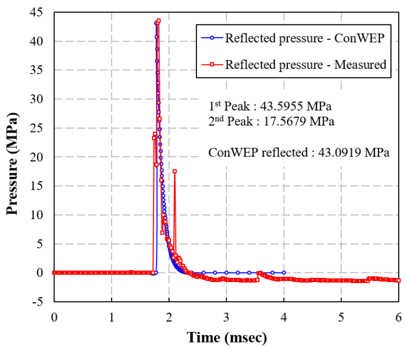
Value			RC35	RC45	RC50	RC55
Free field pressure	Peak pressure (MPa)		0.172	0.297	0.317	0.339
	Duration (msec)		5.981	5.856	5.826	5.881
	Impulse (MPa-msec)		0.360	0.379	0.387	0.444
Deflection (mm)	Maximum	Mid-span (0°)	6.57	14.67	15.27	16.25
		Mid-span (90°)	3.95	7.39	4.76	11.29
		1,000 mm	5.58	8.13	7.71	8.64
	Residual (Mid-span 0°)		2.87	7.02	7.84	8.44
Strain (με)	Rebar longitudinal	Maximum	536.84	908.24	1,476.31	1,487.70
		Residual	228.31	57.24	228.23	641.07
	Rebar lateral	Maximum	3,134.85	16,419.32	20,986.06	21,897.05
		Residual	153.47	6,602.94	4,813.75	11,941.37
	Concrete	Maximum	59.75	169.22	755.56	760.17
		Residual	17.41	63.49	104.31	72.27
Environmental condition	Temperature (°C)		9.2	6.3	2.9	-6.0
	Rel Humidity (%)		45	41	16	31

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.

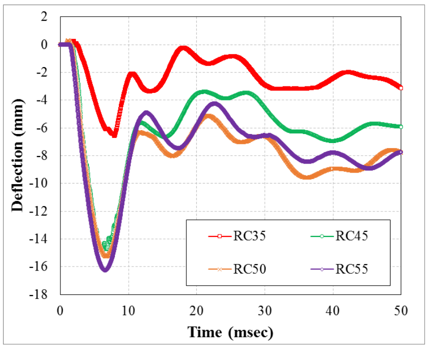


Fig. 5 Time-deflection curves of specimens

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.

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}).

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

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.

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

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.

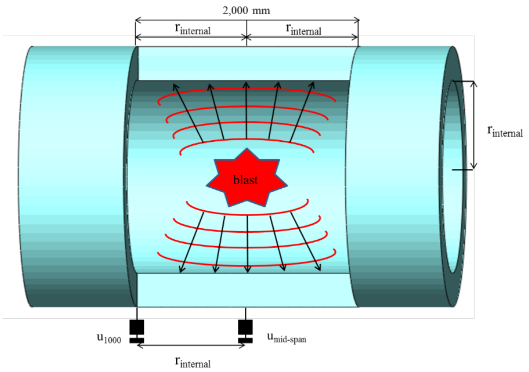


Fig. 6 Internal blast analysis model

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.

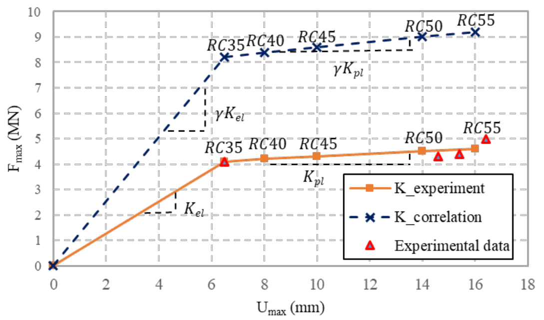


Fig. 7 Comparison of experiment and correlation K value according to specimen

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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