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Evaluation of blast resistance and failure behavior of prestressed concrete under blast loading

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HIGHLIGHTS

- The blast resistant capacities of unbounded bi-directional PSC are experimentally and numerically evaluated.
- The blast test procedure and measurement system are established and used to determine blast resistance capacity.
- The simulation model of prestressed concrete panel under blast loading is calibrated using the test data.
- The PSRC members had significantly better blast resistance than RC and PSC members.

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ABSTRACT

In recent years, frequent terror and military attack by explosion and impact have occurred all over the world. Particularly, World Trade Center collapse and US Department of Defense Pentagon attack on Sept. 11 of 2001 and Fukushima nuclear power plant accident due to Northeast earthquake tsunami on the coast of Japan on Mar. 11 of 2011 resulted in devastating human casualties and structural collapses. These terrors and accidents raised public concerns and anxiety of potential structural collapse of major infrastructures and structures. In order to better combat these problems, the extreme loading resistant structural studies are initiated. Among numerous types of target structures, one of the most important structural types is prestressed concrete (PSC), which is widely used for construction of nuclear containment vessel and gas storage tank. In this study, to evaluate the blast resistance and protective capacity of bi-directional PSC member, blast tests were carried out on 1400 × 1000 × 300 mm reinforced concrete (RC), prestressed concrete without rebar (PSC), prestressed concrete with rebar (PSRC) specimens. The applied blast load was generated by detonating 25 kg ANFO explosive charge at 1.0 m standoff distance. The data acquisitions included blast waves of incident pressure, reflected pressure, and impulse as well as behavioral displacements of deflection, acceleration, and strains of concrete, rebar, and PS tendon. Then, the blast test results are used to calibrate finite element simulation model. Once the simulation model is calibrated, it is used to perform parametric study on bi-directional prestressed concrete specimens to further evaluate the blast resistance of the panels. The study results are discussed in detail in the paper.

1. Introduction

1.1. Background

In recent years, explosions, collisions, and fires have occurred frequently around the world due to terror attacks and impact accidents. Particularly, since the 9.11 terror attacks on the World Trade Center and the Pentagon of the USA in 2001, public anxiety heightened due to lack of safety in our society. According to data published by the National Intelligence Service of Korea in 2009, 55.2% of terror incidents are related to infrastructures, which led to property damages and human casualties [1]. Especially, since the Korea peninsula is the only divided area in the world with unceasing military confrontations, South Korea has suffered various provocative aggressions from North Korea by means of infiltration, terror, provocations, and bombings for the past 63 years after the Armistice Agreement. Since the sinking of Cheonan Battleship of South Korea by the torpedo and cannon attacks of North Korea near the Coast of Yeonpyeong Island in 2010, public concerns of bombing and terror attacks have continuously increased. The aforementioned incidents can be viewed as representative

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examples of possible extreme loading scenarios that can occur for structures and infrastructures. Among all of structures and infrastructures, prestressed concrete containment vessels (PCCVs) and liquefied natural gas (LNG) storage tanks are the most vulnerable structures from terrors and accidents. For example, the public fear of nuclear accidents from nuclear containment vessel damages, which have great physical and environmental consequences, drastically increased since the Fukushima Daiichi nuclear disaster in 2011.

Generally, PCCVs and LNG storage tanks are constructed as bi-directional prestressed concrete (PSC) shell structure. Because of the vulnerability of these containment structures under extreme loading scenarios, various studies on physical and structural safety of PSC structures from extreme loading conditions have been conducted by researchers all over the world [2–10]. However, due to national security reasons, only minute number of blast experimental results on structural blasting have been disclosed or published in the past. Because of lack of published study results, no clear standards or specifications in the form of design codes of civil structures related to explosion protection and structural resistance design are available presently.

When a high strain rate inducing load such as blast or impact is applied to a PSC member, it is near impossible to capture the high strain rate behavior of the member and to obtain accurate test data. Also, due to expensive experiment cost and limited test site availability of blast or impact test, it is difficult to conduct sufficient number of experiments. Therefore, only feasible way to understand the damage behavior of PSC structural member is to study those using High Fidelity Physic Based (HFPB) simulations. In HFPB simulation, precise and accurate high strain rate representing loading conditions, material constitutive relations, detailed structural information, and boundary conditions must be used. Also, due to the high strain rate induced multiple time increment simulation, an explicit rather than implicit finite element analysis (FEA) must be performed. Most importantly, HFPB FEA simulation program has to be calibrated by the precisely controlled experimental results, or else the simulation results cannot be considered accurate. Therefore, in this study, a model blast test series is carried out by minimizing the variabilities that can exist in blast test, such as loading condition, structural details, material properties, and boundary conditions. The blast experiment is performed on bi-directional PSC member using 25 kg ANFO charge with a standoff distance of 1.0 m. The PSC specimen used in blast experiment is modeled as a PSC panel representing an outer wall of prestressed concrete containment vessel (PCCV). Also, the test setup is such that the panel is buried in the ground to only have a top surface directly exposed to the blast pressure to eliminate other reflected blast waves from hitting the specimen. Using the state-of-the-art high strain rate measurement system, the blast test results such as maximum and residual deflections, incident and near field blast pressures, high speed camera recorded deflection behavior, crack pattern, prestressing force loss, and specimen acceleration are obtained. The experimental data, such as fracture mode, energy absorption capacity, displacement, prestressing force variation, and acceleration measured from the blasted specimens are used to calibrate HFPB simulation code. After the calibration, the calibrated HFPB FEA simulation programs can be used to simulate and analyze real extreme loading scenarios of real scale PCCVs and LNG storage tanks.

1.2. Literature review

Numerous researches on the structural behaviors subjected to blast loads have been actively conducted. Study results on blast loading were conducted by Protective Design Center (PDC) in the US Army Corps of Engineers to develop ConWEP, for the calculating blast pressures from bomb explosions and to develop a simple single degree of freedom simulation program SBEBD for designing of protective structures in the 1990 s. Based on these findings, TM5-1300 technical manual was published to establish basic principles about disaster preventive technology for concrete structures and to implement these technologies in the designs. Under the supervision of the US Nuclear Regulatory Commission (NRC), Sandia National Laboratory of the US constructed a 1/6 and 1/4 scale model of a RC and PSC reactor containment structure, respectively, to experimentally evaluate their behaviors at ultimate load [3].

Ross et al. (1997) evaluated the behavior of beams and slabs under explosive loads, ANFO explosion experiments were carried out to determine the explosion resistance performance of concrete members [11]. Muszynski et al. (2003) experimentally evaluated blast behavior of RC members by applying explosive pressure to different reinforced concrete wall structures [12]. Morrill et al. (2004) examined the feasibility of the analytical method by comparing and analyzing the results of the finite element simulations and the deflection behavior of the concrete columns and walls from the explosion tests [13]. Davison et al. (2004) and Oesterle (2009) have experimentally and analytically evaluated the protective performance of concrete masonry walls such as FRP and Polyurea, respectively [14,15].

In Korea, impact resistance design for ultimate load is only required in high security facilities. Currently, no clear design standards on protection and explosion-proof structures have been established in Korea. However, the present design codes need suitable provisions of new, retrofit, and strengthening systems for protection of structures and infrastructure under extreme loading scenarios. Recently, a number of blast protection and explosion-proofing studies were performed. The studies included the development of fiber concrete application technology for containment buildings considering airplane collision [16,17], the development of repair and strengthening technology for fire and explosion proofing [18–20], and the construction of APR-1400 physical protection design system [9,21,22]. They were conducted to improve the impact- and explosion-proof performance of concrete structures.

Also, many experimental investigations on high speed load in concrete structures have been conducted all over the world. However, few experimental data on major containment structures such as PCCVs and LNG storage tanks have been disclosed due to national security reasons. Therefore, the present study aims to obtain precise data on blast loaded PSC members by conducting a set of explosion test to investigate blast-resistance capacity and damage behavior of nuclear PCCV outer wall.

2. Modeling of blast experiments

In order to find a suitable blast loading scenario for a blast incident of nuclear PCCV, a blast scenario of an explosion occurring on a ground level at a short distance away to the target PCCV is considered. In order to model the actual PCCV applied with blast loading, the scale of the target structure and the blast source must be scaled down. Therefore, the theoretical backgrounds of blast induced loading and scaled down structural modeling must be investigated thoroughly.

In this study, a panel specimen representing the wall of a PCCV was fabricated. The thickness of the test specimens is taken as a quarter thickness of the actual thickness. Due to the restriction in dimensions of the test specimens, only feasible thickness was 1/4 thickness. Even though thickness of the specimen was reduced to 1/4 size, the rebar and tendon ratios were kept as same as the actual PCCV wall. Also, the rebar, tendon, and concrete strengths were kept as same as the actual PCCV wall. A report by Construc-