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# Verification of Protection Performance of Concrete Blast-Proof Panels Against Internal Explosions

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**Abstract**

Recently, studies on blast-proof panels, which were attached to structures to protect facilities from local damage caused by explosions, have been actively performed. However, blast-proof panels are impractical yet due to the high installation cost and difficulty in construction, and protection performance for explosions inside a structure is not evaluated. In this study, a blast-proof panel consisting of concrete material was devised to ensure economic feasibility and constructability. Then, the protection performance of the concrete blast-proof panel for internal explosions was analyzed by numerical simulations and field experiments. First, field experiments on concrete explosion-proof panels were conducted for two cases, where panels without and with energy-absorbing foam were installed. As a result, the concrete blast-proof panel reduced the displacement of structures by up to 22% and the acceleration of structures by up to 86%. However, the reliability of the field experiment data was insufficient due to the shear failure of the test structure during experiments. Therefore, additional analysis was conducted by developing a numerical model. A series of numerical simulations was conducted according to the various densities of the energy-absorbing foam that was inserted between the panel and structure. Consequently, the optimum density of the impact-absorbing material differed depending on the type of structure damage to reduce (i.e., the displacement or acceleration of the structure).

**Highlights**

- Concrete blast-proof panel was designed considering economic and constructability.
- Protection performance of panel was numerically and experimentally evaluated.
- The panel significantly reduced displacement and acceleration of structure against internal explosion.
- Density of energy-absorbing foam in panels should be designed based on protective target.

**Keywords** Concrete blast-proof panel, Energy-absorbing foam, Explosion protection, Confined explosion, Internal explosion

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## 1 Introduction

In recent years, explosion threats toward the safety of facilities and public security in cities have been increasing worldwide. In addition to terroristic threats, military facilities with explosion risks are actively being integrated into cities owing to the expansion of city areas (Park & Son, 2016). Moreover, accidental explosion cases from industrial facilities increased as various industries exponentially developed (Due-Hansen & Dullum, 2017). In particular, as the installation of facilities related to the hydrogen industry, e.g., hydrogen charging stations, increases, many explosion accidents in hydrogen storage containers have been reported (West et al., 2022). Although hydrogen charging stations have been installed on the outskirts of cities so far, they will inevitably be installed inside cities as the hydrogen industry develops, continuously enhancing the threat of explosions to cities (Moradf & Groth, 2019). That is, it is time to urgently study practical methods of protection technologies that can decrease threats of explosions from inside facilities located in cities.

Conventional protection technologies for explosions have focused on protecting targets inside structures when explosions occur outside structures using protective walls or blast-proof doors. The primary purpose of protective technologies against external explosions is to construct structures that incur minimal damage and will not collapse. Many verification tests on protective walls and blast-proof doors have been performed because they must pass performance tests before installation (Jung et al., 2017; Yoo et al., 2017), and reliable numerical analysis techniques have been developed (Choi et al., 2016; Lee & Choi, 2018). Recently, the risk of local damage to structures has been increasing due to increased explosion loads and advances in weapon technologies, such as improvised explosive devices, intelligent landmines, self-destructive drones, etc. Accordingly, as the need for protecting small areas of structures increases, studies on blast-proof panels attached to structures to protect facilities or equipment from local damage and enhance the protection performance of a part of structures have been actively performed (Qi et al., 2017; Zhu et al., 2008a).

In general, blast-proof panels include energy-absorbing materials sandwiched between steel plates to reduce impact from explosions by allowing plastic deformation (Liu et al., 2019; San Ha & Lu, 2020; Zhu et al., 2008b). As energy-absorbing materials, aluminum foams and cores with various structures have been widely used (Shen et al., 2010; Yahaya et al., 2015). Among the various core types being studied, the honeycomb core has been widely studied due to its high potential to improve protection performance by varying its geometry and density (Cheng et al., 2017; Liu et al., 2014; Zhu et al., 2009). The protection performance of the honeycomb core has been evaluated by estimating displacement and failure behavior while applying an artificial dynamic load in the laboratory. Wang et al. (2018) fabricated a blast-proof panel by attaching the honeycomb core between plates reinforced with carbon fibers. Then, the strength and stiffness of the panel were investigated according to the core thickness to determine the optimal geometry. Sun et al. (2018) conducted a load test on blast-proof panels consisting of honeycomb cores and developed a numerical analysis model based on the test results. They also analyzed the failure modes of panels according to the thickness of the face sheet, the height and thickness of the core, and the shape of the hexagonal cell of the core. Since experiments that directly generate explosions in the field are difficult to perform several times, numerical analyses were also widely used to identify trends of protection performance according to the configuration of the honeycomb core by simulating explosions. Numerical simulations on a hierarchical honeycomb core in which honeycomb vertices were composed of smaller hexagonal cells were conducted, evaluating to have more excellent specific energy absorption (SEA) than conventional honeycomb core (Sun et al., 2019). Numerical results on the sandwich panel with aluminum foam core were used to verify the applicability of the panel for vehicle armor, and optimal design was determined using an artificial neural network model (Qi et al., 2013). The effect on the deformation and impact resistance of blast-proof panels according to the curvature of the plate has also been investigated through numerical analysis (Qi et al., 2014).

Recently, several studies have been conducted on improving the protection performance of honeycomb cores by changing their materials (Ahmad Mohamed & Abdolreza, 2023). In particular, lots of research is being conducted to configure the material and shape of the core in panels by referring to the shape optimized for energy absorption in nature, called bio-inspired honeycomb cores (Ha & Lu, 2020; Ha et al., 2021; Le et al., 2019). Through finite element simulations for the bio-inspired honeycomb core, configured based on the microstructure of a woodpecker's beak, it was confirmed that SEA increased by up to 125% compared to the conventional honeycomb cores (Ha et al., 2019). In addition, based on the structure of a tree, a bi-tubular tube with a multi-cell type was modeled, and SEA was compared according to hierarchical order, inner diameter, and loading angles (San Ha et al., 2023). Meanwhile, an auxetic core was also studied, which forms a curvature configuration by generating significant displacement differences between the positions, where the load is concentrated and not. The curvature configuration was evaluated to support the external loads more effectively than the flat configuration

(Imbalzano et al., 2016; Lan et al., 2020). Qi et al. (2017) conducted field explosion experiments and indoor drop weight tests on the auxetic core, confirming that it had better protection performance than conventional honeycomb cores. Besides bio-inspired honeycomb and auxetic cores, research has been continuing to use various core shapes such as corrugated cores, tubes, etc. (Li et al., 2014; Liu et al., 2016). Choudhary et al. (2022) analyzed the protection performance by installing hollow mild steel tubes between steel plates and performing numerical analysis on explosion loads. A series of parametric analysis for 85 cases was performed with numerical simulations to provide trends of protection performance according to the configuration of tube cores (Yao et al., 2020). Li et al. (2018) confirmed numerically that the load transfer to the outside can be reduced more significantly than when the aluminum foam is installed by using a square dome-shape kirigami (SDK) structure as a core in a panel. Studies have also been conducted to enhance protection performance by changing the material of the honeycomb core. Liu et al. developed an ultra-micro-circular tube sandwich plate by inserting a metallic tube between the honeycomb structures (Liu et al., 2018). The ultra-micro-circular tube sandwich plate showed less deformation compared to the existing honeycomb core for dynamic loads in numerical simulations, and parametric analysis was performed for various thicknesses, tube insertion types, and explosion loads. Li et al. developed a bamboo-shaped truss core by melting the Inconel 718 alloy, and excellent structural performance was confirmed through material tests (Li et al., 2023).

Even though a lot of research on blast-proof panels with various energy-absorbing materials is being conducted, most developed materials have complex and sophisticated configurations focusing on improving protection performance with light weight to protect small areas such as vehicles, aircraft, barriers, etc. Accordingly, the constructability and economic feasibility of blast-proof panels may be significantly reduced when installed in large areas of inside facilities to protect the surrounding subjects from internal explosions. In addition, since the protection performance of blast-proof panels was mostly confirmed through indoor dynamic load tests or numerical analysis, there is a lack of verification experiments with applying actual explosions to panels. Above all, the protection strategies for explosions inside industrial and military facilities should differ from those for general external explosions. To protect protection targets inside a facility against external explosions, strategies must be established to minimize displacements or damages to the facility itself. On the other hand, if it is necessary to protect protection targets outside a facility from an explosion inside the facility, the purpose of protection should be more focused on reducing pressure and fragments released to the outside through air or ground than preventing the collapse of the facility itself (Park & Park, 2020). In addition, this study was initiated to determine the possibility of obtaining additional protection or reducing the safety distance by attaching blast-proof panels to military facilities, especially ammunition depots. Internal explosions in ammunition depots have a huge explosive load compared to the risk of explosions in common facilities or terrors, and blast pressures are reflected and amplified due to the structural elements blocked in all directions, forming an increased explosion load several times that of an external explosion. Therefore, for facilities that are at risk of powerful internal explosions, such as ammunition depots or hydrogen charging stations, additional protection methods are being applied, such as installing a secondary protective wall in a location away from the facility or reducing the propagation of pressure and fragments through tunnels, assuming the collapse of the facility will occur.

Measures for reducing the blast pressure from internal explosions propagating to the outside have been extensively studied through numerical analyses according to the shape of the internal structure. Measures for reducing the blast pressure from internal explosions propagating to the outside have been extensively studied through numerical analyses according to the shape of the internal structure (Zhang et al., 2014). The mitigating effect of blast pressure was investigated according to the number and angle of tunnel branches (Zhang et al., 2013) and the number, diameter, and angle of vents (Sklavounos & Rigas, 2006). However, research on reduction measures of vibrations in the event of an internal explosion has not been actively conducted except only maintaining safety distance.

This study aimed to confirm whether the propagation of vibration to the external structure in the event of an internal explosion can be minimized by installing an explosion-proof panel, which was previously used to protect the structure from an external explosion. Considering workability and economic feasibility, the plates of blast-proof panels were made of concrete rather than steel, and simple foam with urethane material was used as an energy-absorbing material rather than cores with complex configurations. Although steel is lighter and has better explosion-proof performance than concrete material of the same thickness because concrete is vulnerable to reflected tensile waves caused by the propagation of explosion pressure, concrete has the advantage of low price and easy-to-increase thickness. In particular, in the case of military facilities, the explosion load is very large, and the level of protection required is different for each area, even within the same facility. Therefore, it was determined that concrete blast-proof panels are more advantageous to be applied in military facilities due to their flexibility in design by the ease of changing the thickness and low construction costs compared to existing blast-proof panels consisting of steel plates and cores with complex configurations. In addition, it was expected to ensure the construction of panels in inner areas of facilities with concrete blast-proof panels, even in large areas.

Consequently, in this study, as an initial study of concrete blast-proof panels, field experiments and numerical analyses were conducted to confirm the possibility of an exhibition of protective performance for concrete blast-proof panels. First, the construction method of concrete blast-proof panels to attach the panels to the entire inside area of facilities was developed. Then, field experiments with TNT (trinitrotoluene) explosions were performed to confirm the reduction effect of vibration propagated to the outer structure. Finite element analyses using LS-DYNA, a commercial software program, were carried out to compensate for the uncertainty of the explosion field experiments. The numerical model was verified with field experiment results. With the aid of the developed numerical model, a series of numerical simulations was conducted according to the various densities of the foam to find out the optimum density according to protection strategies.

## 2 Field Experiments for Concrete Blast-Proof Panel

### 2.1 Design of Concrete Blast-Proof Panels

Considering the weight of the concrete blast-proof panels, the size of one segment was chosen, as shown in Fig. 1. Each segment of the panels was connected to the structure using steel hat channels, which were connected to the concrete via anchor bolts.

The panel plates were made from fiber-reinforced concrete (RC) with improved ductile performance. Fiber-RC was evaluated as adequate for protection against explosive loads owing to its high compressive strength and energy absorption capacity (Bibora et al., 2017). The panels were fabricated based on the properties of ductal concrete with a mixture design shown in Table 1 (Blasone et al., 2021). The specific mixture design is not disclosed due to the business secret of the concrete manufacturer.

Each concrete panel was internally reinforced by D10 bars at intervals of 100 mm. 12 bars were inserted in the height direction and 6 bars in the width direction (Fig. 1a).

### 2.2 Construction of Experimental Structure

The experimental structure was designed to investigate the protection performance of the developed concrete blast-proof panels against internal explosions. Initially, the intention was to create a completely confined explosion by blocking the entire direction with slabs, including a ceiling, but there was no way to install TNT before

**Table 1** Mixture design of concrete used in panel plates

| Water to cement ratio | Slump | Maximum aggregate size | Admixtures |
|---|---|---|---|
| 18% | 60 mm | 1.2 mm | Quartz, silica fume, steel fiber, super-plasticizer |

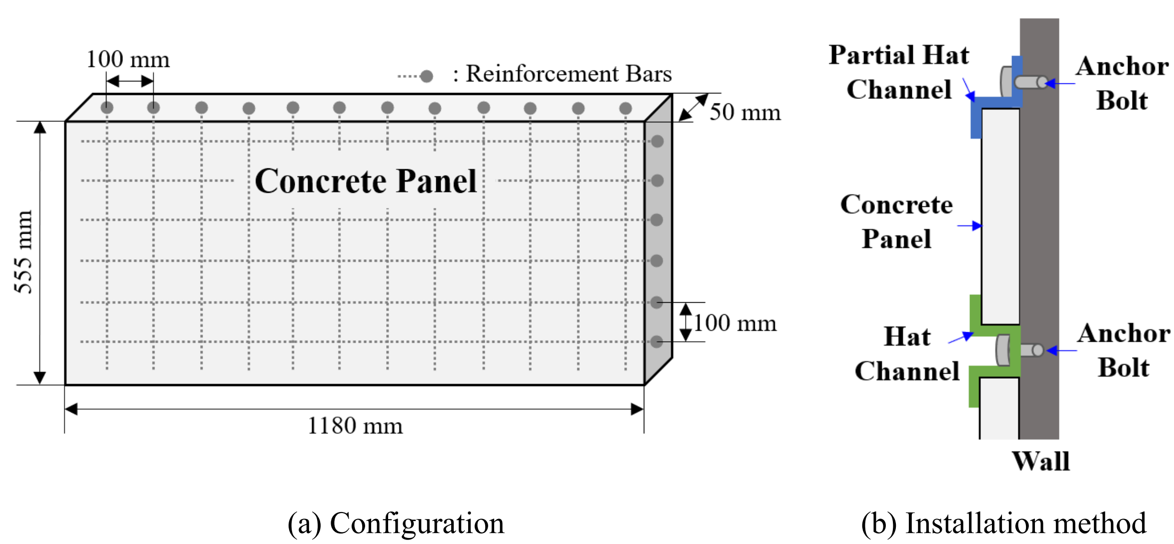



**Fig. 1** Configuration and installation method of concrete blast-proof panels

testing without installing an entrance door. A plan to pour the ceiling or walls after installing TNT was also considered, but canceled due to the safety issues during the curing period. Consequently, TNT explosions occurred inside a space with only four walls and a floor, but no ceiling. In other words, a partially confined explosion was induced. Of course, less reflection and amplification of the explosion pressure would have occurred than in completely confined explosions. However, compared to an external explosion, it was determined that reflection and amplification of the explosion pressure would have occurred enough. The net explosive weight of TNT was set to 5.9 kg (13 lb). The TNT was placed on a 0.3-m-tall wooden box inside the RC structure. Each wall of the RC structure had a size of 1.5 × 1.5 m so that two concrete blast-proof panels could be installed in the vertical direction. The thickness of the wall was set to 25 cm, in accordance with Unified Facilities Criteria (UFC) 3-340-02, to prevent severe scabbing and avoid damage to the measuring instruments installed on the wall during the field experiments (US Department of Defense 2008). D13 reinforcement bars and D10 stirrup bars were placed at 100 mm intervals within the RC structure, considering the required minimum reinforcement ratio of the structure. The concrete of the experimental structure was constructed to have a density of 2300 kg/m$^3$ and a compressive strength of 80 MPa.

The concrete blast-proof panels were installed only on one wall inside the RC structure. The measuring locations were installed on the outer side of both walls to compare the acceleration and displacement of the walls with and without the panels. An energy-absorbing foam was inserted between the concrete blast-proof panels and the wall. Fig. 2 shows the configuration of the experimental structure.

The reflected pressure applied to the inner wall and displacements and accelerations propagated to the outer wall were measured during field experiments. The displacements were measured at the top of the outer walls, while accelerations were measured at the top and bottom of the outer walls. Reflected pressure was only measured at the center of the inner wall without panels due to the installation of panels. Measurement locations for field experiments are shown in Fig. 3.

In the field experiments, two types of concrete blast-proof panels were used. One encased an energy-absorbing foam with a density of 320.37 kg/m$^3$, while the other was installed without energy-absorbing foam to obtain reference test results. Obviously, the damage to the wall decreases as the thickness of the concrete wall increases. In addition, since this study considered the plate as a concrete material, the effect of reducing displacement and acceleration could be analyzed on the same principle as it was caused by a thicker wall. Therefore, considering the case where energy-absorbing material was not inserted between the concrete plate and wall, the acceleration and displacement reduction effects between cases where the concrete thickness was simply increased and where

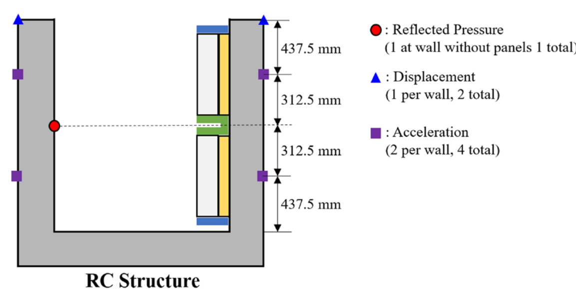



**Fig. 3** Measurement locations for field experiments

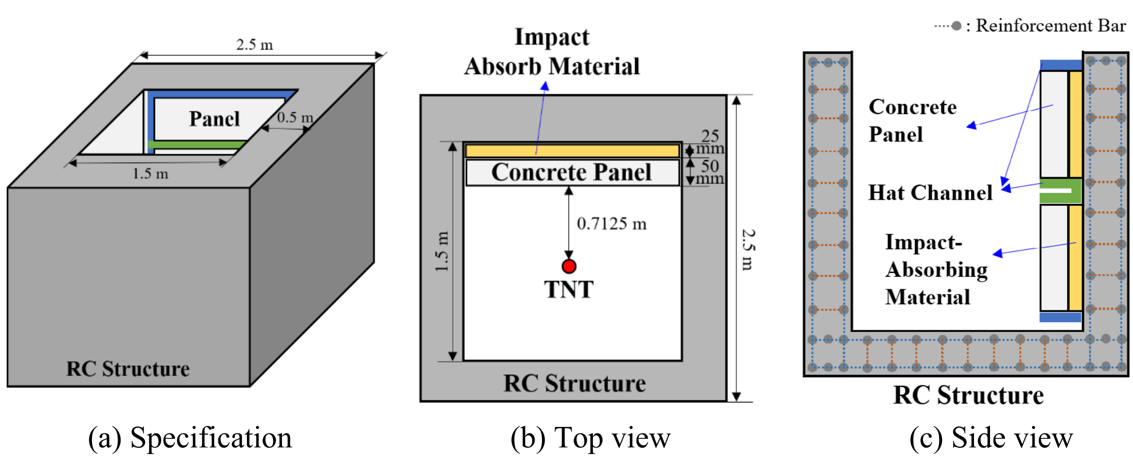



**Fig. 2** Configuration of experimental RC structure for field experiments

**Table 2** Types of concrete blast-proof panels applied in constructed experimental structures

| Experimental structure | Energy-absorbing foam in concrete blast-proof panels |
| --- | --- |
| Structure 1 | Without energy-absorbing foam |
| Structure 2 | Urethane foam with density of 320.37 kg/m$^3$ |

panels with energy-absorbing material were installed were compared. Consequently, two experimental structures were constructed as summarized in Table 2. Fig. 4 shows RC structures constructed for field experiments.

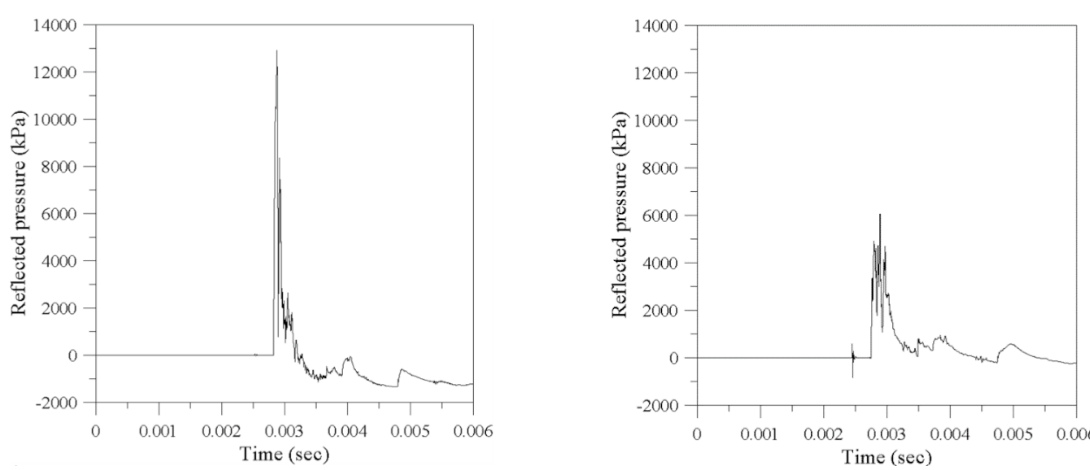
### 2.3 Results of Field Experiments

The reflected pressure at the internal wall measured during the experiments is shown in Fig. 5.

Two pressure peaks occurred in both experimental structures because the incident pressure that was not reflected by the floor or surrounding walls was applied to the wall first, and then the pressure reflected and amplified by the floor and surrounding walls was applied to the wall secondarily. In general, when the explosion occurs while floating slightly in the air, the triple point of blast pressure is generated by the combination of incident pressure, reflected pressure by floor, and Mach front. Below the triple point, plane waves are developed. In the field experiments, the distance between the explosion and the adjacent wall was too close to generate a plane wave higher enough than the wall height. Consequently, after incident pressures were applied to the wall, which generated the first pressure peak, pressures reflected by surrounding structures generated a second pressure peak. The maximum reflected pressure values for the first and second peaks of pressure are listed in Table 3.

In Table 3, the concrete blast-proof panels without energy-absorbing foam were attached to Structure 1, whereas Structure 2 had the concrete blast-proof panels

**Fig. 4** Constructed RC structures for field experiments




(a) Experimental structure 1 (b) Experimental structure 2

**Fig. 5** Reflected pressure at internal wall of RC structures estimated by field experiment

**Table 3** Maximum reflected pressure applied on internal wall measured by field experiments

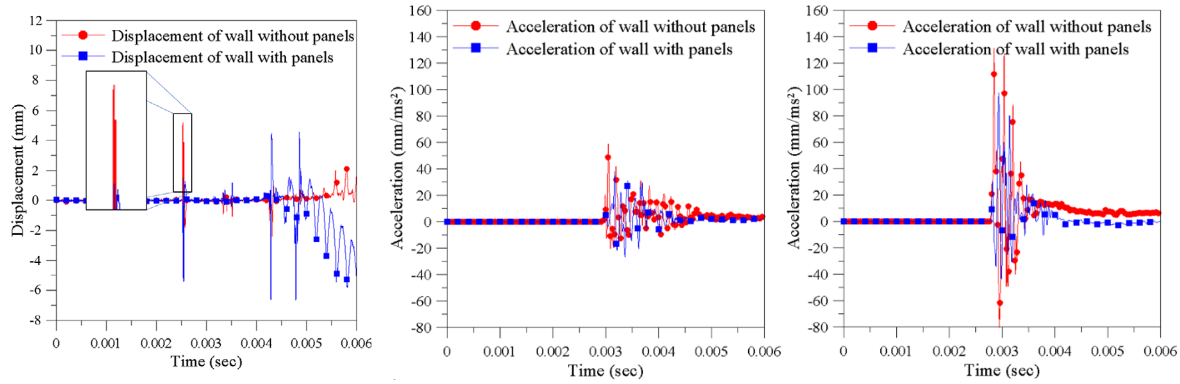
| Peak pressure | Structure 1 | Structure 2 | UFC 3-340-02 |
|---|---|---|---|
| 1st peak pressure (kPa) | 69 kPa | 841 kPa | 14,893 kPa |
| 2nd peak pressure (kPa) | 12,914 kPa | 6060 kPa | |

with energy-absorbing foam (refer to Table 2). The first pressure peak was higher at Structure 1 than at Structure 2, whereas the second was the opposite. Moreover, the difference in pressure peak values measured in Structure 1 and Structure 2 was quite significant. Therefore, in order to evaluate the reliability of experiment data, the reflected pressure at the inner wall of the RC structure was predicted through UFC 3-340-02 and compared with experiment data in Table 3. UFC 3-340-02 provides charts that can predict the maximum reflected pressure at various positions on the inner wall for unidirectional unconfined explosions. These charts were created based on the results of various explosion verification tests and have been commonly used for the design of military and civilian protection structures based on reliable data. The difference between the second pressure peak at the field experiment and the maximum reflected pressure predicted through UFC 3-340-02 was about 15% in the data of Structure 1 and about 145% in the data of Structure 2.

The first peak pressure may increase as the distance between the explosion and the wall becomes closer. In addition, the increased first peak pressure can cause damage to the wall before the second peak pressure is applied to the wall. In the field explosion experiments, the experimental conditions for Structure 1 and Structure 2 were the same. The only difference was that the point, where the TNT was installed was closer to the pressure measurement point in Structure 2 than in Structure 1 by approximately 12.25 mm due to the thickness of energy-absorbing material inserted between the concrete plate and wall. However, this difference caused a significant difference in the size of the first peak pressure applied to the wall during experiments. The size of the first peak pressure applied to the wall was relatively larger in Structure 2 than in Structure 1. Even though about 841 kPa of first peak pressure was measured in Structure 2, more significant impact by blast pressures and fragments would have been applied to the bottom part of the inner wall because the pressure value was measured at the center of the inner wall. Consequently, in Structure 2, it can be determined that shear failure of the wall occurred initially due to the incident pressure applied primarily, and as a result, the superposition of pressure reflected by surrounding structures did not occur sufficiently as in Structure 1 or as expected by UFC 3-340-02. The excessive shear failures occurred in the wall of Structure 2 could be observed after the experiments, as shown in Fig. 6.

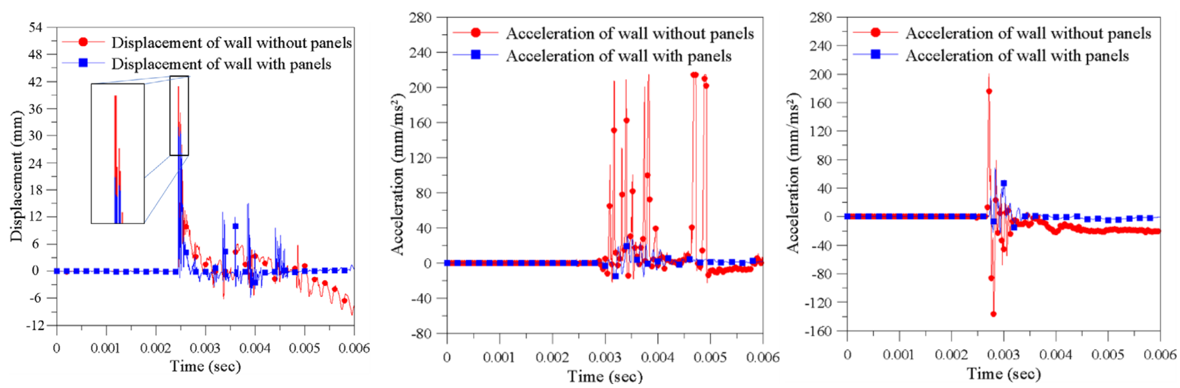
The shear failures that occurred in Structure 2 during the field experiments could also be confirmed by measurement results of displacements and accelerations of the wall. Figs. 7 and 8 show the variations of displacement and acceleration of the walls measured at Structure 1 and 2, respectively. In addition, the maximum displacements and accelerations of the walls for each structure are summarized in Table 4.

**Fig. 6** Shear failures of wall in Structure 2 during field experiments




(a) Displacement (b) Acceleration at top of wall (c) Acceleration at bottom of wall

**Fig. 7** Variations of displacement and acceleration of wall for Structure 1 estimated by field experiment




(a) Displacement (b) Acceleration at top of wall (c) Acceleration at bottom of wall

**Fig. 8** Variations of displacement and acceleration of wall for Structure 2 estimated by field experiment

**Table 4** Maximum displacement and acceleration of wall measured in field experiments

| Position | Displacement (mm) | Acceleration (mm/ms$^2$) | |
|---|---|---|---|
| | | At top of wall | At bottom of wall |
| Structure 1 | | | |
| With panels | 5.42 | 37.88 | 97.44 |
| Without panels | 5.20 | 58.88 | 131.47 |
| Reduction ratio | −4.23% | 35.67% | 25.88% |
| Structure 2 | | | |
| With panels | 31.94 | 30.77 | 68.44 |
| Without panels | 40.94 | 214.96 | 200.80 |
| Reduction ratio | 21.98% | 85.69% | 65.92% |

The displacement and acceleration of the wall were much more significant in Structure 2 than in Structure 1, irrespective of the installation of panels, despite the smaller reflected pressure. This result demonstrates that the shear strength of Structure 2 was weakened due to the shear failures, causing more significant displacements and accelerations despite the lower blast loads. In addition, even though the acceleration of the wall should be large at the bottom of the wall close to the explosion location, the accelerations at the top and bottom of the wall were similar in Structure 2, which indicates the occurrence of shear failures at Structure 2.

The concrete blast-proof panels with energy-absorbing foam were more effective in reducing the displacement and acceleration of the wall than the panels without energy-absorbing foam. Despite the shear failures in Structure 2, to which the concrete blast-proof panels with energy-absorbing foam were attached, displacement was reduced by up to 21% and acceleration by up to 85%. On the other hand, when the energy-absorbing foam was not inserted into the panels, the acceleration was reduced by up to 35%, and the displacement rather increased. When comparing Figs. 7a and 8a, the rebound of the wall occurred significantly when the energy-absorbing foam was not inserted into the panels due to the different behavior of the panels and the wall, which rather caused an increase in the maximum displacement of the wall with panels. Conversely, this indicated that the concrete blast-proof panel inserted with the energy-absorbing foam was effective not only in reducing the maximum displacement but also in preventing the rebound of the wall. In addition, the duration of acceleration of the wall was reduced when installing concrete blast-proof panels inside the wall.

However, since shear failures occurred in Structure 2 during field experiments, the protection performance of the concrete blast-proof panels, especially those inserted with the energy-absorbing foam, could not be accurately evaluated. The shear failure that occurred in the early stages of the explosion during the experiment for Structure 2 means that the experiment was not performed under optimal conditions. In addition, although the impact was smaller than in Structure 2, structural problems would have occurred in Structure 1, too, by the first peak of blast pressure before receiving reflected pressures. Therefore, in this study, a numerical analysis model was developed to evaluate the protection performance of concrete blast-proof panels thoroughly.

## 3 Numerical Analyses for Concrete Blast-Proof Panel

### 3.1 Development of Numerical Analysis Model

The experimental structure and concrete blast-proof panels were modeled in the same configurations and specifications as structures used in field experiments. The volumes of air inside and outside the RC structure were modeled using a computational fluid dynamic (CFD) domain to simulate the occurrence and propagation of pressure from the explosion. Then, the impulse estimated by CFD analysis was coupled to load for computational structure analysis (CSD). The propagation of the blast waves through structures and the resulting deformation and behavior of the structure were analyzed by applying an arbitrary Lagrangian–Eulerian (ALE) formulation. The TNT explosion load was simulated using the Jones–Wikens–Lee (JWL) equation of state (EOS). The boundary conditions of the RC structure, blast-proof panels, and the ground were modeled as fully reflective solid surfaces.

As the material model, the Karagozian & Case (K&C) concrete model (MAT_CONCRETE_DAMAGE_REL3) provided by LS-DYNA was applied to the RC structure and concrete plates in the numerical model. The K&C concrete model was known to exhibit accurate behavior of ductile concrete considering the confinement effects, three-invariant deviatoric stress, shear dilatancy, strain rate effects, and tensile fracture (Liao et al., 2022; Liu et al., 2022). In the K&C concrete model, appropriate EOS and model parameters can be obtained by only inputting general material properties such as uniaxial compressive strength, material density, and Poisson's ratio. In addition, several studies have been performed to simulate more precise behavior by adjusting the automatically generated model parameters. In this study, physical property tests or triaxial compression tests on the produced concrete were not conducted. Therefore, the parameter values provided by Liu et al., where the parameter values were adjusted through experiments on contact explosion, were used in numerical analyses (Liu et al., 2022). In particular, the K&C concrete model numerically simulates the strain effect using EOS with dynamic increase factor (DIF) applied. Among the many empirical formulas for DIF, the formula provided by Fujikake et al. was used (Fujikake et al., 2006). MAT_HONEYCOME model and MAT_SOIL_AND_FOAM model were used to simulate the structural behaviors of energy-absorbing foam and ground, respectively. The material properties considered in numerical simulations were assumed with reference to the literature, as summarized in Table 5 (Hung et al., 2014; Liao et al., 2022; Liu et al., 2022; Manjusha & Althaf, 2020; Park et al., 2021).

Mesh was configured in a hexahedral shape. Fig. 9 shows the results of numerical modeling and mesh configuration of the experimental structure.

**Table 5** Material properties considered in numerical simulations

| Properties | Concrete of panels | Concrete of RC structure | Energy-absorbing foam |
|---|---|---|---|
| Density | 2425 kg/m$^3$ | 2300 kg/m$^3$ | 320 kg/m$^3$ |
| Young's modulus | 52 GPa | 30 GPa | 200 MPa |
| Compressive strength | 145 MPa | 80 MPa | 8 MPa |
| Shear modulus | 20 GPa | 12 GPa | 50 MPa |
| Shear strength | 30 MPa | 14 MPa | 4 MPa |
| Tensile strength | 11 MPa | 8 MPa | 5 MPa |

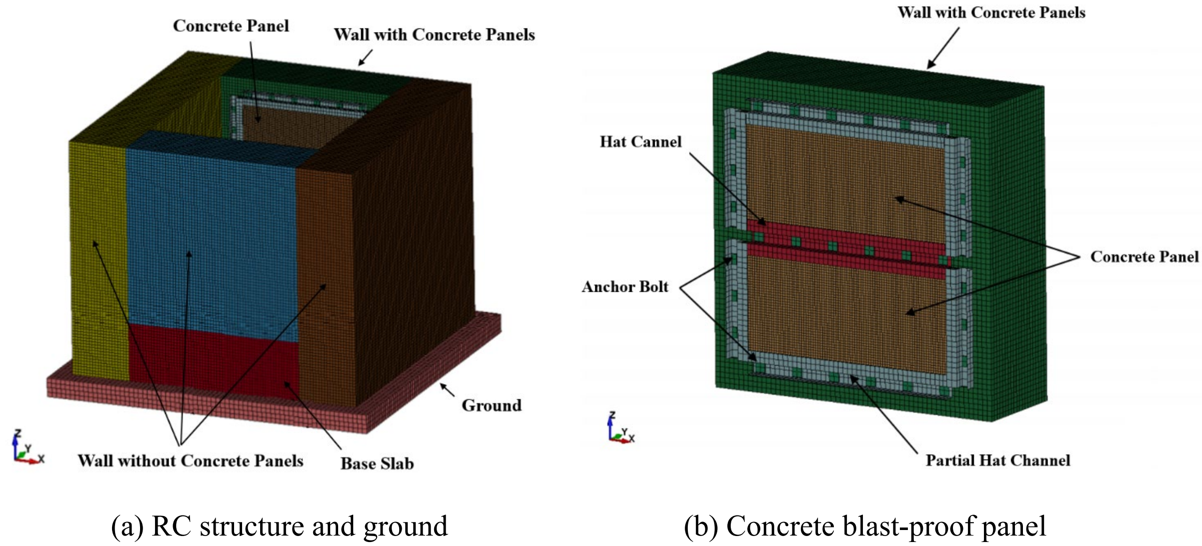



**Fig. 9** Numerical modeling and mesh configurations of experimental structure

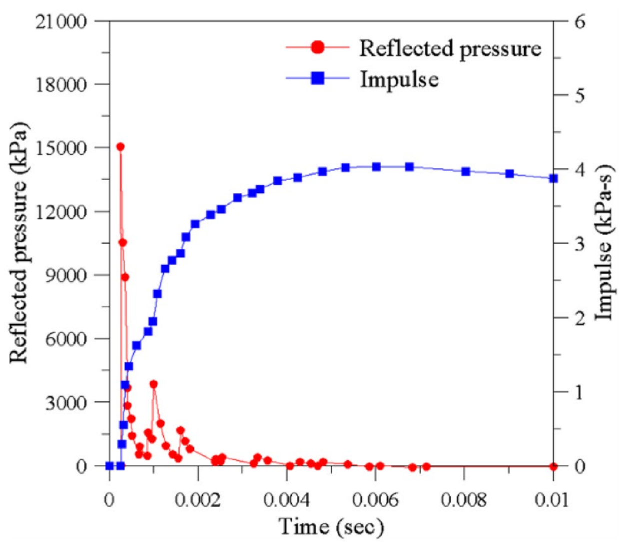



**Fig. 10** Reflected pressure and impulse measured at inner wall of RC structure

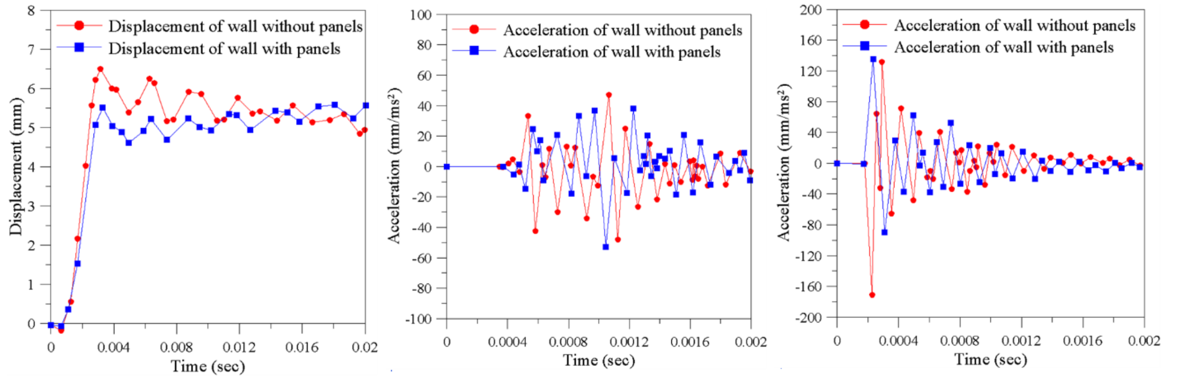
To analyze the reliability of the developed model, numerical simulations were performed with the same conditions as field experiments. First, the reflected pressure applied to the inner wall during an internal explosion was compared with field experiment data. Fig. 10 shows the reflected pressure and impulse at the center of the wall without panels measured by numerical simulation. In addition, the reflected pressure measured by numerical simulation was compared with field experiment data as summarized in Table 6.

**Table 6** Comparison of maximum reflected pressure at inner wall of RC structure predicted by numerical simulation and field experiment

| Field experiment | Numerical simulation | Difference |
|---|---|---|
| 12,914 kPa | 15,100 kPa | 16.93% |

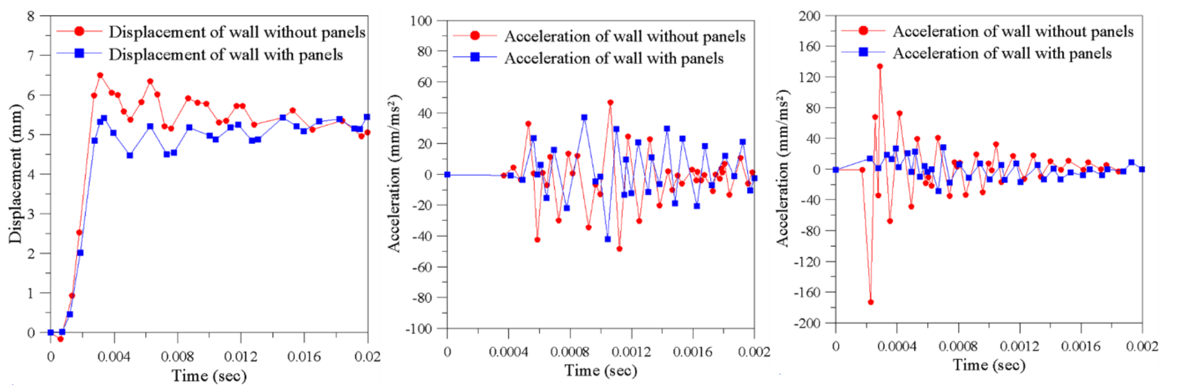
Compared with the field experiment data, the reflected pressure at the inner wall simulated through numerical analysis showed a large value by about 17% difference. Blast pressures caused in in-site explosion have numerous variables and are very sensitive to those variables. They can vary significantly depending on weather, temperature, shape of the TNT installation, and even a fragment by stone next to the explosion, etc. Accordingly, even the graphs in UFC 3-340-02, which were developed based on the results of numerous field explosion experiments and were known to accurately predict blast pressures, conservatively predict blast pressures by 20% of the amount of explosives. In addition, the purpose of this study is not to simulate the field explosion experiment accurately but to confirm whether the concrete blast-proof panel considered in this study has the ability to reduce the displacement and acceleration of the wall caused by the internal explosion. Considering the uncertainty of the in-site explosions and the purpose of this study, it was concluded that the CFD simulation of the explosion was conducted with an acceptable error.

Figs. 11 and 12 show variations of displacement and acceleration of the wall estimated by numerical simulation for Structure 1 and Structure 2, respectively. The




(a) Displacement (b) Acceleration at top of wall (c) Acceleration at bottom of wall

**Fig. 11** Variations of displacement and acceleration of wall for Structure 1 estimated by numerical simulation




(a) Displacement (b) Acceleration at top of wall (c) Acceleration at bottom of wall

**Fig. 12** Variations of displacement and acceleration of wall for Structure 2 estimated by numerical simulation

**Table 7** Maximum displacement and acceleration of wall predicted by numerical simulations

| Position | Displacement (mm) | Acceleration ($mm/ms^2$) | |
|---|---|---|---|
| | | At top of wall | At bottom of wall |
| Structure 1 | | | |
| With panels | 5.58 | 53.00 | 137.00 |
| Without panels | 6.50 | 49.10 | 173.00 |
| Reduction ratio | 14.15% | −7.94% | 20.81% |
| Structure 2 | | | |
| With panels | 5.44 | 42.40 | 36.00 |
| Without panels | 6.51 | 49.10 | 173.00 |
| Reduction ratio | 16.44% | 13.65% | 79.19% |

maximum displacement and acceleration of the wall are summarized in Table 7.

As with the results of field experiments, it was confirmed in numerical analyses that the acceleration and displacement of the wall could be effectively reduced in the event of internal explosions by installing concrete explosion-proof panels at the inner walls. The reduction effect was further increased when the concrete panels were installed with the energy-absorbing foam in both field experiments and numerical simulations. In particular, the acceleration of the wall was reduced by up to 79% (up to 85% in the field experiment), indicating that the concrete explosion-proof panels were more effective in reducing the acceleration than the displacement reduction for internal explosions. However, contrary to the field experiment, the displacement decreased and the acceleration at the top of the wall increased in the numerical analyses when the panels without energy-absorbing foam were attached to the wall. This is because the panels and the wall behaved separately during the field experiments, resulting in a secondary impact on the wall by the panels, while they behaved in integrating during the numerical simulations. Since the blast load is generally very large and the load duration ends before the structure completely moves, the displacement decreases and the acceleration increases as the mass of material increases. The maximum displacement and acceleration of the wall predicted by numerical simulation and field experiment are compared in Table 8.

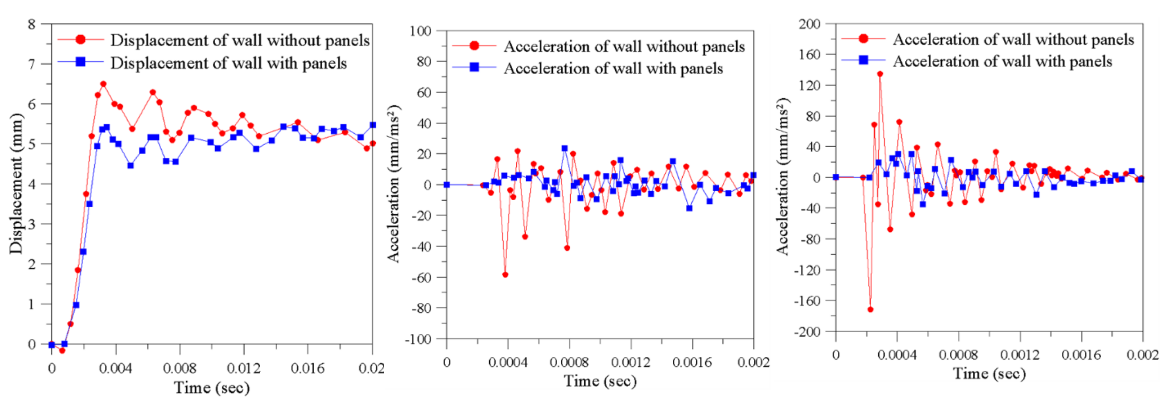
**Table 8** Comparison of maximum displacement and acceleration of wall predicted by numerical simulation and field experiment

| Position | Difference between simulations and field experiment | | |
|---|---|---|---|
| | Displacement (mm) | Acceleration (mm/ms$^2$) | |
| | | At top of wall | At bottom of wall |
| Structure 1 | | | |
| With panels | 2.95% | 39.92% | 40.60% |
| Without panels | 25.00% | 16.61% | 31.59% |
| Structure 2 | | | |
| With panels | 82.97% | 37.80% | 47.40% |
| Without panels | 84.10% | 77.16% | 13.84% |

Compared to the field experiment data, the results of numerical simulations showed an average difference of about 26% for Structure 1 and about 57% for Structure 2. The significant difference in Structure 2 was induced because the shear failures that occurred during the field experiments were not simulated in the numerical simulation. The difference between field experiment data and the results of numerical simulations was not negligible for Structure 1 as well. However, the main purpose of this study was to confirm whether the concrete blast-proof panel can exhibit a protective performance. In addition, since the properties of materials used in the field experiments could not be accurately measured, there were limitations in predicting the exact behavior of the materials through numerical simulations. Considering that a 17% larger maximum reflected pressure was applied to the wall in the numerical simulations and structural problems occurred during field experiments due to the first peak of pressure, it was concluded that the developed numerical model could analyze the trend of structural behaviors reasonably in the event of internal explosions. Consequently, additional numerical analyses were conducted with the aid of the developed numerical model to investigate the effect of the density of energy-absorbing foam inserted into the concrete blast-proof panels on protection performance for an internal explosion.

### 3.2 Effect of Energy-Absorbing Foam Density on Protection Performance of Concrete Blast-Proof Panels

Additional numerical simulations were conducted by applying higher and lower densities of energy-absorbing foam (400.46 kg/m$^3$ and 240.28 kg/m$^3$, respectively)




(a) Displacement (b) Acceleration at top of wall (c) Acceleration at bottom of wall

**Fig. 13** Variations of displacement and acceleration of wall for energy-absorbing foam densities of 400.46 kg/m$^3$ estimated by numerical simulation

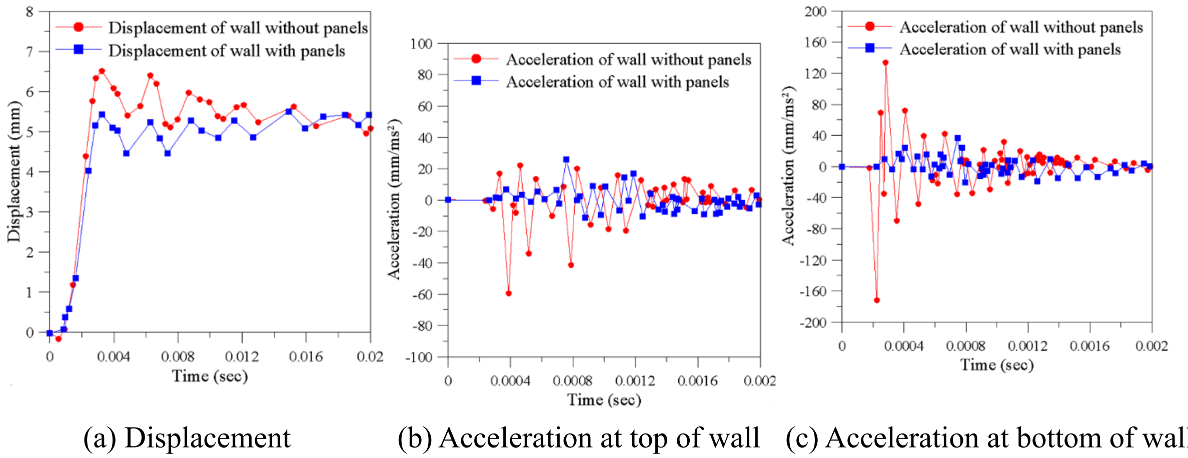



**Fig. 14** Variations of displacement and acceleration of wall for energy-absorbing foam densities of 240.28 kg/m$^3$ estimated by numerical simulation

**Table 9** Maximum displacement and acceleration of wall according to the energy-absorbing foam densities predicted by numerical simulations

| Energy-absorbing foam density | Displacement (mm) | Acceleration (mm/ms$^2$) | |
|---|---|---|---|
| | | At top of wall | At bottom of wall |
| 400.46 kg/m$^3$ | | | |
| With panels | 5.48 | 37.8 | 30.0 |
| Without panels | 6.50 | 49.1 | 173 |
| Reduction ratio | 15.69% | 23.01% | 82.66% |
| 320.37 kg/m$^3$ | | | |
| With panels | 5.44 | 42.40 | 36.00 |
| Without panels | 6.51 | 49.10 | 173.00 |
| Reduction ratio | 16.44% | 13.65% | 79.19% |
| 240.28 kg/m$^3$ | | | |
| With panels | 5.40 | 46.8 | 39.0 |
| Without panels | 6.52 | 49.1 | 173 |
| Reduction ratio | 17.18% | 4.68% | 77.46% |

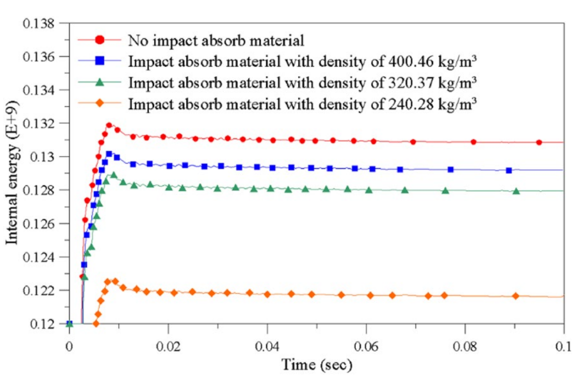



**Fig. 15** Change in internal energy of panels according to densities of energy-absorbing foam

than the density used in field experiments (320.37 kg/m$^3$) to the developed numerical model. Figs. 13 and 14 show variations of displacement and acceleration of the wall estimated by numerical simulation for energy-absorbing foam densities of 400.46 kg/m$^3$ and 240.28 kg/m$^3$, respectively. The maximum displacement and acceleration of the wall according to the energy-absorbing foam densities are summarized in Table 9.

As the energy-absorbing foam has a lower density, the maximum displacement of the wall was more effectively reduced. Fig. 15 shows the changes in the internal energy of the panels, which increased as the density of the energy-absorbing foam decreased. The blast-proof panels reduced the displacement of the outer wall by absorbing dynamic energy with the aid of the foam, which was more effective as the density of the foam was lower. However, the difference in displacement reduction ratio did not occur significantly depending on the density of the energy-absorbing foam.

The decreased ratio in the accelerations by installing panels, measured at the outer wall, increased as the density of the energy-absorbing foam increased, contrary to the decreased ratio in the displacement of the wall. The higher density of energy-absorbing material showed improved performance in vibration attenuation. Consequently, the density of the energy-absorbing foam inserted into the concrete explosion-proof panel should be applied differently depending on what damage of the facility is to be protected (i.e., displacement or acceleration of the facility) in the event of an internal explosion.

## 4 Discussion

There are existing field experiment results performed with blast-proof panels consisted of energy-absorbing material made of aramid fiber and steel plates (Park et al., 2021). The experiments were conducted with blast-proof panels attached to only one side, identical to this study. The size of the internal space of test structures and the amount of TNT explosion were the same, but the thickness of the blast-proof panel was different. However, the openings of the structure were made on the front and back sides to reduce the risk during TNT installation, and the TNT exploded on the floor. Therefore, since comparing the absolute values of the data obtained by two different experiments is inappropriate, the relative difference in how much the acceleration of the wall was reduced when panels were attached compared to that without panels during an internal explosion was compared. In the existing field experiments, the blast-proof panels composed of steel plates showed that the acceleration of the outer wall was reduced by approximately 28.87% for normal strength test structure and 45.13% for high-strength test structure. Meanwhile, the concrete blast-proof panels with energy-absorbing material reduced the acceleration of the outer wall by 46.42% on average in the field experiments conducted in this study (i.e., average value of the acceleration reduction rate obtained at the upper part and the lower part of Structure 2 wall). Obviously, because the experimental conditions are different, it is inappropriate to evaluate that the protective performance of concrete blast-proof panels is superior just because the acceleration reduction effect was greater in concrete blast-proof panels. However, it was concluded that existing blast-proof panels consisting of steel plates could be sufficiently replaced with a simple configuration of panels with concrete plates and an energy-absorbing foam inserted between the panels and wall for protection design against internal explosion.

It was concluded that both concrete plate and energy-absorbing material are crucial to exhibit protection performance. If normal concrete were used as plates of panels, the plates might be vulnerable to damage due to high explosive loads, and ultimately, the energy-absorbing material would not be able to provide sufficient performance because the material could not be protected sufficiently. Meanwhile, when comparing the experimental results of Structure 1 and Structure 2, it was confirmed that energy-absorbing material plays a significant role in reducing the impact by internal explosion. When the energy-absorbing material was not installed, the acceleration could be reduced by protecting the wall with panels, but the reducing ratio was smaller than when the panels were installed with energy-absorbing material. Moreover, the displacement rather increased due to the rebound of the wall when installing the panels without energy-absorbing material. In addition, through numerical analysis, it was confirmed that internal energy can be effectively reduced by inserting energy-absorbing materials into the panels. However, in order to examine the precise energy absorption mechanism, material tests must be conducted under strictly controlled conditions.

Meanwhile, the reduction efficiency of the displacement and acceleration of the wall attached to the concrete explosion-proof panels varied depending on the density of the energy-absorbing foam. In other words, the reduction efficiency for the displacement of the wall increased as the density of the energy-absorbing foam decreased, while that for the acceleration of the wall increased as the density of the energy-absorbing foam increased. Consequently, the density of the energy-absorbing foam should be designed according to the purpose of the protection facility and the characteristics of the protection target. For example, a concrete blast-proof panel installed in ammunition depots or hydrogen stations at ground level should prioritize preventing the collapse of the structure and the external propagation of pressure in the event of an internal explosion. Therefore, the displacement must be minimized by decreasing the density of the energy-absorbing foam. For underground facilities, the propagation of acceleration through the ground must be prevented to avoid damaging nearby facilities. It means that the acceleration must be minimized by increasing the density of the energy-absorbing foam. It was expected that the results of this study would be used as fundamental data for designing concrete blast-proof panels to protect facilities or structures from internal explosions by being installed on entire walls.

Since this study aimed to confirm the feasibility of using concrete explosion-proof panels against an internal explosion, the precise behavior of the panels according to material properties or construction methods was not analyzed. In addition, consistent experimental data could not be obtained due to weather conditions worsened by snow and shear failures of the test structure during the field experiments. As a result, it was difficult to accurately determine the reliability of the developed numerical model. Therefore, it is judged that additional field experiments for the protection performance of concrete blast-proof panels should be conducted to more precisely evaluate the structural behaviors of panels and improve the numerical model. The additional field experiments are planned to be conducted with TNT on the floor and maintain a large distance between the wall and the TNT to eliminate variables such as structure damage due to the time difference between reflected pressure and incident pressure. In addition, the optimal experiment method for accurately predicting the protection performance and behavior of concrete blast-proof panels and using the experimental data in design, the structure without panels should be constructed with a thickness equal to the total thickness including the wall and panels. In other words, when the thickness of the wall without panels and the total thickness of the structure, where its thickness increases by attaching panels are the same, the exact protection performance of the panels can be examined. In future research, additional experiments or numerical analyses are needed considering the same thickness, same density, same installation cost, etc.

## 5 Conclusion

In this study, a novel type of blast-proof panel consisting of concrete plates and an energy-absorbing foam was developed for the purpose of preventing damage from internal explosions. By replacing the existing blast-proof panel made of steel plates and honeycomb core, it was intended to secure economic feasibility and constructability for enabling to be installed on entire areas of a facility. The protection performance of the concrete blast-proof panel was evaluated by conducting field experiments. Then, a numerical model was developed based on the field experiment data, and the effect of the density of the energy-absorbing foam was investigated. The key findings of this study are as follows:

1. Field experiments on concrete explosion-proof panels were conducted for two cases, where panels without and with energy-absorbing foam were installed. The reflected pressure on the inner wall measured during the field experiment for panels with energy-absorbing foam was smaller than that predicted through UFC 3-340-02. It was believed that the shear failure of the test structure occurred during field experiment for panels with energy-absorbing foam, resulting in low reflected pressure on the inner wall and unclear experimental data.
2. The field experiments showed that concrete blast-proof panels with energy-absorbing foam could effectively reduce the displacement and acceleration of the walls in the event of an internal explosion. However, in concrete blast-proof panels without impact-absorbing material, the displacement of the walls rather increased by a secondary impact from panels.
3. The numerical model was developed by simulating the field experiments. Comparing numerical simulation results with field experiment data, it was concluded that the developed numerical model could reasonably analyze the trend of structural behaviors in the event of internal explosions. The results of numerical simulation also indicate that the displacement and acceleration of the wall due to an internal explosion can be reduced by installing concrete blast-proof panels. Displacement and acceleration of the wall were further reduced when the energy-absorbing foam was inserted between the panels and the wall.
4. The reduction ratio for the displacement of the wall increased as the density of the energy-absorbing foam inserted into panels decreased, while that for the acceleration of the wall increased as the density of the energy-absorbing foam increased. Consequently, it was concluded that inserting an energy-absorbing foam with optimal density according to the purpose of the protection facility or the characteristics of the protection target is necessary for designing concrete blast-proof panels.

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**Author Contributions**
SP: software, investigation, data curation, writing—original draft, writing—review and editing; KK: methodology, validation, investigation, data curation; DK: validation, data curation, writing—original draft, visualization; YJP: conceptualization, methodology, supervision, project administration; BS: conceptualization, software, validation, data curation.

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**Data Availability**
Data will be made available on request to the corresponding author.

## Declarations

**Ethics Approval and Consent to Participate**
Not applicable.

**Consent for Publication**
Not applicable.

**Competing Interests**
The authors declare that they have no competing interests.

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