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LPG 폭발로 인한 건설현장 굴착웅덩이의 구조물 파손 특성에 관한 연구

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A Study on the Failure Characteristic of Excavation Puddle by LPG Explosion using AUTODYN

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Abstract

Gas explosion accidents could cause a catastrophe. we need specialized and systematic accident investigation techniques to shed light on the cause and prevent similar accidents. In this study, we had performed LPG explosion simulation using AUTODYN which is the commercial explosion program and predicted the damage characteristics of the structures by LNG explosive power. In the first step, we could get LPG's physical and chemical explosion properties by calculation using TNT equivalency method. And then, by applying TNT equivalency value about the explosion limit concentration of LPG on the 2D-AUTODYN simulation, we could get the explosion pressure wave profiles (explosion pressure, explosion velocity, etc.). In the last step, we performed LPG explosion simulation by applying to the explosion pressure wave profiles as the input data on the 3D-AUTODYN simulation. As a result, we had performed analyzing of the explosion characteristics of LPG in accordance with concentration through the 3D-AUTODYN simulation in terms of the explosion pressure behavior and structure destruction and damage behavior. The analyses showed that the generated stresses of the structures were lower than the compressive strengths in cases 1(two lane) and 2(four lane), while the generated stress in case 3(six lane) was 8.68e3 kPa, which exceeded the compressive strength of 5.89e3 kPa.

Key words : TNT equivalence method, AUTODYN, explicit dynamics, integrity evaluation

I. Introuduction

It is essential to cut iron bars using gas-cutting equipment for use in the excavation pits of pier foundations required for the construction of urban overpasses or underground railways. Nevertheless, explosion accidents have consistently occurred in these types of constructions owing to gas leakages from the cutting equipment attributed to equipment defects and poor operation practices. Typically, gases for cutting equipment used in the construction sites, including explosive acetylene or liquefied petroleum (LP), are highly combustible and typically used for the generation of combustion heat. Particularly, if combustible gases within the explosive range are leaked within a closed or semi-closed workspace and premixed with air, drastic combustion reactions may be triggered by mechanical and electric ignition sources, such as friction or static electricity generated during the construction work. This will ultimately lead to an explosion and to a considerable increase in pressure (Choi et al., 2007). Specifically, gas explosion accidents that occur in the excavation of holes result in massive casualties and material damages pri-

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marily caused by the blast pressure. These outcomes are attributed to the nature of the construction work within small underground spaces. Furthermore, secondary damages due to the collapse of the structure also caused by blast pressure may accelerate the entire sequence of events, potentially leading to catastrophic disasters. Thus, the systematic elucidation of the accident's mechanism and its causes and the development of technologies for the prediction and prevention of such accidents are imminently needed (Kim and Choi, 2016; Jo and Lee, 2012; Jo et al., 2012; Jo et al., 2013). According to the statistics on accidents obtained from the Korean Gas Safety Corporation, gas explosions which constitute the most common types of accidents account for 36% of the entire number of gas accidents. Of these, 67% are attributed to LP gas accidents. The main causes of these types of gas explosions are mostly the leakages of gases owing to a) poor pipe connections, b) cracks in pipes or hoses, and c) defects in gas equipment. Although material damages and casualties exhibit a decreasing trend, they still represent an increased proportion with respect to the total number of safety accidents. Previous studies, mainly investigated the characteristics of gas explosions. Regarding explosion accidents, focus was placed on the assessment of the overpressure characteristics and the prediction of damages based on the use of simulations. However, the stability evaluations and the impacts of structural damages caused by the overpressure developed following gas explosions, and their secondary risks including building collapses have never been studied. Given that the power of the explosion varies significantly depending on the gas, leakage amount, the content of mixed oxygen, leakage volumes, and building wall materials, the design and execution of experiments to recreate the gas leakage accidents are impossible. Accordingly, the power of the explosion due to gas leakage and the resulting damages on structures cannot be estimated. Hence, it is difficult to predict the collapse of structures in such accidents. In this study, the possibility of the collapse of the structure owing to gas leakage explosions was investigated in the case of the excavation of pits for pier foundations based on the application of a numerical analysis technique which is used for the elucidation of the accident mechanism and the identification of the underlying causes. First, the amount of LPG with maximum explosion energy was calculated for each excavation pit structure, and the amount of the leaked LPG volume was estimated based on the TNT equivalence method and was converted into a TNT explosive energy. Finally, excavation pit failures owing to the explosion and structural integrity damages were evaluated based on the 2D and 3D analyses of the excavated pond structures using the software AUTODYN.

II. STRUCTURE AND TNT EQUIVALENT WEIGHT

2.1 Outline of numerical analyses

The excavation of holes for bridge piers is directly related to the economic feasibility of the project, and are generally classified into three types according to the number of the traffic lanes. Shallow foundations are those associated with excavation with depths < 5 m, whereby the construction is typically undertaken by excavating up to the depth of the bedrock (limestone). However, in special cases, the construction extends up to weathered soil after testing the bearing capacity. The soil condition of excavated holes obtained by H-piles and earth plates is shown in Fig. 1. In this study, it was assumed that the sidewall material was a ferro concrete structure, and that LPG leaked in each hole in a semi-closed state (lack of an upper lid) for the assessment of the impact of the blast pressure. Although the explosion characteristics of LPG varied depending on the gas composition, the general explosion range was set to be within the range of 2.1–9.4% at atmospheric pressure (1 kgf/cm^2), and the value of the maximum blast pressure corresponded to 5.8%, which is in the middle of the range.

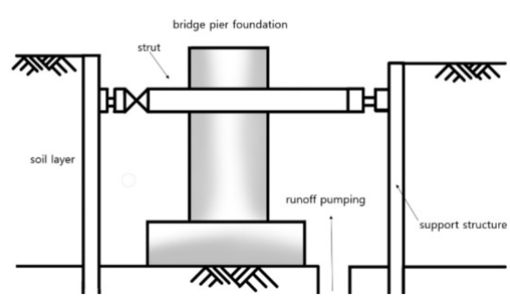


Fig. 1. The condition of excavated holes obtained by H-piles.

2.2 Calculation of TNT equivalency value

AUTODYN used in this study is a commercial finite element analysis program developed for the analysis of nonlinear dynamics problems with large-scale deformations, such as impact, penetration, and explosion. It can be used as a tool for validation, evaluation, and analyses for the conducted tests, but can also provide an analytical method for phenomena for which experiments are practically impossible. Therefore, this program can minimize experimental costs, and can simulate the actual experiments that cannot be reproduced (Jo and Lee, 2012; Jo et al. 2012; Jo et al., 2013). However, unlike conventional solid explosives, combustible gases have irregular shapes and their blast pressure and explosive velocity vary greatly depending on the gas composition, mixture characteristics, and the state of compression. Subsequently, it is difficult to apply AUTODYN directly to them. Therefore, the TNT equivalency method is used to define the gas explosion characteristics (Kim et al., 2015). The TNT equivalency method is described in the US Army Technical Manual TM 5-1300, and is mainly used to convert the explosion spread distance and predict the explosion damage. The TNT equivalent denotes the expression of energy generated when a substance explodes, and is represented by the weight of TNT that produces the same energy (Cowl, 1969). The characteristics of TNT are highly reliable because the explosion characteristics, such as the blast pressure and the explosion energy at the time of the explosion, are measured in detail based on conducted experiments. Blast pressure characteristics can be obtained with the application of the TNT equivalency method according to the composition ratio and leakage amount of combustible gas and the explosion analyses performed with AUTODYN. However, several assumptions need to be postulated, and errors may occur in the analyses with short explosion spread distances. The amount of leaked combustible gases or flammable substances based on the equation of state for ideal gases can be expressed according to Eq. (1). Correspondingly, Eq. (2) allows the calculation of TNT equivalents.

$$M = \frac{P \times V \times m}{R \times T} \tag{1}$$

$$W = \frac{\mu \times M \times E}{1{,}100} \tag{2}$$

where R: ideal gas constant (L•atm/K•mol), T: gas temperature (K), P: gas pressure (atm), V: gas volume (L), m: molecular weight (g/mol), W: TNT equivalent (kg), μ: explosion yield factor (a value of 0.5 is used), M: leaked combustible gas amount (kg), and E: combustion heat caused by the explosion material (kcal/kg).

2.3 Conditions and analysis steps

The gas explosion analysis was performed in this study using AUTODYN according to the following two steps. Step 1 is an interpretation used to calculate the blast pressure propagation profiles, including the blast pressure and explosive velocity, from a two-dimensional model where only air and TNT are taken into consideration according to the definition of the gas explosion characteristics using the TNT equivalents described earlier. Step 2 is a full explosion analysis based on the application of the results obtained in step 1 to a three-dimensional model as input data. The biggest advantages of AUTODYN is the coupled Eulerian Lagrangian analysis according to which the characteristics of the fracture behaviors of the structures evoked owing to the blast pressure and the blast wave propagation can be determined (Kim et al., 2011). In this study, it was assumed that the sidewall material of the hole was ferro concrete for each type of excavated pier hole presented in Table 1. In the case of an LPG leakage with a volume approximately equal to 5.8% of the volume of the hole in the referred space, which is also equal to the maximum occurrence range of explosion, the characteristics of the gas explosive power and the resultant impact of the damage on the structures were compared and assessed using the TNT equivalency method. The main components of LPG are propane and butane with molecular weights of 44 g/mol and a heat of combustion of 12,000 kcal/kg. With these values, the amount of leaked combustible gas (kg) can be calculated based on the ideal gas Eq. (1). This amount of combustible gas can be applied to Eq. (2) to calculate

TABLE 1. Type of puddle according to traffic lane

Type of Lane	Size(M)	Case No.
Two Lane	10(W)*5(D)*12(H)	Case 1
Four Lane	15(W)*5(D)*12(H)	Case 2
Six Lane	25(W)*5(D)*12(H)	Case 3

TABLE 2. Common contents for numerical analysis

Classification	Value
Initial pressure (atm)	1.0
Molecular weight of LPG (g/gmol)	44
Ideal gas constant (1 · atm/K · gmol)	0.082
Temperature (K)	293
Burning calorie of LPG (kcal/kg)	12,000
Explosion yield coefficient	0.5

TABLE 3. TNT equivalent quantity according to case

Classification	Case 1	Case 2	Case 3
Space total volume(L)	600000	900000	1500000
Gas volume(L)	34800	52200	87000
Leakage gas weight(kg)	63.7	95.6	159.3
TNT equivalent(kg)	347.6	521.4	869.1

the TNT equivalents with the equivalent explosive energy. Tables 2 and 3 show the variables and TNT equivalent values for the calculations of TNT equivalents for each hole type.

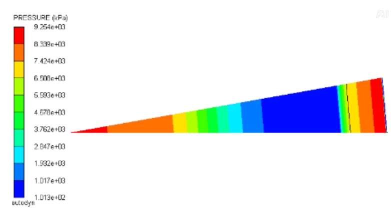
III. STRUCTURAL FRACTURE EVALUATION USING AUTODYN

3.1 Calculation of basic explosion characteristics

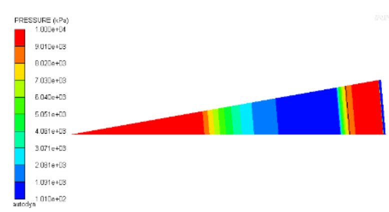
Two-dimensional analyses were performed to calculate the gas blast pressure data for each hole type using the TNT equivalents calculated in Table 3, and the two-dimensional analysis model is presented in Fig. 2. The air domain was configured with the use of the 2D wedge shape to simulate the pressure propagation shape (spherical shape). Accordingly, the size of the TNT domain was determined by considering the volume which corresponded to the TNT equivalents. The graphs corresponding to the explosion characteristics of each case were estimated in accordance with the basic analysis are shown in Fig. 3 and are summarized in Table 4.

3.2 Explicit dynamics analyses

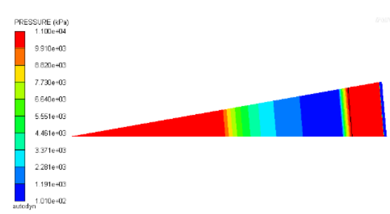
The results of the two-dimensional basic explosion analysis listed in Table 4 were applied to the three-dimensional hole model, and the behavioral characteristics of the wall structure and the propagation characteristics of the blast pressure caused by the LPG leakage were determined to compare and assess the explosive power and the resultant damage impact on the side wall of the structure. As shown in Fig. 4, the three-dimensional analysis model was constructed by coupling the combined concrete and ferro-concrete models, which had a Lagrangian structure, with the air model, which had a Eulerian structure. For boundary conditions, it was assumed that a) the ignition sources of the gas explosion existed at the center of left and right parts within the considered space, and b) the complete combustion



(a) case 1.



(b) case 2.



(c) case 3.

Fig. 2. Result of explosion analysis using 2D-AUTODYN.

TABLE 4. TNT radius and Max pressure according to case

Classification	Case 1	Case 2	Case 3
TNT radius(m)	0.371	0.424	0.503
Max Pressure (kPa)	9.035e3	1.0867e4	1.344e4

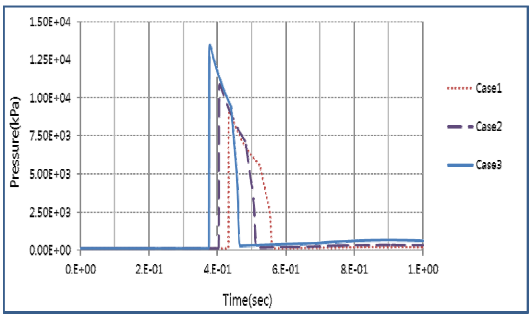


Fig 3. Explosive pressure value of 2D wedge model.

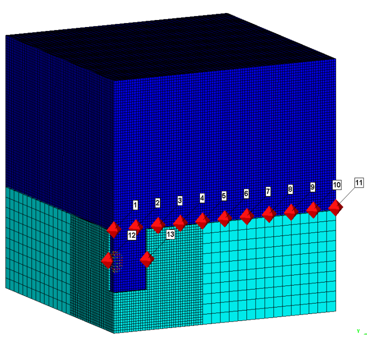


Fig 4. Model of explosion analysis using D-AUTODYN.

would occur when the gas was uniformly distributed within this space. It was also assumed that the blast pressure generated by the ignition source was uniformly propagated from the origin of the explosion. As shown in Fig. 2, the blast pressure propagation profile obtained earlier from the two-dimensional analyses was applied as the explosion input data to execute the analyses. Accordingly, the material properties of ferro-concrete, air, and TNT used in the analysis were based on the

TABLE 5. Material properties of reinforced concrete applied to analysis

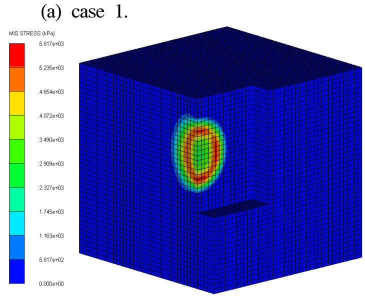
Strength and Strain	Value
Shear Modulus [kPa]	1.67e+07
Compressive Strength [kPa]	5.89e+03
Tensile Strength [kPa]	8.33e-02
Shear Strength [kPa]	1.80e-01
Intact Failure Surface Constant A	1.60e-00
Intact Failure Surface Exponent N	6.10e-01
Tens./Comp. Meridian Ratio	6.80e-01
Brittle to Ductile Transition	1.05e-02
Elastic Strength [kPa]	7.00e-01
Fractured Strength Constant B	1.6e+00
Fractured Strength Exponent M	6.1e-01
Compressive Strain Rate Exp. Alpha	3.2e-02
Tensile Strain Rate Exp. Delta	3.6e-02
Max. Fracture Strength Ratio	1.0e+20

AUTODYN database, as shown in Table 5 (Kim, 2018). To analyze the blast pressure propagation behavior, a total of 13 gauges were installed at 5 m intervals, and the blast pressure was extracted at each gauge. Assuming that the ferro-concrete of the side wall was the weathered rock, a value of 5.89e3 kPa was applied as the compressive strength, while 1/12 of the compressive strength was applied as the tensile strength according to the standards of the Ministry of Land, Infrastructure, and Transport, and the Korean Highway Corporation. Figs. 5, 6 show the results and the blast pressure propagation inside and outside of the puddle, and the stress distribution conditions of the structure in the three studied cases.

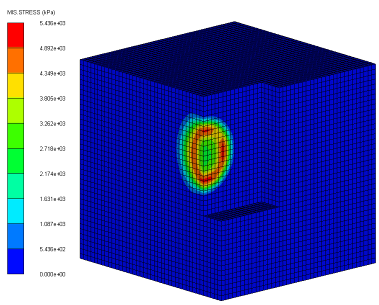
3.3 Assessment of structural failure based on the analyzed results

The possibility of collapse for each studied case in terms of the maximum blast pressures in the puddle, the

(a) case 1.



(b) case 2.



(c) case 3.

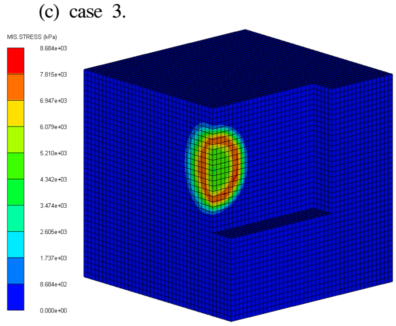


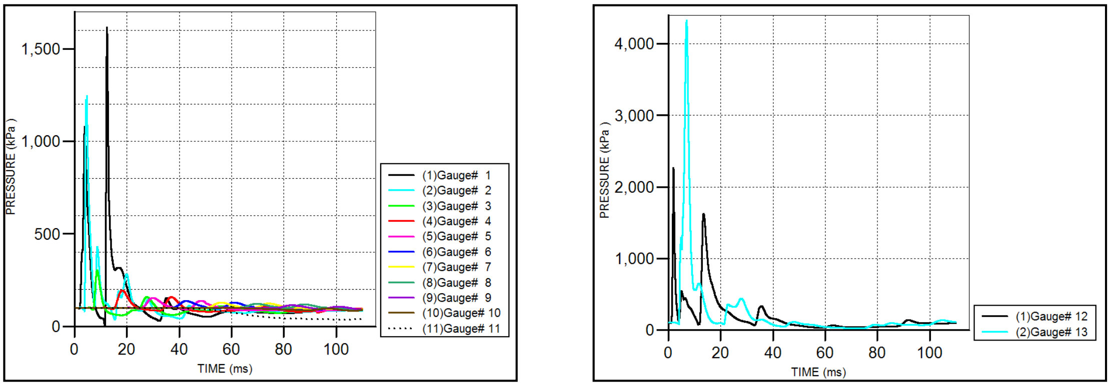
Fig. 5. Result of explosion analysis using 3D-AUTODYN.

distance of blast pressure propagation, and the stress distribution of the internal structure of the puddle based on the values obtained in Fig. 5, Fig. 6 are summarized as follows. First, in the case at which an explosion occurred in the central part of the pier hole for the two-lane bridge construction owing to LP gas leakage with a gas volume equal to 5.8% of the volume of the hole, the maximum pressure in the direction of the excavation was 1.61e3 kPa, the maximum internal pressure of the hole was 4.33e3 kPa, the distance of the blast pressure propagation was 45 m, and the maximum stress of the internal structure of the hole was 5.44e3

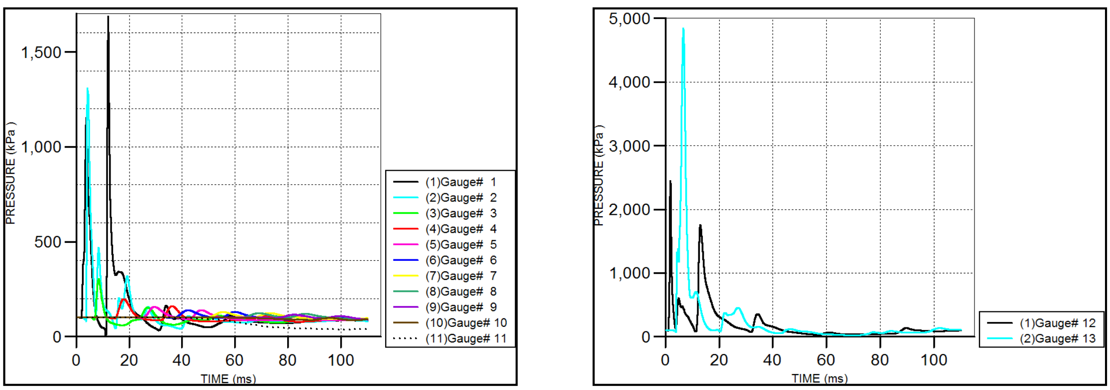
TABLE 6. Result of explosion analysis according to case

Classification	Case 1	Case 2	Case 3
Maximum pressure to ground(kPa)	1.61e3	1.69e3	3.06e3
Maximum pressure in puddle(kPa)	4.33e3	4.75e3	5.23e3
Explosive pressure propagation distance(m)	45	48	50
Maximum stress of puddle structure (kPa)	5.44e3	5.82e3	8.68e3

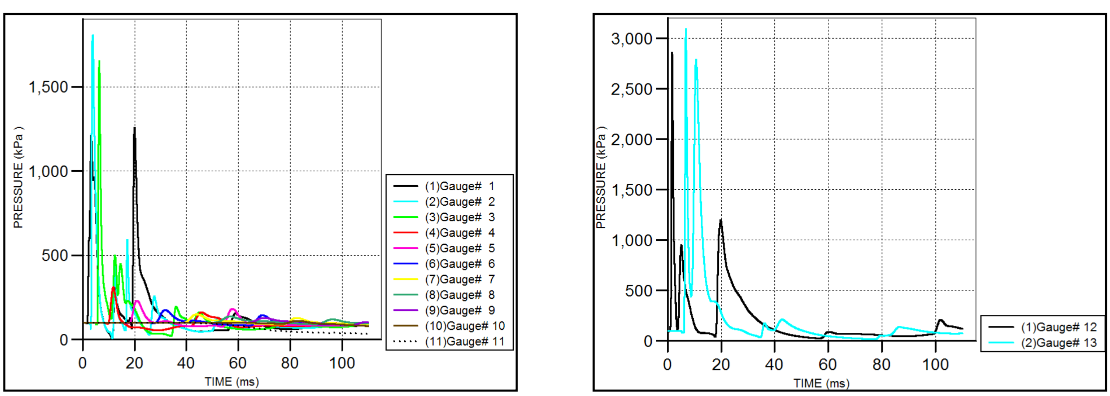
kPa. These outcomes indicate the low possibility for structural collapse. Second, in the case at which an explosion occurred in the central part of the pier hole for four-lane bridge constructions owing to LP gas leakage with a gas volume equal to 5.8% of the volume of the hole, the maximum pressure in the direction of the ground was 1.69e3 kPa, the maximum internal pressure of the hole was 4.33e3 kPa, the distance of the blast pressure propagation was 48 m, and the maximum stress of the internal structure of the hole was 5.82e3 kPa, which also suggests that the possibility of structural collapse was low. These results are summarized in Table 5. Third, in the case at which an explosion occurred in the central part of the pier hole for six-lane bridge constructions owing to LP gas leakage with a gas volume equal to 5.8% of the volume of the hole, the maximum pressure in the direction of the ground was 3.06e3 kPa, the maximum internal pressure of the hole was 5.23e3 kPa, the distance of blast pressure propagation was 50m, and the maximum stress of the internal structure of the hole was 8.68e3 kPa. These outcomes are higher than those for the compressive strength, thereby indicating the possibility of structural collapse. All the analytical results for each case mentioned above were compared and analyzed, and are presented in Table 6.



(1) Case 1



(2) Case 2



(3) Case 3

Fig. 6. Explosive pressure value for each gauge.

Ⅳ. CONCLUSION

In this study, the amount of leakage was calculated based on the TNT equivalency method after the calculation of the amount of LPG that would yield the maximum explosion energy for the excavation of the pier holes of bridge foundations with different number of lanes. Accordingly, two-dimensional and three-dimensional analyses of explosive power were conducted based on AUTODYN. Based on these, the impact of the damages on the hole structures and their stabilities in the cases of gas explosion accidents were assessed, and the possible damage characteristics were predicted. The analyses showed that the generated stresses of the structures were lower than the compressive strengths in cases 1 and 2, while the generated stress in case 3 was 8.68e3 kPa, which exceeded the compressive strength of 5.89e3 kPa. This suggests that there is a potential risk for a disaster owing to the existence of a possibility for secondary collapse of the structure due to the explosion in case of the LPG leakage with a gas volume equal to 5.8% of the volume of the hole. Thus, preventive measures are urgently needed. In this study, the power of the LPG accident for each type of hole was quantified using a commercial program to determine the possibility of collapse of the structure owing to the explosion of leaked gas. The setup is highly advantageous because it cannot be recreated experimentally. It is considered that this process can be used to analyze the cause of gas explosion accidents and estimate their impacts. It is envisaged that this process will be used in the future to allow gas leakage estimations and structural stability assessments. Furthermore, it is expected that this process will be extensively used in the field of gas safety following the improvements of its analytical reliability and validity.

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