NUMERICAL SIMULATION OF HYDROGEN EXPLOSION TESTS WITH A BARRIER WALL FOR BLAST MITIGATION

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ABSTRACT

We have investigated hydrogen explosion risk and its mitigation, focusing on compact hydrogen refueling stations in urban areas. In this study, numerical analyses were performed of hydrogen blast propagation and the structural behavior of barrier walls. Parametric numerical simulations of explosions were carried out to discover effective shapes for blast-mitigating barrier walls. The explosive source was a prismatic 5.27 m^3 volume that contained 30% hydrogen and 70% air. A reinforced concrete wall, 2 m tall by 10 m wide and 0.15 m thick, was set 2 or 4 m away from the front surface of the source. The source was ignited at the bottom center by a spark for the deflagration case and 10 g of C-4 high explosive for two detonation cases. Each of the tests measured overpressures on the surfaces of the wall and on the ground, displacements of the wall and strains of the rebar inside the wall. The blast simulations were carried out with an in-house CFD code based on the compressive Euler equation. The initial energy estimated from the volume of hydrogen was a time-dependent function for the deflagration and was released instantaneously for the detonations. The simulated overpressures were in good agreement with test results for all three test cases. DIANA, a finite element analysis code released by TNO, was used for the structural simulations of the barrier wall. The overpressures obtained by the blast simulations were used as external forces. The analyses simulated the displacements well, but not the rebar strains. The many shrinkage cracks that were observed on the walls, some of which penetrated the wall, could make it difficult to simulate the local behavior of a wall with high accuracy and could cause strain gages to provide low-accuracy data. A parametric study of the blast simulation was conducted with several cross-sectional shapes of barrier wall. A T-shape and a Y-shape were found to be more effective in mitigating the blast.

1. INTRODUCTION

Hydrogen has recently attracted a great deal of attention as an eco-friendly fuel. In particular, a vehicle powered by a fuel cell that uses hydrogen is expected to be the post-gasoline car of the future. Against this background, the development of hydrogen refueling stations for such vehicles has been aggressively pursued.

However, since hydrogen gas can burn in mixtures with air ranging from very lean to quite rich, if hydrogen gas were to leak at a hydrogen refueling station, the probability for ignition and a possible subsequent pressure loads on the surrounding structures would be high. Therefore, it is necessary to design so as to protect against the potential for serious damage to windows and also serious harm to people in the vicinity of an accident, and several such investigations have been undertaken [1].

Furthermore, since any flying debris from the blast destruction of a reinforced concrete (RC) wall would create hazards of its own, it is necessary to confirm the soundness of any barrier wall and the walls of the equipment room at the site. Therefore, it is important to predict the blast pressure of any explosion. Yet making such predictions for RC walls based on actual experiments would require a vast site and great time and expense, so a highly precise prediction by numerical simulation is needed.

In this study, we conducted hydrogen explosion tests with a barrier wall and we measured blast pressure propagation and the structural behavior of the barrier wall. A CFD (computational fluid dynamics) simulation for this explosion was also carried out, and the predictive accuracy of the numerical simulation was estimated and the distribution of the maximum blast pressure was predicted. Using the time history of blast pressure obtained by CFD, a structural simulation of a barrier wall was performed and the predictive accuracy of the numerical simulation was verified by comparison with actual explosion experiments. Finally, parametric blast simulations were conducted to find more effective shapes for barrier walls to mitigate blast effects.

2 EXPLOSION TEST

2.1 Outline of an explosion test

The explosive source was a prismatic 5.27 m^3 volume that contained 30% hydrogen and 70% air. A reinforced concrete wall, 2 m tall by 10 m wide and 0.15 m thick, was set at 2 or 4 m from the front surface of the source. Figure 1 shows the wall and explosion source. The source was ignited at the bottom center by a spark for the deflagration case and by 10 g of C-4 high explosive for the two detonation cases. Table 1 shows the test parameters.

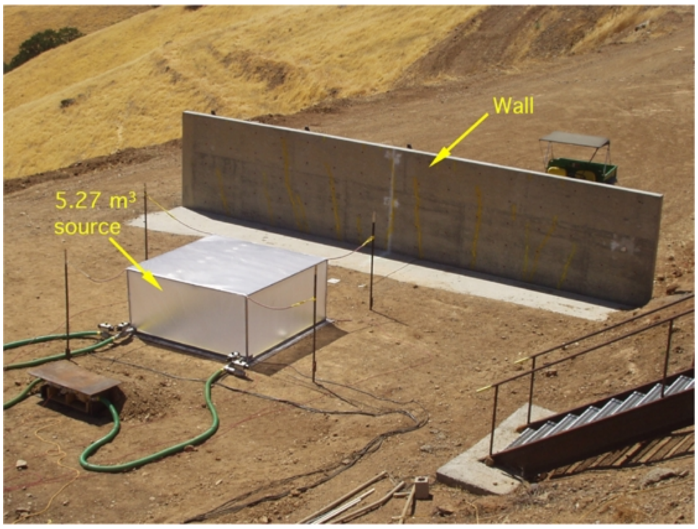


Figure 1. Wall and explosive source

Table 1. Test parameters

Test	Wall Range (m)	H_2 (%)	Ignition	Temp. (℃)	Wind (m/s)
Case1	4	30.0	Spark	27.2	2.2
Case2	4	30.0	Explosive	29.8	0.4
Case3	2	30.3	Explosive	22.4	1.3

Instrumentation for these tests consisted of three pressure transducers located along the ground surface in front of and behind the wall, as well as six sensors on the surface of the wall (three on the front and three on the back) as shown in Figs. 2 and 3. Also, wall motion was measured with six displacement sensors on the top of the wall and at the mid-height of the wall at three locations. The rebar response was monitored with pairs of strain gauges installed on the rebar near the front and back surfaces of the wall at 15 locations.

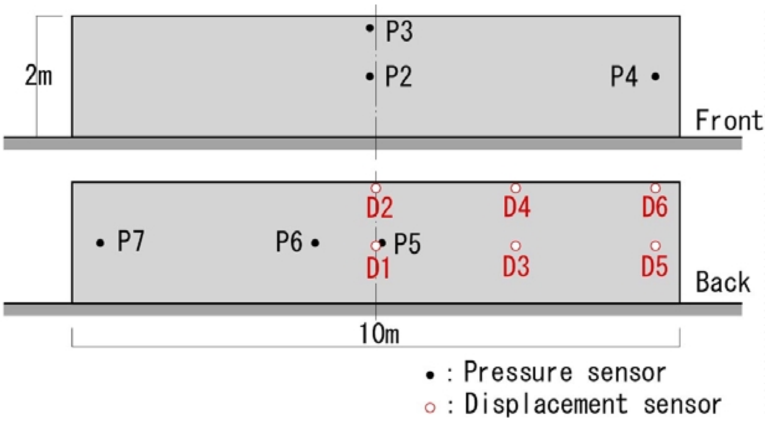


Figure 2. Pressure and displacement sensor locations on the surface of the wall

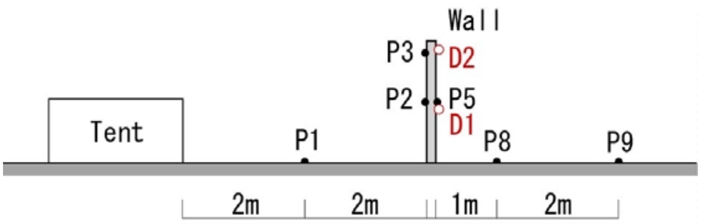


Figure 3. Pressure and displacement sensor locations along the ground surface

2.2 Results of an explosion test

Figure 4 shows frames from the video records of Case1 and Case2. The detonation (Case2) produced a loud sound, an earth tremor, and a cloud of dust.

The pressure time histories (P2 and P5) for Case1 and Case2 are shown in Figs. 5 and 6. Some pressure transducers on the front face of the wall show a small late time negative drift due to the thermal load from the hydrogen/air explosion. In the deflagration case (Case1), there is a slight difference in the pressure on the front and back faces of the barrier wall. In contrast, in the detonation case, the pressure differences are large.

Figure 7 shows the displacement time history (D1 and D2) in Case1 and Case2. It can be seen that with deflagration the wall vibrates at its natural period. With detonation, after a large displacement at the first sharp blast wave, the wall vibrates at a higher frequency containing its natural period.

Figure 8 shows range versus peak pressure. This is in good agreement with data obtained in the IAE/NEDO tests [2] though the peak pressure of deflagrations is slightly lower than IAE/NEDO results because the tent is not cut before ignition.

Figure 9 shows the distribution of cracks on the front and back sides of the barrier wall. Horizontal cracks became visible after the first detonation test (Case2) at the mid-height of the wall.

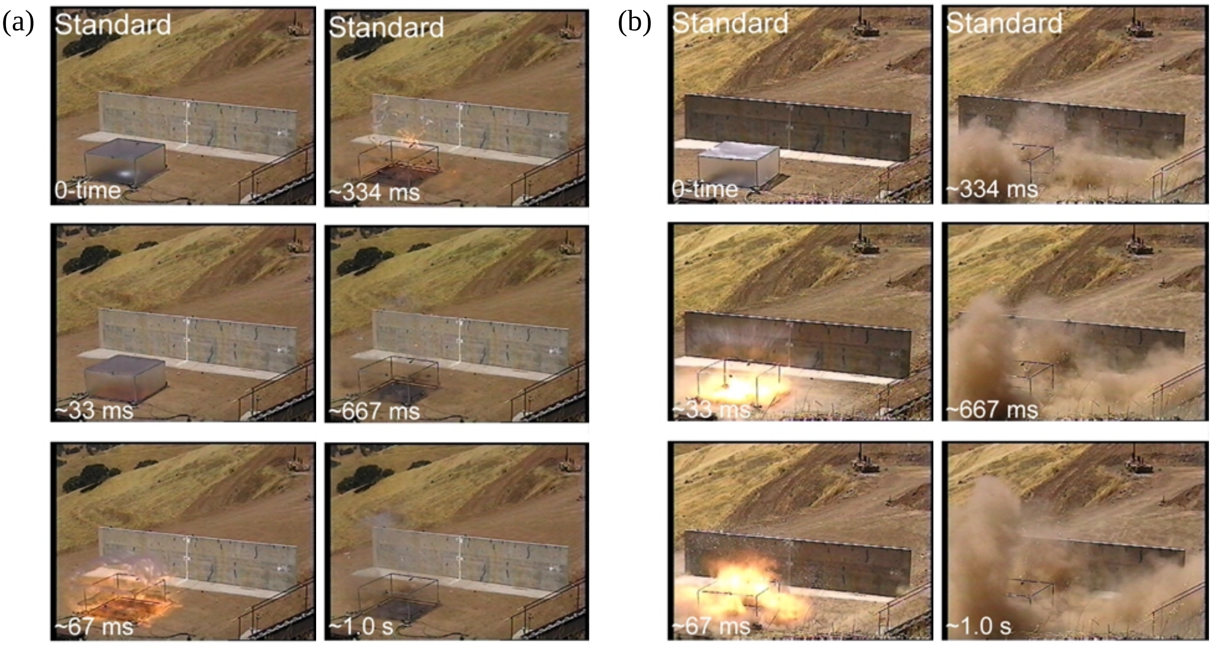


Figure 4. Video frames of (a) Case1 and (b) Case2

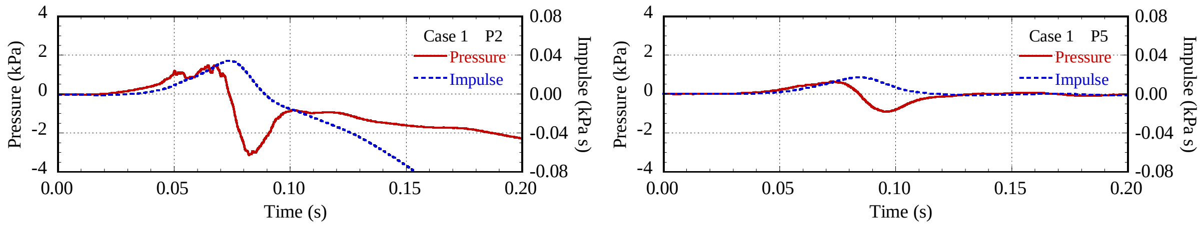


Figure 5. Pressure time history in Case1 (P2 and P5)

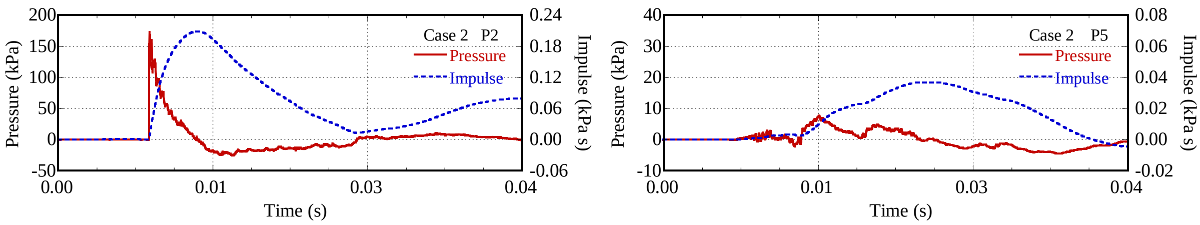


Figure 6. Pressure time history in Case2 (P2 and P5)

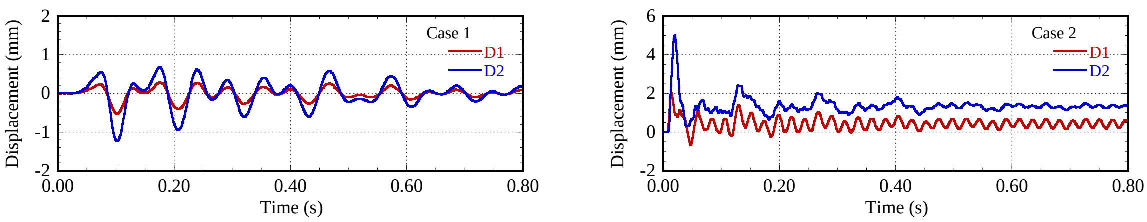


Figure 7. Displacement time history in Case1 and Case2 (D2)

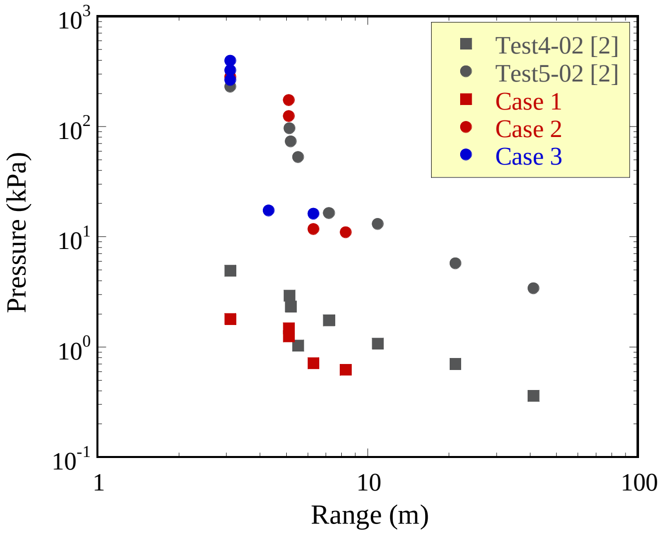


Figure 8. Range versus peak pressure.

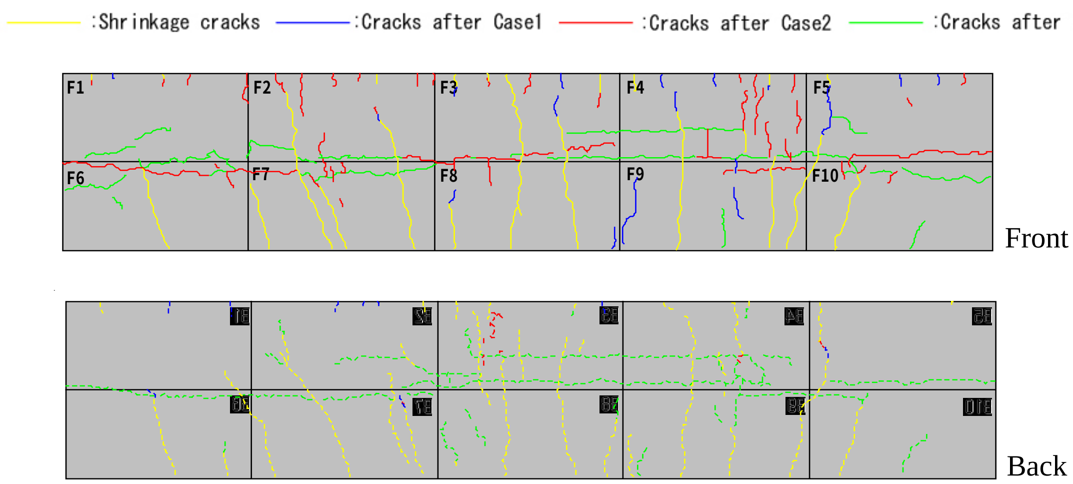


Figure 9. Distribution of cracks after each test

3. NUMERICAL SIMULATION OF BLAST WAVE PROPAGATION

3.1 Outline of blast simulation

Numerical simulations of blast wave propagation were performed with an in-house CFD code based on the 3D compressive Euler equation. The calculation domain was 22 m × 20 m × 12 m in the X-, Y-, and Z-directions (see Fig. 10). The barrier wall was located as it was in the explosion tests and the simulation cases are the same as in the explosion test cases. The grid is Cartesian equidistant comprised of 221×201×61 cells. The horizontal cell resolution is 0.1 m, and the vertical cell resolution is 0.2 m. The time step in the deflagration case is 2.35×10^{-4} s, and that in the detonation case is 5.88×10^{-5} s. The spatial difference used the third-order MUSCL-TVD scheme with Roe's approximate Riemann solver. The time integration scheme used the second-order Runge-Kutta method.

Since the combustion simulation was not conducted, the total combustion energy estimated from the volume of hydrogen was a time-dependent function for the deflagration and was considered to be released instantaneously for the detonations [3].

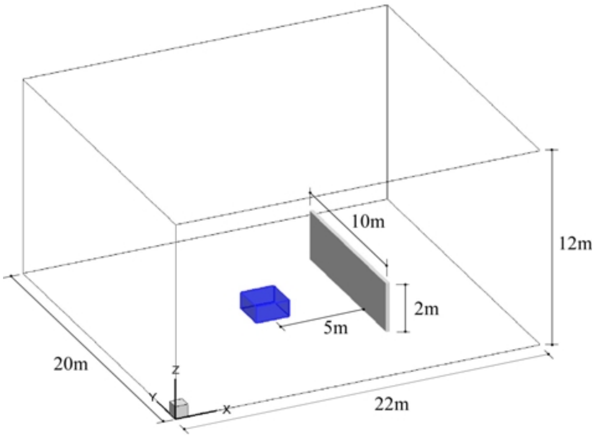


Figure 10. Calculation domain

3.2 Results of blast simulation

Figure 11 shows instantaneous pressure contours and pressure iso-surfaces at various time steps in the detonation case. In the first stage of the explosion, the blast wave was a hemisphere, and when it encountered the barrier wall it was reflected, and diffraction occurred at the corner of the wall.

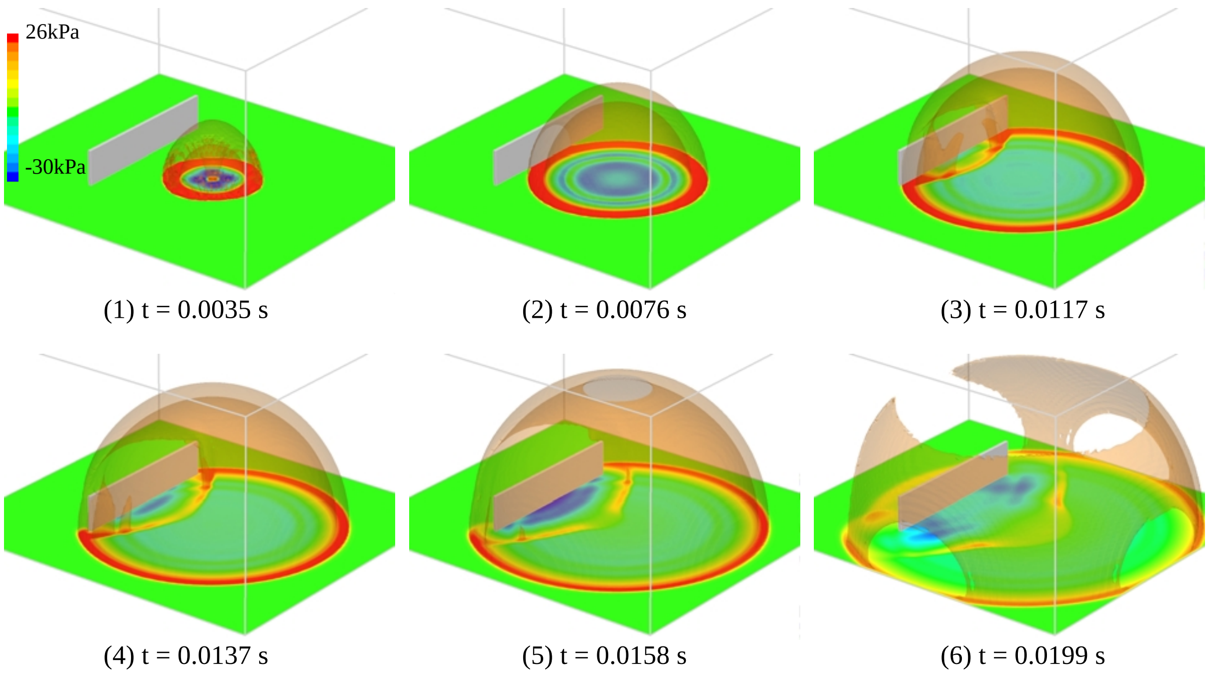


Figure 11. Instantaneous pressure contours and pressure iso-surfaces at various time steps in the detonation case (Case2)

Figures 12 and 13 show blast pressure time histories on the front and back faces of the barrier wall. The CFD results captured the characteristic shape of the peak value of the detonation (Case2). Especially for P5 of Case2, all peak positions and values reproduced the experimental results. In the explosion test, there was a slight pressure difference between the front and back faces of the barrier wall in the deflagration case, but there was a large difference with a detonation. CFD results reproduced these phenomena well.

Figure 14 shows the distribution of the peak blast pressure on the barrier wall. On the back surface of the wall, it was large in the area from the corner to the lower side because of the union of the blast wave from the upper surface and that from the side of the wall. In contrast, on the front surface of the wall, the blast pressure decreased with distance from the center of explosion.

The distribution of the peak blast pressure around the barrier wall is shown in Fig. 15. The peak value diminished in proportion to the distance from the center of explosion. Although the effect of blast pressure mitigation by a barrier wall can be confirmed, its effect is comparatively small in the deflagration case compared with the detonation case.

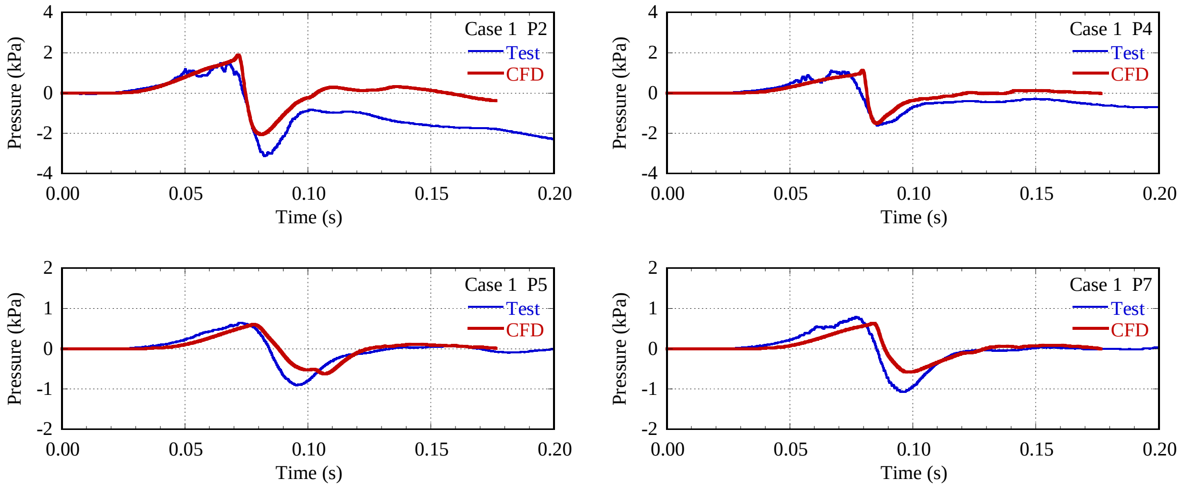


Figure 12. Blast pressure time histories on the barrier wall in Case1

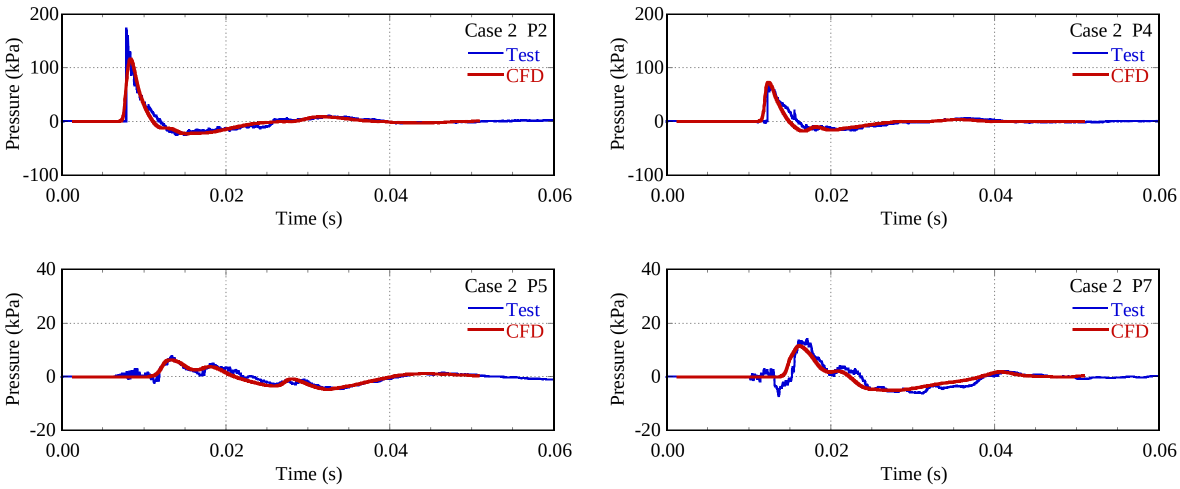


Figure 13. Blast pressure time histories on the barrier wall in Case2

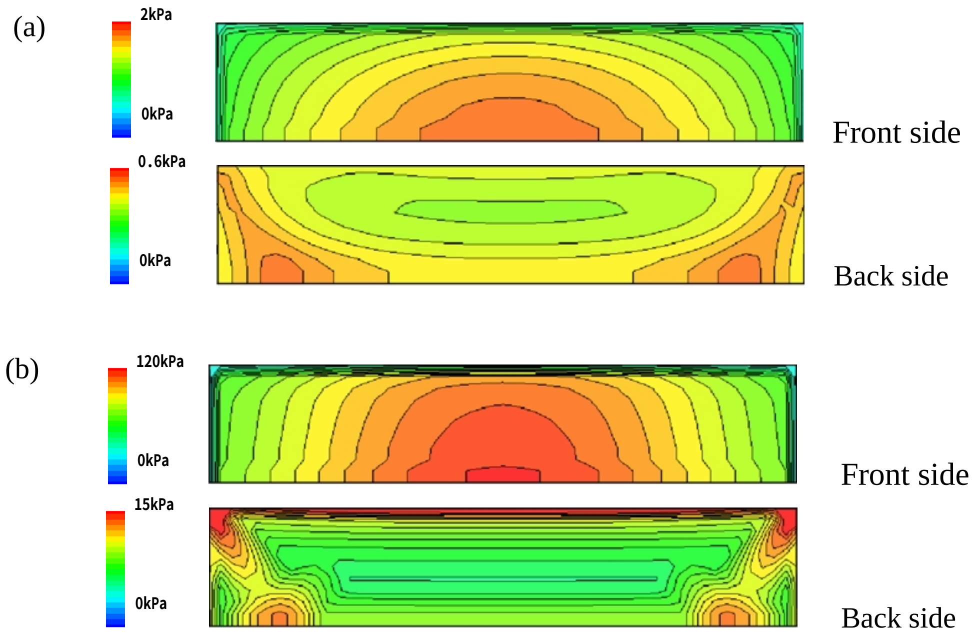


Figure 14. Distribution of the peak blast pressure on the barrier wall for (a) Case1 (b) Case2

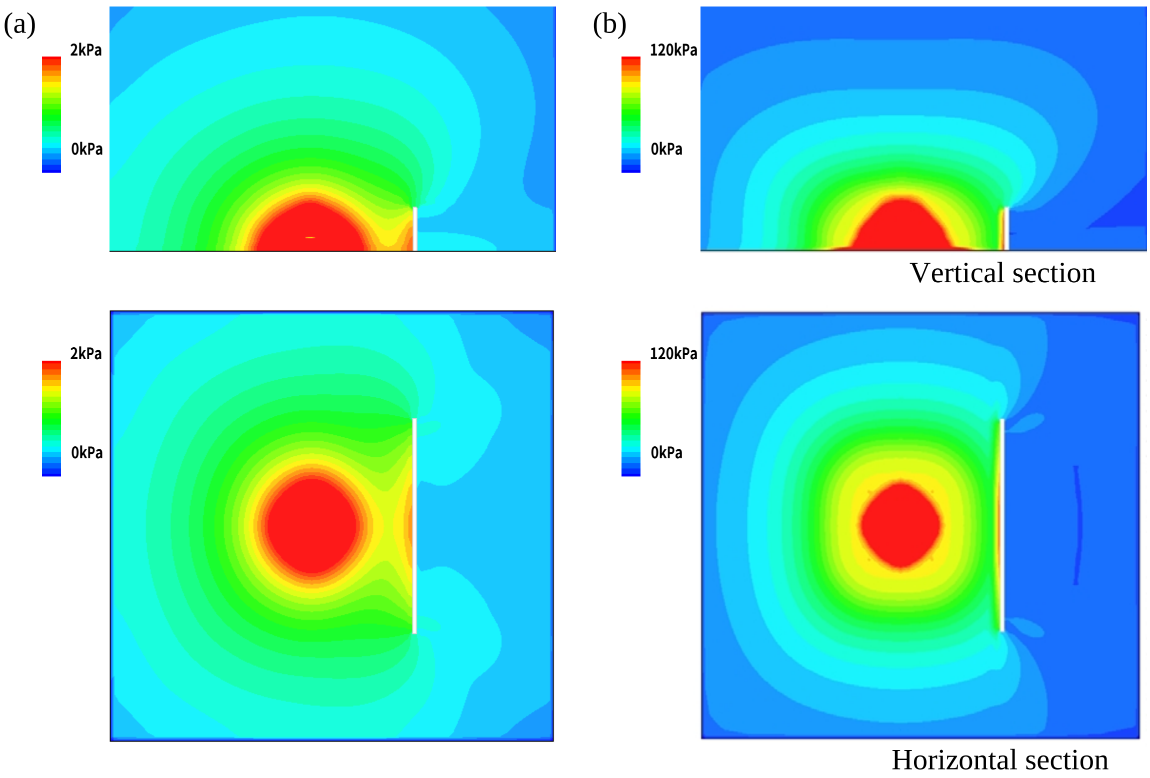


Figure 15. Distribution of the peak blast pressure around the barrier wall for (a) Case1 (b) Case2

4. NUMERICAL SIMULATION OF STRUCTURAL BEHAVIOR OF A BARRIER WALL

4.1 Outline of structural simulation

Using the time history of blast pressure obtained by CFD, a structural simulation of barrier wall performance was made. Half of the barrier wall was modeled, with the other half assumed to be identical by symmetry, and the bottom of the wall was modeled as being in a fixed state. The wall was assumed to be a finite-element model with a square shell (200 mm × 200 mm). The concrete was modeled by being divided into 9 slices in the direction of thickness, and the rebar was modeled as a shell element with an area equal to the actual cross-sectional area. The material characteristics of the barrier wall were determined based on material test results for rebar and concrete. DIANA, a finite element analysis code released by TNO, was used for the structural simulations of the barrier wall. The time step was 5.0×10^{-4} s, and the space-time solver used ß–Newmark integration scheme.

4.2 Results of structural simulation

Figures 16 and 17 show the displacement of the wall in Case1 and Case2. In the figures, the blue lines represent the test results, and the red lines represent the numerical simulation results. The structural analyses simulated the displacements well, although the simulation results in the deflagration case had a slight phase shift and the test results in the detonation case had a positive drift.

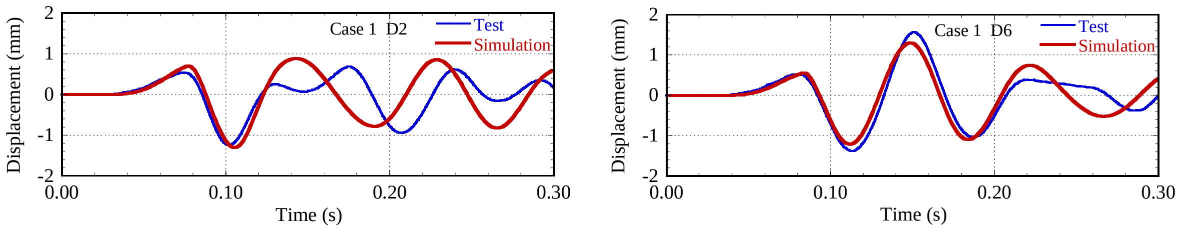


Figure 16. Displacement of D2 and D6 (Case1)

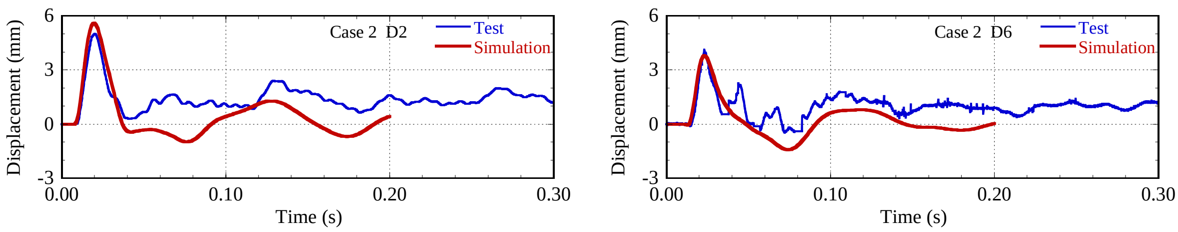


Figure 17. Displacement of D2 and D6 (Case2)

Figure 18 shows the concrete strains on the front surface of the wall in Case2 at various time steps. In the figure, a red area represents the level where a crack occurred because the concrete stress exceeded the tensile strength of the concrete. In the detonation test (Case2), cracks were generated at the mid-height of the wall, and this numerical simulation matched the test result. However, the cracks at the bottom of the wall in the numerical simulation were not observed in the test. It is possible that the bottom of the wall was not actually a fixed edge because of the low density of rebar at the wall foundation.

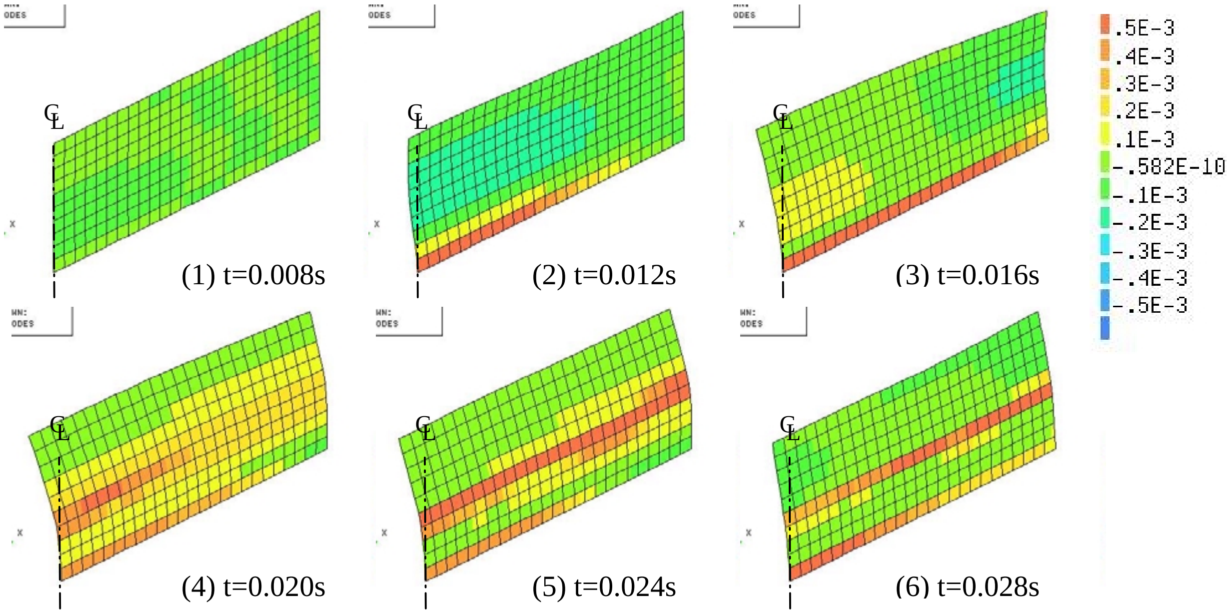


Figure 18. Concrete strains on the front surface of the wall in Case2 at various time steps

5. EFFECTIVE SHAPES OF A BARRIER WALL FOR BLAST PRESSURE MITIGATION

5.1 Outline of the model case

A parametric study of the blast simulations was conducted to find effective cross-sectional shapes for a barrier wall to mitigate blast pressure. Figure 19 shows the barrier wall shapes that were analysed. Blast pressure was measured at points located 2 m and 6 m from the back surface of the wall (see Fig. 20.). These walls were 2 m tall (3 m in Case1) by 10 m wide and 0.15 m thick. Other calculation conditions were the same as in Sec. 3. In this analysis, the detonation case is examined.

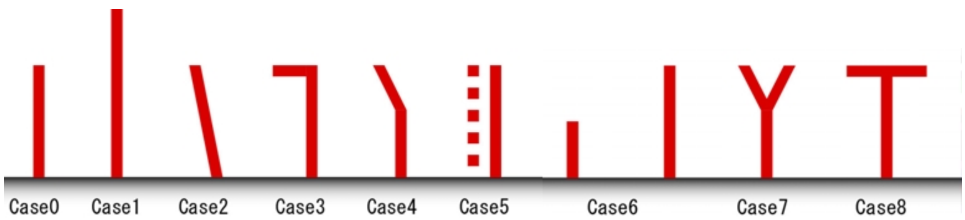


Figure 19. Analysed cross-sections of barrier wall shapes

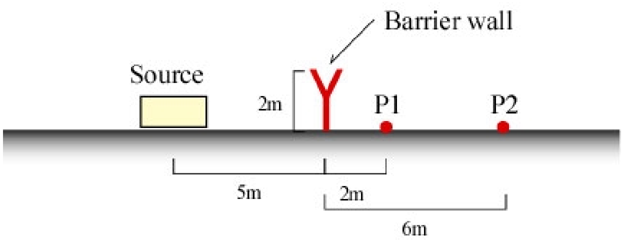


Figure 20. Pressure measurement points

5.2 Results of the blast mitigation

Figure 21 shows blast pressure time histories at measurement points P1 and P2 in various cases. The second peak of the time histories is due to the refracted blast wave around the side of the wall. In

Case1 (wall height = 3 m) and Case8 (T-shape), not only a positive pressure peak value but also a negative pressure peak value can be mitigated.

Table 2 shows the maximum value of the blast pressure in each case. These values are expressed non-dimensionally as a fraction of the maximum value in the no-barrier case and Case0. A Y-shape mitigated the blast pressure by 26% at point P1 and a T-shape mitigated pressure by 42% at point P1. A T-shape was found to mitigate the blast pressure more than a 3 m high wall with an I-shape (Case1). These shapes (Case7 and Case8) also mitigated the blast at points distant from the wall (point P2).

Figure 22 shows the instantaneous pressure contours in a Case0, Case7 and Case8. In these cases (Case7 and Case8), wave diffraction occurred twice at the top edge of the wall, mitigating the blast wave pressure. It appeared that the effect of this wave diffraction was similar to that of a sound isolation wall [4], and we confirm that it is effective for a shockwave.

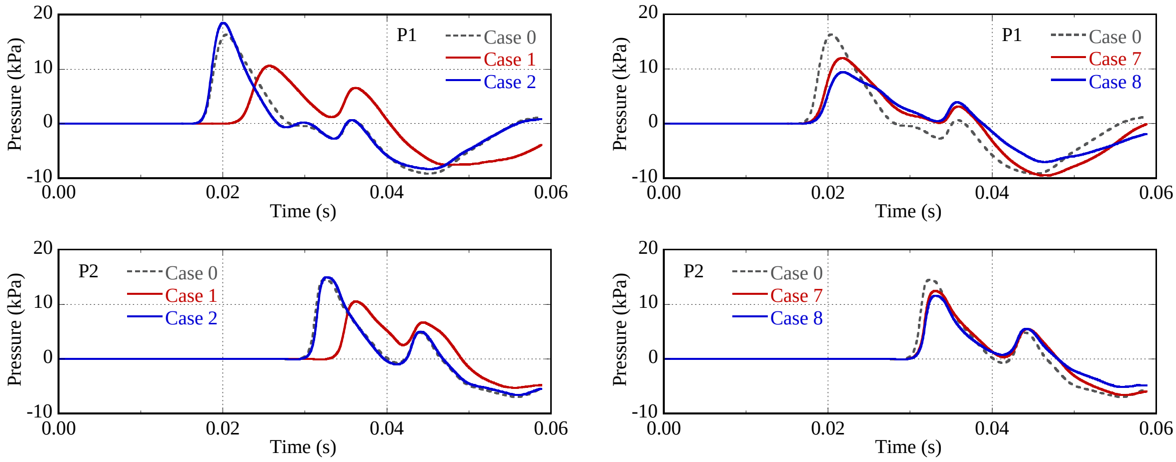


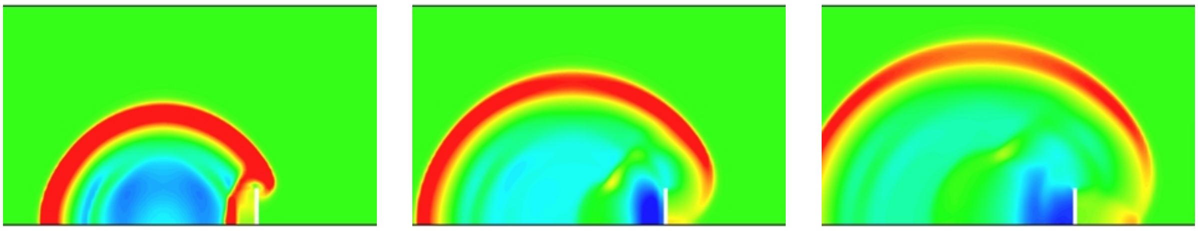
Figure 21. Blast pressure time histories at points P1 and P2

Table 2. Non-dimensional maximum value of the blast pressure

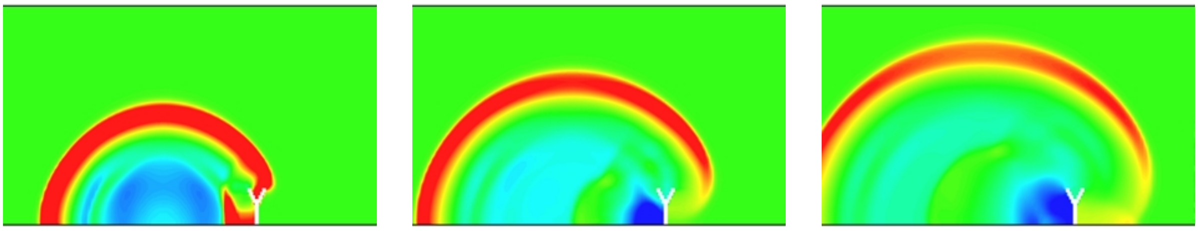
case	wall shape	P1/P1(no wall)	P2/P2(no wall)	P1/P1(case0)	P2/P2(case0)	case	wall shape	P1/P1(no wall)	P2/P2(no wall)	P1/P1(case0)	P2/P2(case0)
Case0		0.32	0.61	1.00	1.00	Case5		0.30	0.58	0.96	0.96
Case1		0.21	0.44	0.65	0.72	Case6		0.27	0.52	0.85	0.86
Case2		0.36	0.63	1.14	1.03	Case7		0.23	0.52	0.74	0.86
Case3		0.28	0.54	0.89	0.89	Case8		0.18	0.48	0.58	0.80
Case4		0.31	0.59	0.97	0.98						

6. CONCLUSIONS

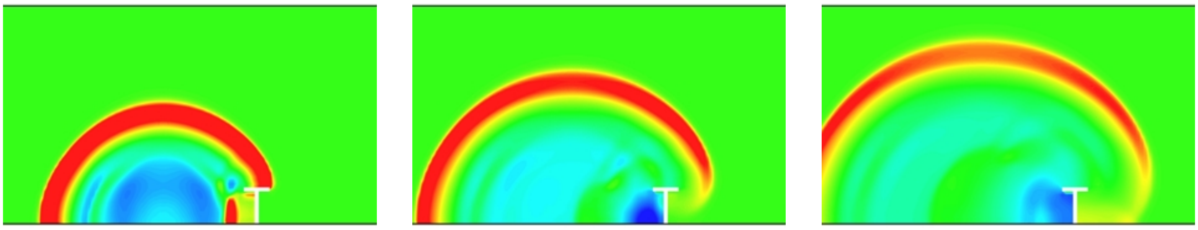
In this study, numerical simulation was performed to examine the events following a hydrogen explosion, and the predictive accuracy of the simulation was verified, as the calculated results reproduced tests with actual explosions. Also, effective wall shapes for blast mitigation have been found with CFD. Specifically, the following conclusions were drawn:



(1) I-shape (Case0)



(2) Y-shape (Case7)



(3) T-shape (Case8)

Figure 22. Instantaneous pressure contours in Case 0, Case 7 and Case 8

1) It was confirmed that numerical simulation can reproduce both deflagration and detonation tests with good accuracy if appropriate initial energy conditions are chosen.
2) When the blast pressures on the surface of a wall are obtained with good accuracy, the behavior of a RC wall can be reproduced by a structural simulation.
3) It was confirmed that T-shape and Y-shape walls are more effective in mitigating blast pressure because the wave diffraction at the top edge of the wall occurs twice.

ACKNOWLEDGEMENTS

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