SIMULATION ABOUT EFFECT ON EXPLOSION SPALLING OF THERMAL STRESS AND VAPOR PRESSURE

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Abstract

The effect on explosion spalling of thermal stress and vapor pressure was investigated numerically using a developed method in order to simulate fire explosion behavior. In the method, 3-dimensional Rigid Body Spring Model (RBSM) based on dynamic equation of motion as structural analysis and truss network model as mass transfer analysis were integrated. It was understood by the numerical results that the contributions of thermal stress and vapor pressure depend on the boundary conditions for the constraint of thermal expansion deformation. Although the vapor pressure is usually main factor of explosion spalling, the effect of thermal stress may become predominant under the constraint boundary condition.

1. Introduction

The fireproof and safety of concrete structures are time dependent combination problem of material, structure and mass transfer such as temperature, moisture and vapor. Moreover, the fireproof closely relate with the explosion at the surface of concrete structure. There are three reliable explanations of the concrete explosion. That is, the effect of thermal stress, the vapor pressure and the combination of both have been generally widespread acknowledgment.[1] In order to evaluate fireproof performance of concrete, the mechanisms of the explosion spalling of concrete in fire should be elucidated.

A numerical method to simulate explosion spalling behavior of concrete subjected to high temperature has been developed by authors [2]. The method is that 3-dimensional Rigid Body Spring Model (RBSM) as structural analysis and truss network model as mass transfer analysis are integrated. The method can simulate structural behavior due to thermal stress and vapor pressure considering the changes of distributions of temperature and vapor pressure obtained from truss network model.

In this study, the effect on explosion spalling of thermal stress and vapor pressure is investigated numerically using a developed method in order to simulate fire explosion spalling behavior. The effects are seperately investigated considering the cracking propagation behaviors of specimen inside. Moreover, the effect of constraint condition of thermal expansion deformation is discussed.
2. **ANALYTICAL METHOD**[2]

2.1 **3-Dimensional RBSM**

3-dimensional RBSM with Voronoi diagram is used as structural analysis, which represents a continuum material as an assemblage of rigid particle elements interconnected by zero-size springs along their boundaries. RBSM is easy to deal with crack propagation of concrete directly, since it is one of the discrete approaches. Each rigid particle has three translation and three rotational degrees of freedom defined at nuclei. The interface between two particles consists of several springs as shown in Figure 1. That is, a boundary surface is divided by triangles with the center of gravity point and vertices of the surface, and individual one normal and two tangential springs are set at the integral point.

![Figure 1: Rigid Body Spring Model](image)

2.2 **Truss network model**

3-dimensional truss network model integrated with RBSM is applied to both heat conduction analysis and vapor pressure transfer analysis. Voronoi particle is linked by the truss elements with the node at the nuclei and the intermediate points of particle boundary, as shown in Figure 2. Each truss is assumed to have the area corresponding to the area of the Voronoi particle boundary surface. Then, a simplified 1-dimensional diffusion equation using truss element is employed to carry the potential flow such as the heat and the vapor pressure.

![Figure 2: Truss network model](image)

2.3 **Concrete material models**

The tensile behavior of concrete up to the tensile strength is modeled by using a linear elastic, while bilinear softening branch according to 1/4 model is assumed after cracking, as shown in Figure 3(a) which is represented by the tensile strength, $f_t$, the tensile fracture energy, $G_{ft}$, and the distance between nuclei, $h$. The behavior of concrete under compression is modeled using a parabolic curve up to compressive strength $f'_c$. The slope of a linear softening branch is defined by considering the compressive fracture energy, $G_{fc}$.

Tangential springs represent the shear transfer mechanism of uncracked and cracked concrete. The shear strength is assumed to the Mohr-Coulomb type criterion with tension and compression caps. After shear stress reaches the yields strength, the stress moves on the yields surface. The shear transfer capacity at crack interfaces depends on crack opening. Thus, the shear stress is calculated by the function of crack width, shear stiffness and shear strain. It is noted that the material properties are assumed by the ones at normal temperature for simplicity, although they show the temperature dependency.

![Figure 3: Stress-strain relationship](image)

<table>
<thead>
<tr>
<th>Table 1: Material properties of concrete</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressive strength (MPa)</td>
<td>88.4</td>
</tr>
<tr>
<td>Tensile strength (MPa)</td>
<td>6.9</td>
</tr>
<tr>
<td>Young modulus (GPa)</td>
<td>41.0</td>
</tr>
</tbody>
</table>
3. OUTLINE OF ANALYSIS

Figure 4 shows the analytical flow in the developed method. The method is combined with the heat conduction analysis, the vapor pressure transfer analysis and the structural analysis. First, the heat conduction analysis is performed by truss network model, in which the temperature dependent parameters of specific heat $c(T)$ and heat conductivity $\lambda(T)$ are defined by the temperature in previous step. Then, the temperature distribution obtained from the heat conduction analysis is used to estimate the saturated vapor pressure $P^*$ and the thermal expansive strain $\Delta e_n$.

In the vapor pressure transfer analysis, the production of vapor pressure is calculated by considering the estimated saturated vapor pressure and relative humidity obtained in previous step. The distribution of vapor pressure is calculated by solving moisture transfer equation. The estimated vapor pressure is applied to structural analysis and the relative humidity is renewed for next step.

The structural analysis is performed by considering the thermal stress and the vapor pressure. The thermal stress is considered by initial strain problem using the thermal expansion strain. The vapor pressure is considered by initial stress problem, which is applied to normal spring in RBSM. The dynamic analysis is performed by solving the equation of motion in order to simulate the explosion spalling behavior. The equation of motion is solved by Newmark’s $\beta$ method implicitly. The value of $\beta$ is 0.25. Time step is set as 12(s) in usual condition and is set as 0.06(s) during explosion spalling. The structural analysis provides the cracking and the explosion spalling behavior. Moreover, the effect of cracks is considered in the vapor pressure transfer analysis, in which larger parameters are set.
4. OUTLINE OF EXPERIMENT

The configuration and dimensions of a tested specimen is shown in Figure 5. The specimen had dimensions of $400 \times 400 \times 100$ mm. The material properties of concrete are shown in Table 1. Two pairs of steel pipes were placed in the concrete at distances of 10 and 20 mm from the heated face in order to measure the vapor pressure, and set parallel to the heated face. Six thermocouples were placed in the central zone of the specimen at 5, 10, 20, 30, 40, and 50 mm from the heated face in order to measure the temperature. An electric furnace was used for heating the specimen. In the heating tests, the temperature was increased with the rate of 1000 °C/hour.

The heating curve and the variations in internal temperature at 5, 10 and 30 mm from the heated face are shown in Figure 6. The internal temperature at 5 mm from the heated face reached 350 °C at 55 minutes which is maximum temperature. Figure 7 shows the history of the vapour pressure at 10 and 20 mm from the heated face. The vapour pressure started to increase at 100 °C and reached to 3.0 MPa before explosion spalling at 55 minutes. The depth of spalling was about 10mm.

4. ANALYTICAL MODEL

4.1 Analytical Model

The analytical model is shown in Figure 8. The analysis is performed by 1/4 model ($200 \times 200 \times 100$ mm) considering the symmetry of the specimen and the heating condition. The specimen is divided by the Voronoi particles, and the mean element size is about 2mm near the heating area. Four point simple supports are assumed as the structural boundary conditions.

Table 2 indicates the heat transfer coefficients. The values depend on surface temperature and were decided by prior analysis to obtain similar temperature changes with test results. Table 3 shows the parameters of vapor pressure transfer analysis. The values through cracks are assumed 10 times of bulk concrete. The values were decided by prior analysis considering depth of explosion spalling in the test, since the values affect to the distribution of vapor pressure. Table 4 indicates the other properties of concrete used in the analysis. The relative humidity at the heating surface is assumed to be 0 as the convective boundary condition of vapor pressure transfer.

<table>
<thead>
<tr>
<th>Surface temperature°C</th>
<th>0-100</th>
<th>100-170</th>
<th>170-275</th>
<th>275-300</th>
<th>300+</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat transfer coefficient(W/m².K)</td>
<td>7.0</td>
<td>14.0</td>
<td>21.0</td>
<td>25.2</td>
<td>30.8</td>
</tr>
</tbody>
</table>
4.2 Analytical Result

Figure 6 and Figure 7 show the comparison between test and analytical results of the temperature and the vapor pressure histories, respectively. Good agreements can be seen in both results, since the parameters were set by the prior analysis considering the adaptability. The explosion spalling occurred at about 50 minutes. The time is similar with the test result.

Figure 9 shows the distribution of the temperature, the vapor pressure and the relative humidity on symmetric boundary just before explosion spalling. The vapor pressure distributes around slight inside from the surface. The relative humidity decreases to the surface due to the effect of fire heat. The vapor pressure has a close relationship with the relative humidity and the temperature. The peak of vapor pressure is located about 10 mm depth from the surface and it almost coincides with spalling depth observed in the test. The maximum value of the vapor pressure is about 2.2 N/mm², which is smaller than the tensile strength of concrete. Figure 10 shows the deformation behavior during explosion spalling. The deformation increase at the surface and explosion spalling is observed with the spreading deformed area. The explosion spalling occur suddenly and during very short time. The developed method can simulate the spalling behavior directly, since it is based on discontinuous mechanics with dynamic equation of motion.

Figure 11 show the cracking behavior on symmetric boundary. The red parts correspond to the cracking where tensile stress become smaller than 1/4 ft and the green parts correspond to the cracking where tensile stress reaches to the tensile strength, ft. At 38 minutes, the cracks of specimen inside occur and the cracks grow and propagate in the specimen. The cracks are caused by thermal stress due to internal constraint. Then, cracks near the surface occur from an area where cracks of the specimen inside are propagating. Finally, the cracked area spread along surface with explosion spalling behavior. The cracks near surface are strongly related to the distribution of vapor pressure.

<table>
<thead>
<tr>
<th>Table 3: Parameters of vapor pressure transfer</th>
<th>Table 4: Material properties of concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td>moisture conductivity g/m²·hr·mmHg</td>
<td>concrete</td>
</tr>
<tr>
<td>0.0095</td>
<td>950</td>
</tr>
<tr>
<td>moisture capacity g/m³·mmHg</td>
<td>2500</td>
</tr>
<tr>
<td>evaporation ratio g/m³·hr·mmHg</td>
<td>500</td>
</tr>
<tr>
<td>Thermal expansion coefficient</td>
<td>1.00×10⁻⁵</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.18</td>
</tr>
<tr>
<td>Mass density kg/m³</td>
<td>2300</td>
</tr>
</tbody>
</table>

![Figure 9](image1.png) Distribution of temperature, vapor pressure and relative humidity before explosion

![Figure 10](image2.png) Explosion behavior (magnification of 1.0)

![Figure 11](image3.png) Cracking behavior at symmetric boundary
5. EFFECT OF THERMAL STRESS AND VAPOR PRESSURE

5.1 Effect of Thermal Stress and Vapor Pressure of Tested Specimen

The advantage of analysis can investigate the effect of several factors separately. The effect of thermal stress only is investigated by neglecting the vapor pressure. Figure 12 shows the deformation and cracking behavior after 50 minutes. In the analysis, the heating curve is assumed to keep maximum temperature after 55 minutes as shown dotted line in Figure 6. The assumption amplifies the effect of thermal stress. The cracks occur at specimen inside and do not develop near surface. Moreover, the spalling behavior does not occur due to thermal stress only. Black lines of Figure 13 show the stress histories at surface and specimen inside. The stress at surface does not increase remarkably and it does not follow the spalling behavior. The compressive stress at surface become small based on the equilibrium condition, since stress of specimen inside is negligibly small where the cracks occur due to thermal stress of internal constraint.

![Figure 12: Deformation and cracking behavior at symmetric boundary due to thermal stress](image)

The effect of vapor pressure only is investigated by neglecting the internal stress due to thermal expansion. Figure 14 shows the deformation and cracking behavior during spalling. Before spalling, cracks occur and propagate only near the surface and no cracks of specimen inside are observed. It is understand that the vapor pressure is closely related to the explosion spalling behavior obviously, though the effect is limited near the surface. The explosion spalling occurred at about 55 minutes, which is later than the case accompanying the effect of thermal stress as discussed in previous section. And the maximum value of vapor pressure at spalling was about 8.0N/mm², which is larger than tensile strength of concrete and is larger value than the above case. These results suggest that the vapor pressure is main factor of explosion spalling and the thermal stress contribute the occurrence of explosion spalling at earlier time and smaller vapor pressure in the test specimen.

![Figure 14: Crack behavior at symmetric boundary due to vapor pressure](image)
5.2 Effect of Constraint of Thermal Expansion

Analytical results showed that the thermal stress is not the main factor to explosion spalling in tested specimen. The test specimen was set on the electric oven without constraint condition. However, the segment concrete of tunnel structures is constrained by the deformation along circular direction and the boundary condition is different from the condition of test specimen. Therefore, the analysis of test specimen considering constraint of thermal expansion deformation in horizontal direction is performed. In order to discuss the relationship between thermal stress and constraint condition, the analysis is performed by neglecting the effect of the vapor pressure. In the analysis, same heating curve with above case is applied and the horizontal deformation at side of specimen are fixed as constraint boundary condition.

Figure 16 shows the deformation and cracking behavior after 50 minutes. The cracks of specimen inside due to thermal stress of internal constraint are not observed. On the other hand, the surface cracks gradually develop. Finally, the spalling behavior is observed due to the effect of thermal stress only, though the behavior is not explosive. This behavior can be understood from the stress histories at surface and specimen inside as shown in Figure 13. The stress of specimen inside behaves in compression for constraint effect of deformation. As a result, compressive stress at surface increases remarkably based on the equilibrium condition. The compressive stress at surface reach to compressive strength and compressive failure occur. This results indicate that the spalling behavior due to thermal stress may become predominant under constraint condition of deformation.

5. CONCLUSIONS

1. A developed numerical method, which is an unified structural analytical method with the heat conduction analysis and the vapor transfer analysis, can simulate fire explosion spalling behavior of concrete.

2. The vapor pressure is a main factor of explosion spalling and the thermal stress contribute the occurrence of explosion spalling at earlier time and smaller vapor pressure in the test specimen.

3. The spalling behavior due to thermal stress may become predominant under constraint condition of thermal expansion deformation.

REFERENCES