ANALYTICAL ESTIMATION OF RESISTANCE PERFORMANCE OF FIBER REINFORCED CONCRETE WALLS UNDER HIGH-SPEED IMPACT LOADING

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ABSTRACT

In this paper, we focus on the assessment of the resistance performance of fiber reinforced concrete (FRC) walls with steel fiber and polyamide fiber comparing with normal concrete wall in analytical methods. Finite element analysis of reinforced concrete walls, which were applied with normal concrete, steel 1% FRC, and polyamide 2% FRC, respectively, was performed regarding impact load. Considering asymmetric feature of the model, a full 3D model was produced. The displacement, stress and equivalent plastic strain of the walls were presented. From the comparison of deformation area of the walls and the deformation of missile, the possibility of FRC walls as a measure against impact was estimated.

INTRODUCTION

After the September 11 attacks, great concern about the safety of nuclear power plants against terrorist attacks arose. Especially high-speed objects, such as missiles or aircraft engines were considered as risk factor which could evoke damage to important structures of nuclear power plants.

Various measures have been introduced for strengthening the safety of important structures of nuclear power plants against high-speed impacts or missile impacts. As one of the measures, fibers reinforced concrete, which is effective in reducing crack and increasing strength, is considered recently. However, the accurate properties of fiber reinforced concrete have not been studied yet especially with respect to the high-speed impact load.

SIMULATION SPECIFICATION

In 2010, the OECD Nuclear Energy Agency (NEA) organized IRIS_2010 benchmark activity to validate the various evaluation techniques which are used by the different institutes around the world in the integrity assessment of structure impacted by missiles. Three tests were chosen to be simulated in the benchmark; Meppen test during 1980’s, VTT flexural test, and VTT punching test.

The specifications and dimensions from the VTT flexural test were borrowed in this study. The target wall, which was 2.082m wide, 2.082m high and 0.15m thick, was impacted by a stainless and carbon steel pipe missile. The missile, which was also chosen from the test, is a 2m long pipe made of stainless steel. While the target mass of the projectile was 50kg and the target impact velocity 110m/s, the real mass of the missile was 50.5kg and the measured velocity were 110.15 and 111.56m/s in two tests.
FINITE ELEMENT MODELLING

In this study, a general-purpose finite-element analyzer Abaqus/Explicit 6.12 was used to solve highly nonlinear problem originated in impact load, contact and nonlinear complex materials.

A full 3D model was used in this analysis so that 3D behaviors, such as buckling, could be considered. The concrete wall was modeled with 8 nodes solid elements of which thickness were 15mm consisting of 10 layers along the z-direction. In the other two directions, the solid elements had approximately 10% longer than the thickness.

The tested walls included two bidirectional (x and y-direction) layers of rebars of which one had 6mm diameter and spacing was 55mm for each direction. Two nodes beam elements were applied to model each of the 144 rebars. The length of the beam elements was the half of the rebar spacing. The whole beam elements were embedded into the wall model with the constraint function of Abaqus/Explicit, ensuring composite behavior of the reinforced concrete wall.
Boundary conditions at the four edges of the wall were considered implicitly by 50mm-wide bands of fixed nodes, while in the real test, four rollers at each edge and a roller at the bottom of the wall were installed as the boundary conditions.

As the dimension was considerably small comparing with the wall, layers of 4 nodes shell with 5 integration points applied in the missile model. The mass of the finite element model was measured as 51.24kg, which is slightly heavier than the target and real value of the VTT flexural test. The material density of the stainless steel and the carbon steel used for the missile specimen, of which the real value were not informed, might cause the difference.

The impact velocity adopted in the analysis was exact 110m/s. Although in the real tests the velocities was slightly higher, the differences did not exceed 1.5%. The interaction between the wall and the missile is realized with the general contact function of Abaqus/Explicit.
MATERIALS

Concrete

The concrete used in the VTT flexural test was designed to have 60MPa of compressive strength, and the measured value was informed as 76MPa. However, in this study, due to restrictions, neither of the values could be adopted.

The major object of this study was the comparison of performances of concrete walls which were applied normal concrete and fiber reinforced concretes. However, the material properties of fiber reinforced concrete were very restricted. Therefore, instead of the material data of the VTT flexural test, we decided to adopt the material data available to us.

As a member of a research project, we could obtain the material properties of fiber reinforced concretes which were designed to have compressive strength of 41MPa. The tensile tests of the concrete specimen reinforced by 1% of twisted steel fiber and 2% of polyamide fiber were performed by Korea Institute of Construction Technology and Kolon Global, respectively.

Thus, in this study, three types of concrete were considered:

- Normal concrete
- Concrete reinforced by 1% of twisted steel fiber
- Concrete reinforced by 2% of polyamide fiber

As the compressive behavior of the normal concrete and fiber reinforced concrete are known to have similar behavior in compressive domain, compressive stress-strain curve were shared among all three types of concretes.

![Figure 5. Stress-strain curves of normal and fiber reinforced concretes.](image)

For the definition of stress-strain relation, concrete damaged plasticity model of Abaqus/Explicit was adopted as the constitutive model of concrete.

<table>
<thead>
<tr>
<th>Class</th>
<th>Density [kg/m³]</th>
<th>Compressive Strength [MPa]</th>
<th>Poisson Ratio</th>
<th>Elastic Modulus [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete</td>
<td>2,500</td>
<td>41</td>
<td>0.17</td>
<td>37.1</td>
</tr>
</tbody>
</table>

Steel

In the analysis, two types of steel were used; rebar steel for the rebars, and stainless steel for the missile. Among the variable values, general values were selected and these gave mass result of the missile quite coincided with the measured value of the VTT flexural test.
Table 2: Material properties of the steels applied in the analysis.

<table>
<thead>
<tr>
<th>Class</th>
<th>Density [kg/m³]</th>
<th>Yield Strength [MPa]</th>
<th>Poisson Ratio</th>
<th>Elastic Modulus [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rebar steel</td>
<td>7,850</td>
<td>560</td>
<td>0.3</td>
<td>200</td>
</tr>
<tr>
<td>Stainless steel</td>
<td>8,030</td>
<td>502</td>
<td>0.3</td>
<td>180</td>
</tr>
</tbody>
</table>

ANALYSIS

The finite elements analysis was performed for the period of 0.1 seconds. As predicted, the model showed 3D behavior, which was more evident in the positions of the missiles after impact. While the deformations of concrete walls were considerably symmetric, the deformations and the position of missiles were obviously asymmetric. This might be caused by the fact that the missiles were remarkably thin structures and vulnerable to asymmetric deformation, such as buckling. Comparing with missiles, however, concrete walls could be considered to be robust enough to prevent asymmetric deformation.

Energy Balance of the System

In Abaqus/Explicit, time histories of the various energy variables during the analysis were provided with following equation.

\[ E_{TOTAL} = E_{ALLIE} + E_{ALLKE} + E_{ALLVD} + E_{ALLFD} - E_{ALLWK} \]  

where, \( E_{TOTAL} \): total energy  
\( E_{ALLIE} \): internal energy, i.e., total strain energy  
\( E_{ALLKE} \): kinematic energy  
\( E_{ALLVD} \): viscous dissipation  
\( E_{ALLFD} \): frictional dissipation  
\( E_{ALLWK} \): external work

The energy balance of the system could be said to be maintained, if the total energy was close to zero, which meant that few energy appeared or disappeared from the system. The energy-time histories
obtained in this analysis showed similar result to those submitted by some participants of IRIS 2010 benchmark activity. The difference among the types of applied concrete was slight, but FRC concretes showed higher internal energy which appeared earlier than normal concrete.

![Graphs of Energy vs. Time for different concretes](image)

(a) Normal concrete  
(b) Steel 1% FRC  
(c) Polyamide 2% FRC

Figure 7. Deformations of normal and fiber reinforced concretes.

**Concrete Wall**

Displacement and compressive stress of the concrete part of the walls, and equivalent plastic strain (PEEQ) of the concrete were chose to compare the difference of behaviors of the normal concrete and the FRC concrete walls. Displacement and compressive stress were calculated along the z-direction, which is the direction of missile projection. Equivalent plastic strain was used as an index for local ductility capacity in various analyses.

Though a distinct trend of the maximum values which were selected for the comparison among the normal concrete wall and the FRC walls was not found, the FRC walls showed less dispersed deformation than the normal concrete wall.
The 177.3mm of displacement of the normal concrete wall decreased to 152.8mm in the case of polyamide 2% FRC wall, and 25.8mm in the case of steel 1% FRC wall. The maximum compressive stresses of the concrete walls were slightly less than the compressive strength, 41MPa. In the maximum
stress of rebars, as well as the values, significant difference is able to be found in the areas where the increase of stress appeared.

Table 3: Behaviors of the concrete walls.

<table>
<thead>
<tr>
<th></th>
<th>Normal concrete</th>
<th>Steel 1% FRC</th>
<th>Polyamide 2% FRC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum displacement of wall [mm]</td>
<td>177.3</td>
<td>25.8</td>
<td>152.8</td>
</tr>
<tr>
<td>Maximum compressive stress of concrete [MPa]</td>
<td>29.0</td>
<td>38.71</td>
<td>35.59</td>
</tr>
<tr>
<td>Equivalent plastic strain (PEEQ)</td>
<td>0.275</td>
<td>0.262</td>
<td>0.2890</td>
</tr>
<tr>
<td>Maximum stress of rebars [MPa]</td>
<td>559.8</td>
<td>558.0</td>
<td>559.7</td>
</tr>
</tbody>
</table>

**Missile**

We could find significant difference with respect to the behaviors of missiles as well. The shortening length of missiles in longitudinal direction was least in the normal concrete wall and largest in steel 1% FRC wall. As the momenta of the missiles were exact same, this result could be interpreted that, in the case of FRC concrete walls, the missiles dissipated more energy than the case of normal concrete.
CONCLUSION

We performed finite element analysis of the impact of missile and reinforced concrete walls, which were applied with normal concrete, steel 1% FRC, and polyamide 2% FRC, respectively. As asymmetric behavior appeared in the analysis, especially in the missile, it was found that a full 3D model should be applied to the similar analysis modeling. The Energy balance obtained in the analysis showed distribution similar to the submitted result by some participants of IRIS_2010 benchmark activity. The maximum value of displacement decreased with the application of FRC, particularly in the case of steel 1% of which effect was conspicuous. While the stresses of the concrete walls were slightly greater in the case of FRC walls, the distribution of deformation of FRC walls was less dispersed comparing with normal concrete wall. With respect to the missile, greater displacements were observed in the missiles which impacted the FRC walls. This result might mean that FRC walls experienced less energy dissipation or overall deformation, instead the missile which crashed FRC walls deformed. In conclusion, the analysis result stated above showed that the fiber reinforcement for concrete walls improves the resistance performance of reinforced concrete walls, particularly steel fiber is eminently effective comparing with polyamide fiber. It is expected that the use of FRC walls in important structures of nuclear power plants is able to strengthen the safety against high-speed impacts or missile impacts.

ACKNOWLEDGEMENT

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