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Applicability of Discrete-Like Crack Model to Box Culvert

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ABSTRACT

The purpose of this study is to improve the accuracy of crack evaluation for reinforced concrete (RC) nuclear facilities using Finite Element (FE) analysis. The maximum crack width of concrete is used to evaluate leakage resistance of nuclear facilities such as gas-tightness and watertightness. Generally, the smeared crack model is used to evaluate crack of concrete by FE analysis. However, the smeared crack model cannot evaluate the crack width and spacing accurately. We can also use the discrete crack model to evaluate the crack width. However, the discrete crack model constrains the elemental partitioning on the FE analysis model. Whereas, the Discrete-Like Crack model (DLCM) developed by Sato et al. (2014) can evaluate the crack width and spacing of concrete qualitatively. The DLCM will be practical because the model does not impose any constraint on element partitioning. We then conducted FE analyses on a static loading experiment of RC shear wall and RC box culvert with detailed measurements of concrete crack width and spacing to verify the accuracy of the DLCM. The load-deformation relationship, the maximum crack width and crack spacing in each experiment were simulated by the FE analysis using the DLCM well. Therefore, we concluded that the DLCM will be effective in improving the accuracy of crack evaluation for nuclear facilities.

INTRODUCTION

Nuclear facilities are increasingly required to accurately evaluate leakage resistance such as gas-tightness and watertightness after the 2011 Great East Japan Earthquake. The leakage resistance is evaluated by residual maximum crack width of concrete. Sato et al. (2014) proposed "Discrete-Like Crack model" and indicated that the crack characteristics such as crack width of RC structures can be evaluated accurately by FE analysis with the DLCM. The DLCM will be a good tool to evaluate the leakage resistance of nuclear facilities if the DLCM accurately simulates the residual maximum crack width of nuclear facilities. In this paper, FE analyses on a static loading experiment of RC shear wall and RC box culvert were conducted to verify the applicability of the DLCM.

DISCRETE-LIKE CRACK MODEL (DLCM)

The DLCM shown as Figure 1 was developed by Sato et al. (2014) to accurately evaluate the concrete crack width and spacing on FE analysis. Generally, the discrete crack model, in which spring elements are placed at the locations where cracks are expected to occur is used to evaluate concrete crack width in FE analysis.

The discrete crack model can directly calculate the crack width. However, the discrete crack model constrains the elemental partitioning. The smeared crack model is also commonly used to evaluate crack distribution. The smeared crack model has more flexibility in element partitioning than the discrete crack model. However, the smeared crack model cannot calculate the crack width directly. Therefore, Sato et al. developed the DLCM that can evaluate the crack width and spacing even in FE analysis using the smeared crack model. The DLCM can evaluate the crack width even in the plastic zone by calculating the bond stress between concrete and bar, and the stress redistribution by cracking using second-order ordinary differential equations. The calculation time of FE analysis with the DLCM is shorter than that of the conventional models because the DLCM uses a continuous function. Furthermore, the crack distribution is simulated in detail by calculating the center of gravity of each crack and making the cracks in adjacent elements continuous. Therefore, the DLCM can provide a more realistic crack distribution than the conventional smeared crack model. We considered the DLCM to be effective for damage evaluation and residual performance assessment of nuclear facilities after earthquakes. We then introduced the DLCM into the FE analysis program "FINAL" and evaluate cracks in RC box culvert. Details of the DLCM can be found in reference.

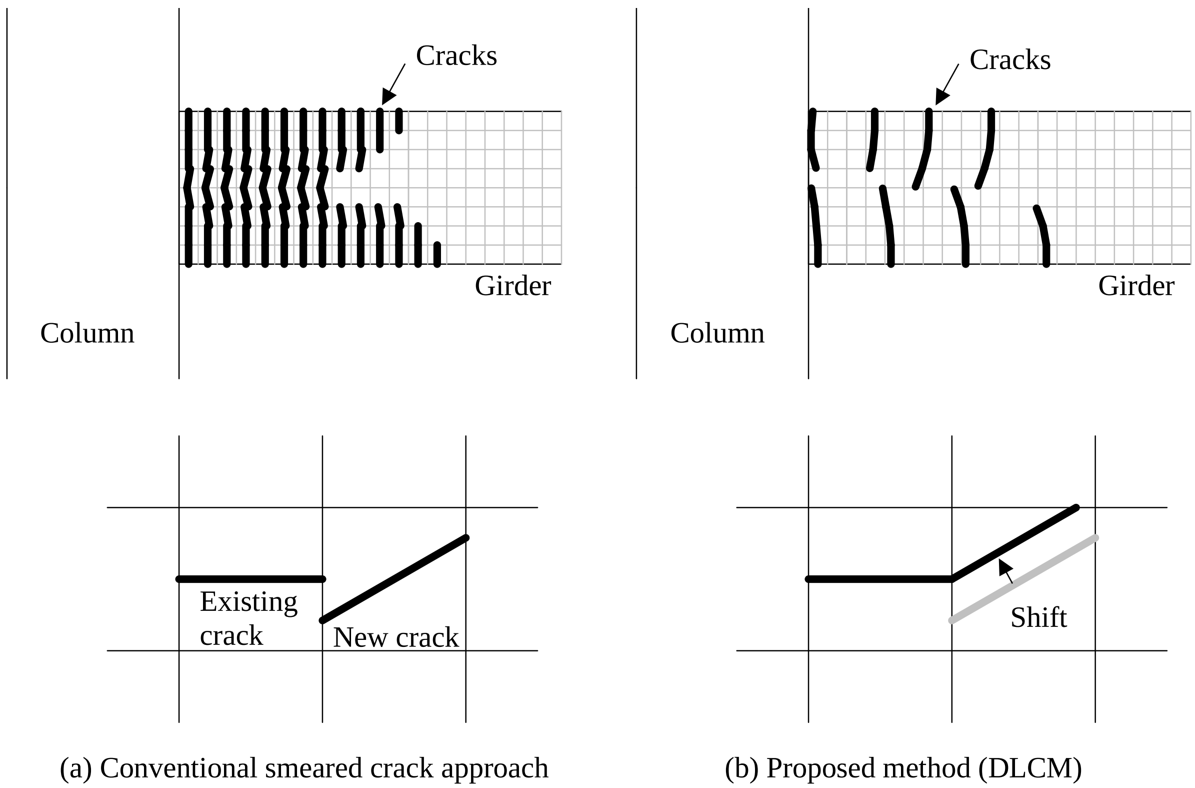


Figure 1. Comparison between conventional smeared crack model and DLCM by Sato et al. (2014)

EXPERIMENT ON RC SHEAR WALL

Prior to the evaluation of crack characteristics in RC box culvert, FE analysis was conducted on a static loading experiment of RC shear wall (No. 1) by Anabuki et al. (2020) to validate the DLCM. Figure 2 shows the test specimen. The test specimen consisted of a shear wall, loading stub, base stub, and columns. First, constant load equivalent to 0.1 times the concrete compressive strength was applied to the top of each column by hydraulic jacks (Photo 1). Next, horizontal load was loaded by the hydraulic jack located at the central height of the loading stub. The crack width in the shear wall was measured in detail and was measured using a crack scale (Photo 2) at the intersection of the crack and meshes drawn at 100 mm pitch. The crack width was measured at initial crack initiation, at the peak of each drift angle and at unloading, respectively.

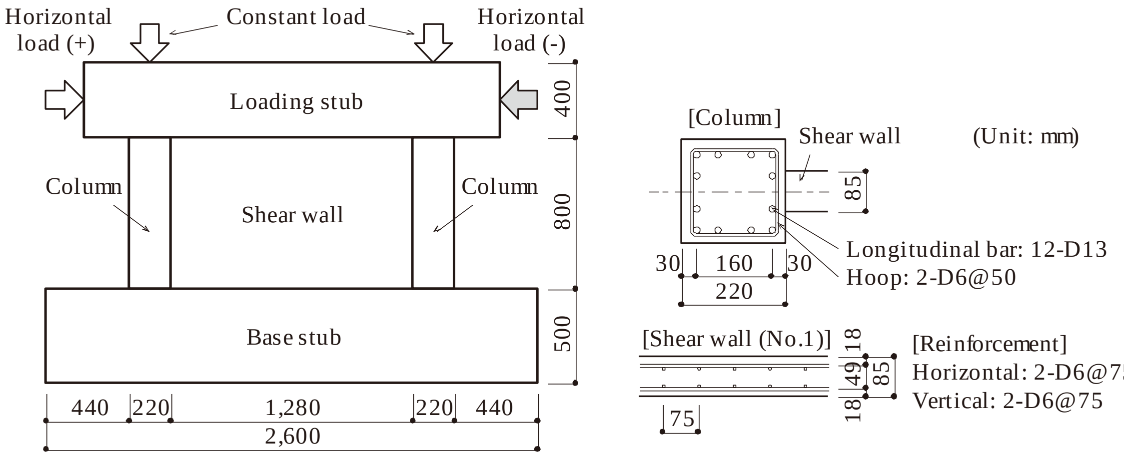


Figure 2. Test specimen of RC shear wall

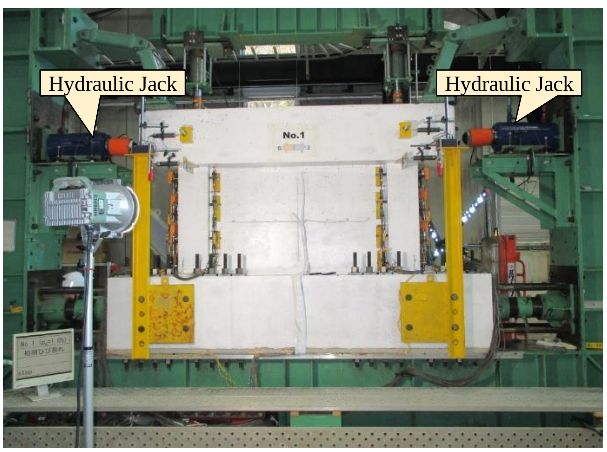


Photo 1. Loading equipment

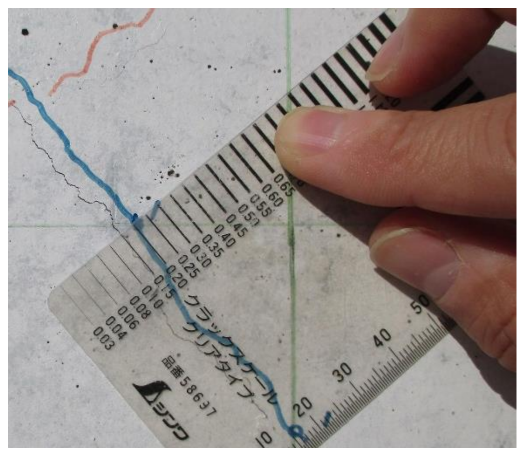


Photo 2. Crack scale

FE ANALYSIS ON RC SHEAR WALL

Figure 3 shows the FE analysis model. The program used for the FE analysis was "FINAL" developed by Obayashi Corporation, Takeda et al (1991) and Naganuma et al. (2004). Half of the specimen was modelled using symmetry condition. The concrete was modelled with hexahedral element. The longitudinal bars of column were modelled with two-node truss elements. Shear reinforcing bars in columns and wall bars were modelled by smeared reinforcements in the concrete. Four-node joint elements were inserted between the longitudinal bars and concrete elements to simulate the bond slip.

The non-orthogonal multidirectional crack model was used as the material model for concrete. The modified Ahmad model (1982) and Nakamura-Higai model (1999) were used for the pre- and post-peak compression history characteristics, respectively. The failure criterion for concrete was Ottosen's four parameter model (1977). For the tension stiffening properties, the Izumo model (1987) (coefficient c = 1.0) and Naganuma-Yamaguchi model (1990) were used for the columns and the wall, respectively. A bilinear history model was used for the model properties of the bar.

All degrees of freedom at the bottom of the base stub were fixed. The horizontal load was applied to the nodal point at the central height of the loading stub after the axial force was applied to the top of the columns.

Figure 4 compares the horizontal force-drift angle relationships between the experiment and the FE analysis. The initial shear crack occurred at drift angle of ±0.02% in the experiment and the FE analysis. Figure 5 compares the crack distribution of the experiment and the FE analysis with the DLCM and the conventional smeared crack model at drift angle of +0.2%. Figure 6 shows the crack width distribution of the FE analysis, and Table 1 shows the maximum crack width of the experiment and the FE analysis. The FE analysis using the DLCM simulated the experiment with better accuracy than that using the smeared crack model.

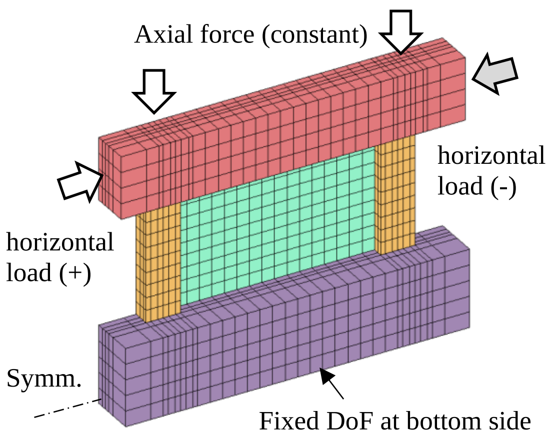


Figure 3. FE analysis model

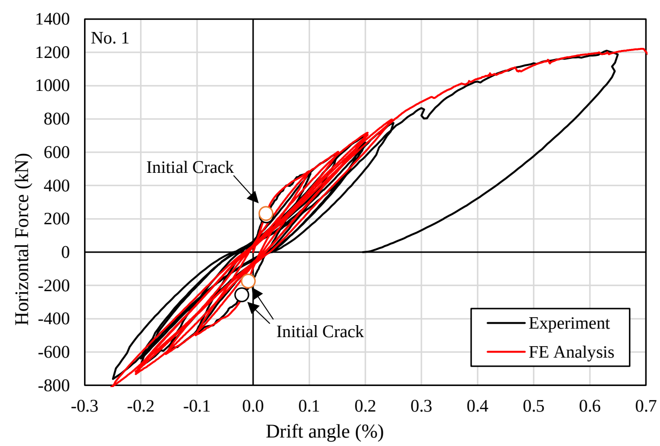
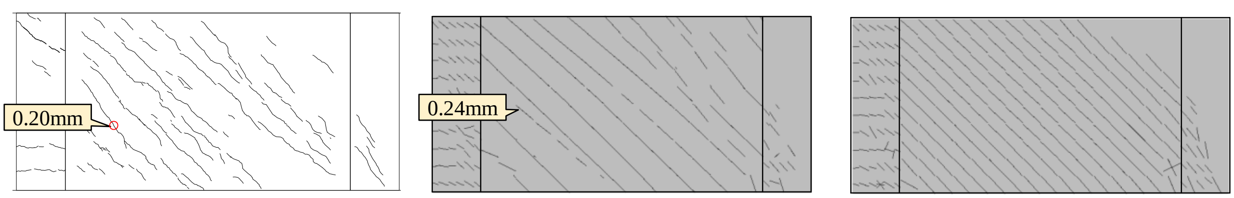


Figure 4. Horizontal force – drift angle relationships



Experiment FE analysis (DLCM) FE analysis (smeared crack model)

Figure 5. Crack distribution (drift angle +0.2%)

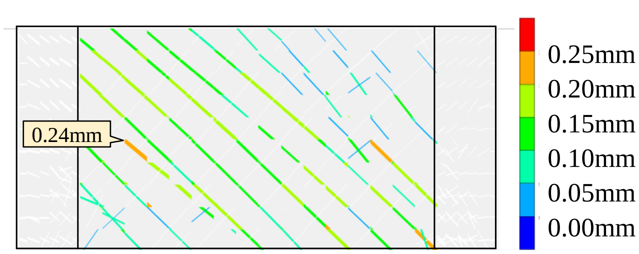


Figure 6. Crack width distribution
on FE analysis with DLCM (drift angle +0.2%)

Table 1: Maximum crack width

Drift angle (%)	Experiment (mm)	FE analysis (DLCM) (mm)
+0.02(initial crack)	0.06	0.06
+0.10	0.10	0.10
+0.15	0.15	0.20
+0.20	0.20	0.24
+0.25	0.25	0.31
+0.30	0.30	0.49

EXPERIMENT ON RC BOX CULVERT

Figure 7 shows the test specimen of RC box culvert. This experiment was conducted by Yamaguchi et al (2020) and Sasaki et al (2020). In general, the performance evaluation of RC box culvert for vertical displacement caused by fault has been examined in the direction orthogonal to the axis of the RC box culvert. However, the examination of fault displacement not orthogonal to the axis of the RC box culvert has not been sufficiently studied. Therefore, a static loading experiment was conducted to investigate the behavior of the RC box culvert by the non-orthogonal fault.

The scale of the test specimen was 1/4. The height, width, and depth of the specimen were 1.25 m, 2.50 m, and 3.75 m, respectively. The wall thickness of the test specimen was 0.25 m. The compressive strength of the concrete was about 30 N/mm^2. The yield strength of the bars was 348 N/mm^2 (D13), 353 N/mm^2 (D10), and 358 N/mm^2 (D6), respectively. Figure 8 shows the loading setup of the test specimen. The support points to simulate the fault line were rotated 45 degrees to the axis of the test specimen. Two jacks, which generate vertical displacement of the fault, were installed at the jack loading points J1 and J2. The load was gradually increased by two jacks.

Image measurement using Digital Image Correlation (DIC) developed by GOM GmbH (2017) was also carried out in addition to conventional equipment such as displacement transducers to measure the complex deformation of the test specimen. DIC is a technique for measuring displacement and strain by applying random patterns on the surface of a test specimen and using two cameras to locate the patterns that have moved by deformation.

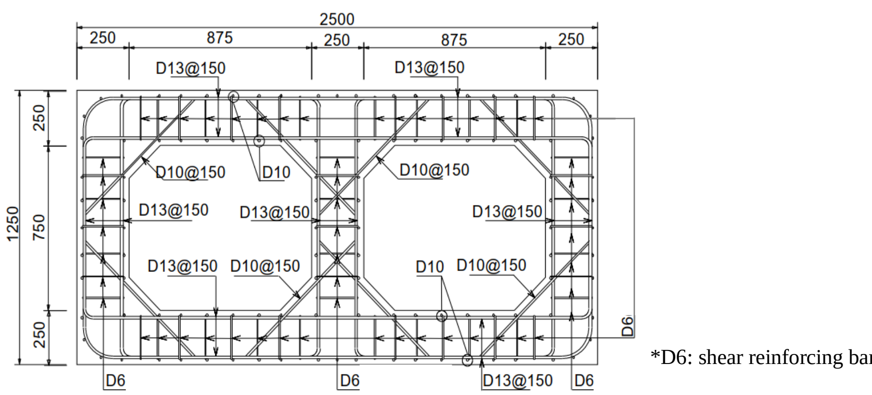


Figure 7. Test specimen of RC box culvert

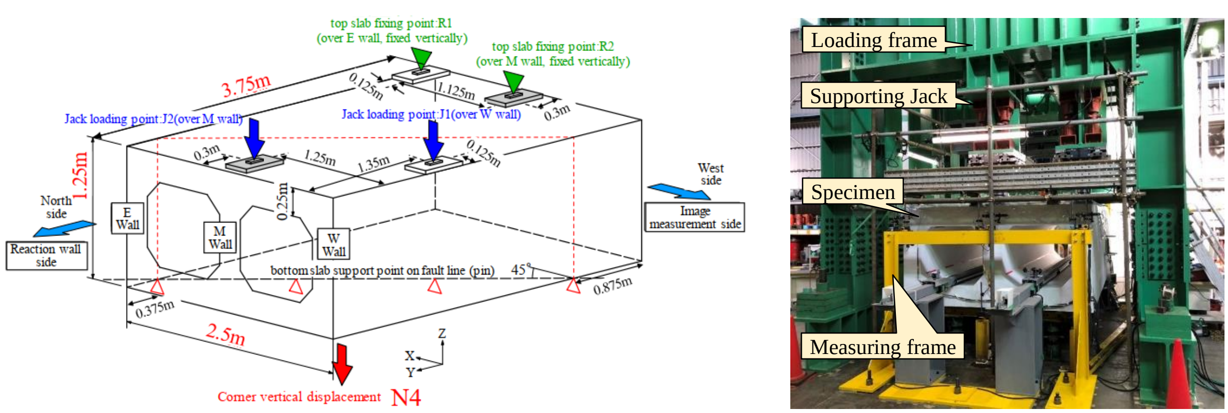


Figure 8. Loading setup

The static loading experiment was conducted until the corner of the specimen was deformed by 140 mm. The test specimen stably supported each load until the end of the experiment. It was confirmed that the required performance of the RC box culvert to maintain the inner space was satisfied because the specimen did not collapse. However, it will be necessary to evaluate the gas-tightness and watertightness because the residual maximum cracks were approximately 20 mm at vertical displacement of 140mm.

Figure 9 shows the jack load-displacement relationship of the test specimen. The load was the sum of the loads by the two jacks. The displacement was measured by displacement transducers located at the corners of the specimen. Photo 3 shows the damage status on the top and side of the specimen after the experiment. The cracks on the top surface of the specimen were extensive. Large cracks appeared just above the fault line, and cracks were dense.

The image measurement by DIC and a sketch made by visual observation on the side surface of the test specimen at the displacement of 40 mm is shown in Figure 10. The crack distribution measured by the image measurement agreed well with that of the sketch.

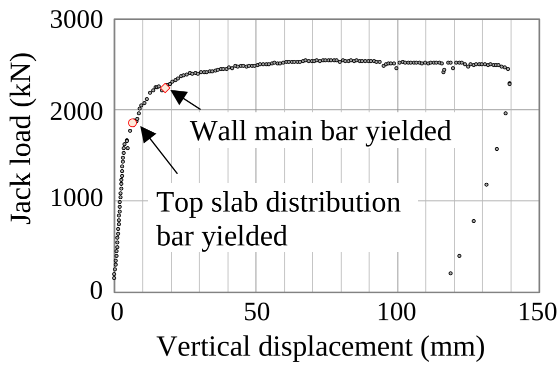


Figure 9. Jack load – Vertical displacement relationship

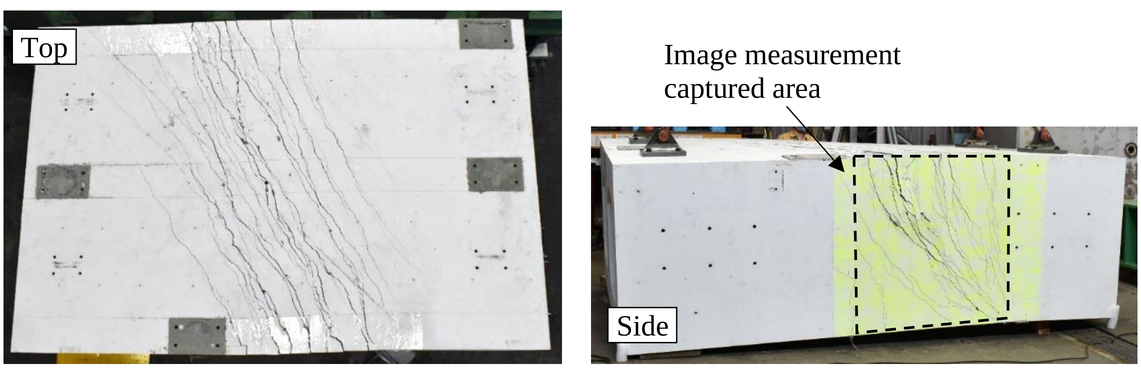


Photo 3. Cracks of test specimen after experiment

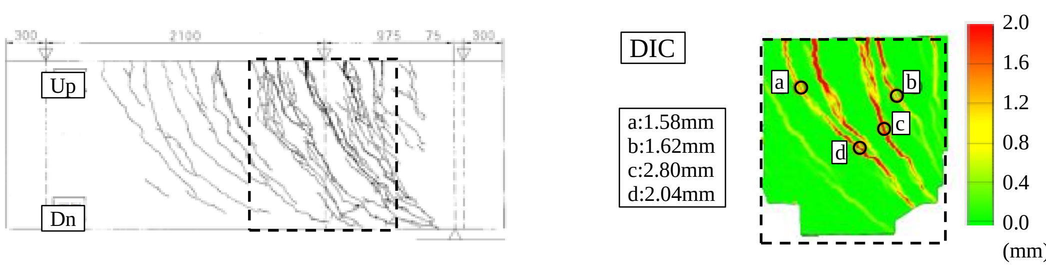


Figure 10. Cracks of test specimen (Experiment vs. image measurement by DIC) (disp. 40mm)

FE ANALYSIS ON RC BOX CULVERT

Figure 11 shows the FE analysis model. The program used for the FE analysis was "FINAL". Full of the specimen was modelled. The concrete was modelled with hexahedral element. The main bars were modelled with truss elements that shared nodal points with the concrete. In other words, bond slip between the bar and the concrete was assumed to be zero. The distribution bars and shear reinforcing bars were modelled by smeared reinforcements in the concrete.

The non-orthogonal multidirectional crack model was used as the material model for concrete. The modified Ahmad model (1982) and Nakamura-Higai model (1999) were used for the pre- and post-peak compression history characteristics, respectively. The failure criterion for concrete was Ottosen's four parameter model (1977) with the parameters proposed by Hatanaka et al. (1987). The Izumo model (1987) (coefficient c = 1.0) was used for the tension stiffening properties. A bilinear history model was used for the model properties of the bar.

All degrees of freedom on the fixed points nodes (R1, R2) and the fault line were fixed. The vertical displacement was given to the applied force points (J1, J2) after the self-weight was given to the concrete element.

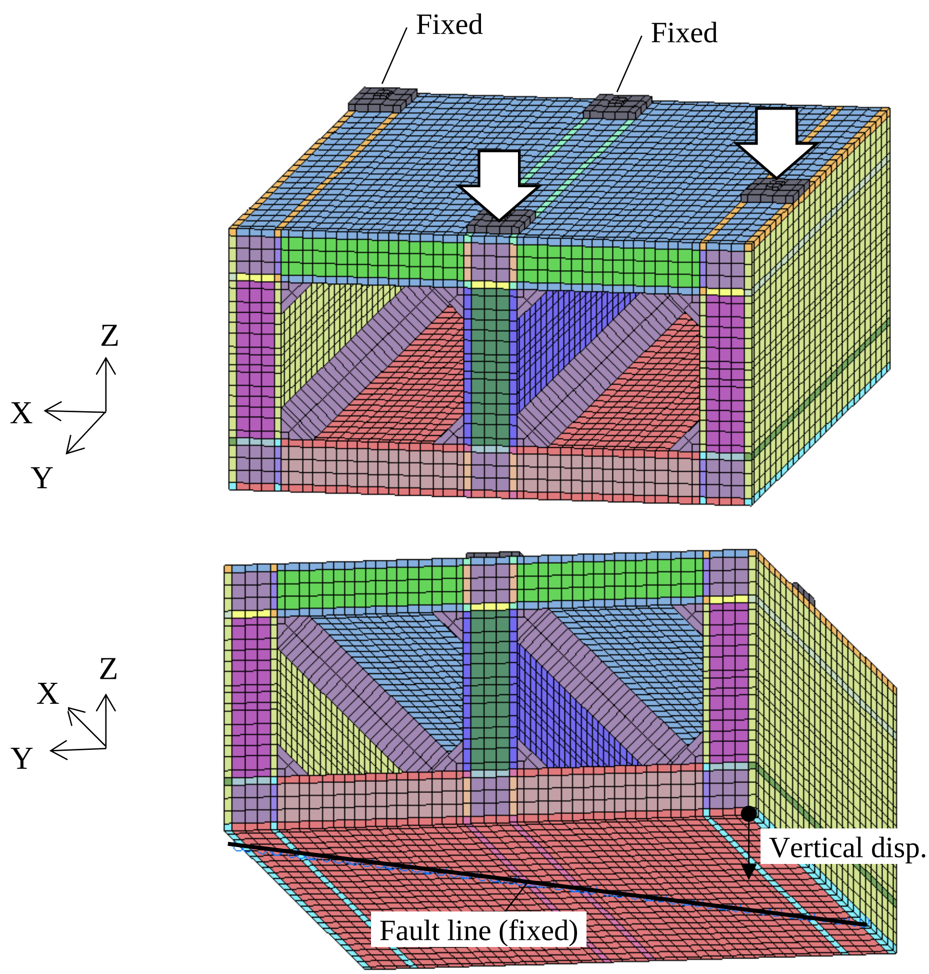


Figure 11. FE analysis model of RC box culvert

Figure 12 compares the jack load-displacement relationships between the experiment and the FE analysis with the DLCM. The load-displacement relationship of the FE analysis simulated that of the experiment well. Figure 13 shows the damage status of the test specimen. The crack distribution at the top of the test specimen of the FE analysis was in good agreement with that of the experiment. The crack distribution area on the side of the test specimen on the FE analysis was slightly wider than that of the experiment. Cracks in the center of the top on the experiment occurred in the same direction as the fault line. These cracks were simulated in the FE analysis well. The crack spacing at the top edge was the same in the experiment and FE analysis. Figure 14 compares the crack distribution between the experiment and the FE analysis. The FE analysis simulated the cracks of the experiment well.

Thus, it was confirmed that the distribution, the maximum width and the spacing of the cracks in the FE analysis with the DLCM were in good agreement with those in the experiment.

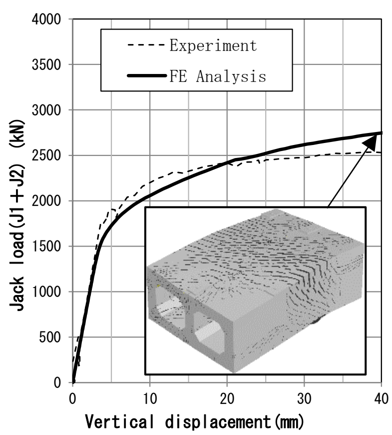
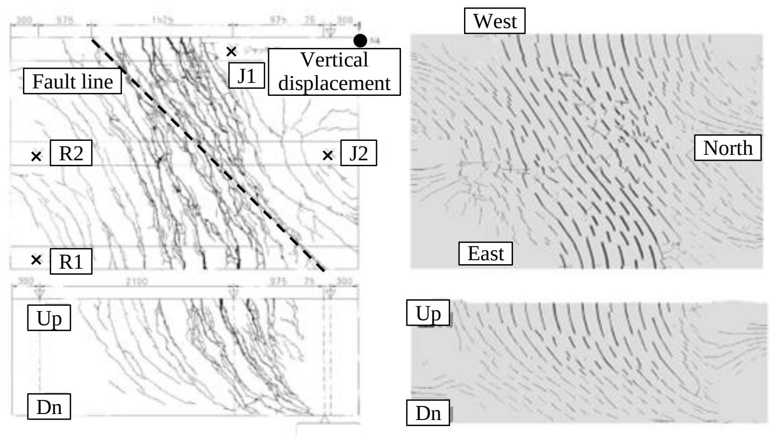


Figure 12. Jack load – Vertical disp. relationships



Experiment FE analysis (DLCM)

Figure 13. Damage status (disp. 40mm)

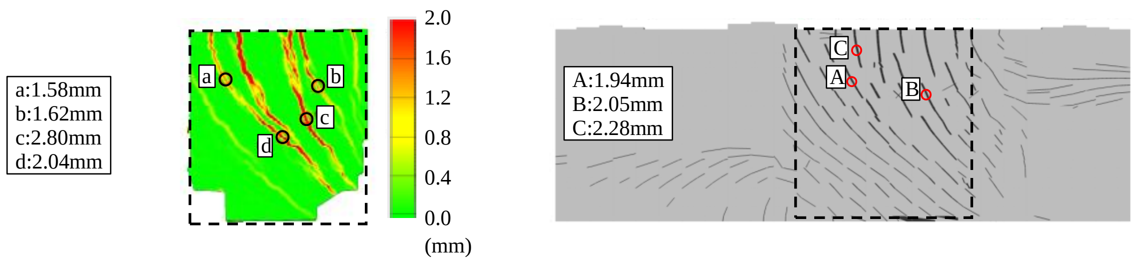


Image measurement FE analysis (DLCM)

Figure 14. Damage status on side of test specimen (disp. 40mm)

CONCLUSION

FE analyses on the static loading experiments of RC shear wall and RC box culvert were conducted to confirm the applicability of the DLCM proposed by Sato et al. (2014). The FE analyses using the DLCM accurately simulated the crack width and spacing in each experiment. We then concluded that FE analysis using the DLCM will be effective in improving the evaluation for the leakage resistance on nuclear facilities. However, further verifications are required to improve the accuracy of the DLCM.

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