NUMERICAL ANALYSIS OF FILLED-HOLE COMPRESSION TESTS WITH DIFFERENT MATERIALS OF INCLUSIONS

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ABSTRACT

In our previous experimental study, we have conducted filled-hole compression tests with pins made from three different materials. In the study, major influence of clearance between the hole and pin on the compressive strength was observed, but the influence of the different materials, on the other hand, was not clearly recognized. In the present study, finite element analyses with consideration of contact between the hole and pin by modeling the specimens and pins as elastic body were conducted to explain the trend of the experiments. Loads carried through vicinity of the hole was estimated for comparison of results from OHC and FHC tests. It was demonstrated that the load was not significantly dependent on the materials of the pin, but mainly on the clearance between the hole and pin. It was found by the analyses that insertion of the pin has effect to delay progress of damage in 0-degree layers at the sides of the hole, which was starting point of the failure of the specimens in the experiments.

1 INTRODUCTION

Strength of specimens containing holes under tensile and compressive loading have been extensively studied because of its difference to strength of unnotched specimens [1-5]. Especially, the open-hole laminates subjected to compressive loading show complex failure pattern due to fiber buckling [6-8].

In practical composites structures, the laminates are joined with fasteners such as bolts and rivets in many cases. Therefore, difference between strength of a laminate with an inclusion in the hole, which is so-called a filled-hole specimen, and the specimen without inclusions should be known. Although it was reported that strengths of the specimens with and without inclusions were considerably different by a limited number of studies [9-11], the damage mechanisms which differ the strength of open- and filled-hole specimens have not been completely understood.

In these circumstances, effect of parameters such as materials of inclusions and clearance between holes and inclusions to the strength has been experimentally studied in our research program [12]. In the present study, further investigation by means of numerical analyses with consideration of contact between the specimens and deformable inclusions was conducted to explain the experimental results.

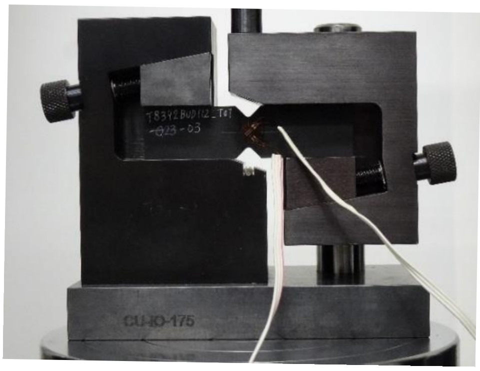
2 EXPERIMENTS

2.1 Characterization of Laminates

To obtain elastic constants of laminates for numerical analyses, series of tensile tests were conducted. 0° laminates with strain gauges in transverse direction was tested for evaluation of E_L and ν_{LT}. Similarly, E_T was evaluated from experiments of 90° laminates. ν_{LZ} was assumed to equal to ν_{LT}, *and* ν_{LZ} was assumed to be 0.5. For shear constants, Iosipescu tests were conducted. Test setup for the Iosipescu tests are shown in Figure 1. An example of relationships between stress and strain obtained from the experiments are shown in the right side of the figure. Since the relationship exhibits significant non-linearity, the shear elastic constant was evaluated by a tangent when the strain was 0.1%. Sets of elastic constants obtained from this procedure are shown in Table 1.

E_L	E_T	E_Z	ν_{LT}	ν_{LZ}	ν_{TZ}	G_{LT}	G_{LZ}	G_{TZ}
153 GPa	8.00 GPa	8.00 GPa	0.34	0.34	0.50	4.64 GPa	4.46 GPa	2.25 GPa

Table 1. Elastic Constants of a lamina evaluated from the experiments.



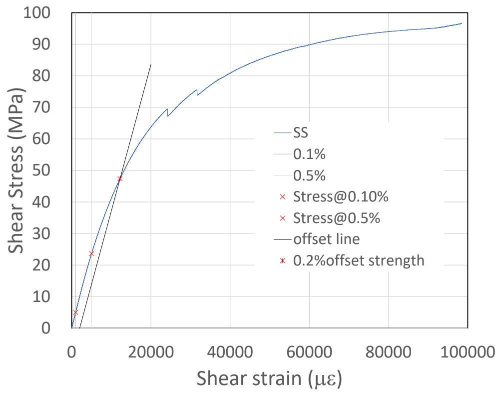


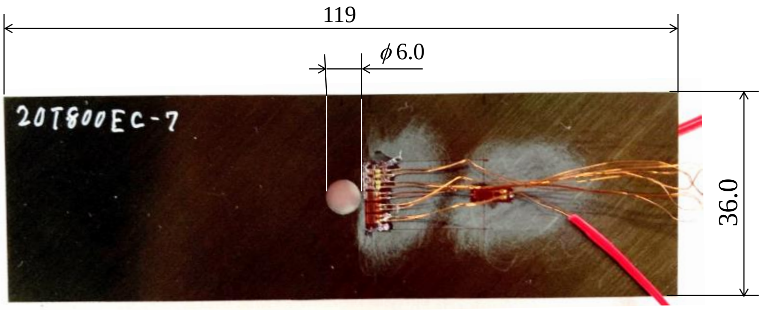
Figure 1. Test Setups and Stress-Strain Relationship in a Iosipescu Test for In-plane Shear Property.

2.2 Preparation of Specimens

Quasi isotropic specimens with stacking sequence of $[45/0/\text{-}45/90]_{2S}$ were fabricated by autoclave molding with prepreg made from T800S-24K Fiber and #3900-2B epoxy resin (Toray Inc.). The laminated plates were cut into a dimention shown in Figure 2. Thickness of the fabricated laminates were 3.1 mm. A hole with diameter *D*=6 mm was drilled in a center of the specimen.

Cylindrical pins with different materials including (a) tool steel (SKH51), (b) pure titanium (TB340) and (c) aluminium alloy (T7075-T6) were inserted in the holes. Material properties of the pins obtained from datasheets from the manufacturers are shown in Table 2. Pins with different diameters were used to evaluate effects of clearance between the holes and pins. The clearance *c* are defined as follows.

$$c = \frac{D - d}{D} \times 100 \tag{1}$$



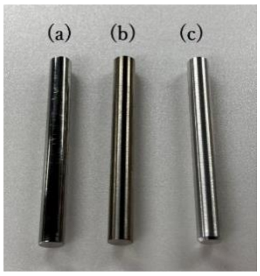


Figure 2. A Sample of Specimen for Filled-Hole Compression Tests and Pins Inserted to the Holes.

Tool steel		Pure Titanium		Aluminium Alloy	
E	***ν***	***E***	***ν***	***E***	***ν***
220 GPa	0.3	106 GPa	0.34	71.6 GPa	0.33

Table 2. Material Properties for the pins inserted to the holes.

2.3 Filled-Hole Compression Tests

Compression tests with JIS K7093 fixture were conducted as shown in Figure 3. Failure loads were evaluated for each value of clearance for the different materials [12]. Relationship between the failure load and the clearance *c* was summarized in Figure 4. The results showed a clear trend that the failure load increased as the clearance *c* decreased. The strength of the FHC specimen with *c*=0% was about 30% higher than that of OHC. There was no significant difference on strength with respect to different materials of pins. Post-failure observation of cross-section of the specimens using SEM was conducted as shown in Figure 5. The results showed that failure events such as fiber-buckling were mainly occurred in 0° layers [12].

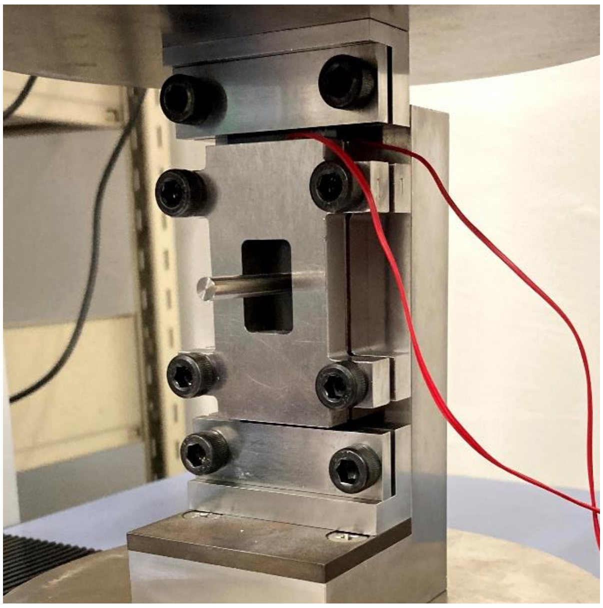


Figure 3. Test Setup for Filled-Hole Compression Tests and Pins with Different Materials.

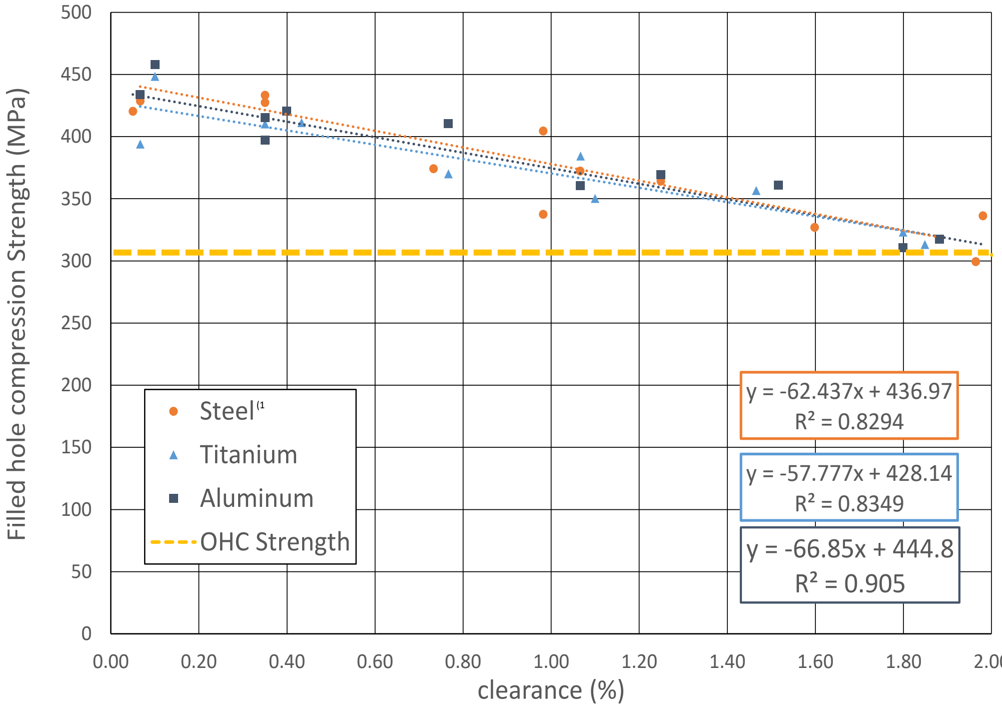


Figure 4. Relationship of Filled Hole Compressive Strength and Clearance between pins and holes.

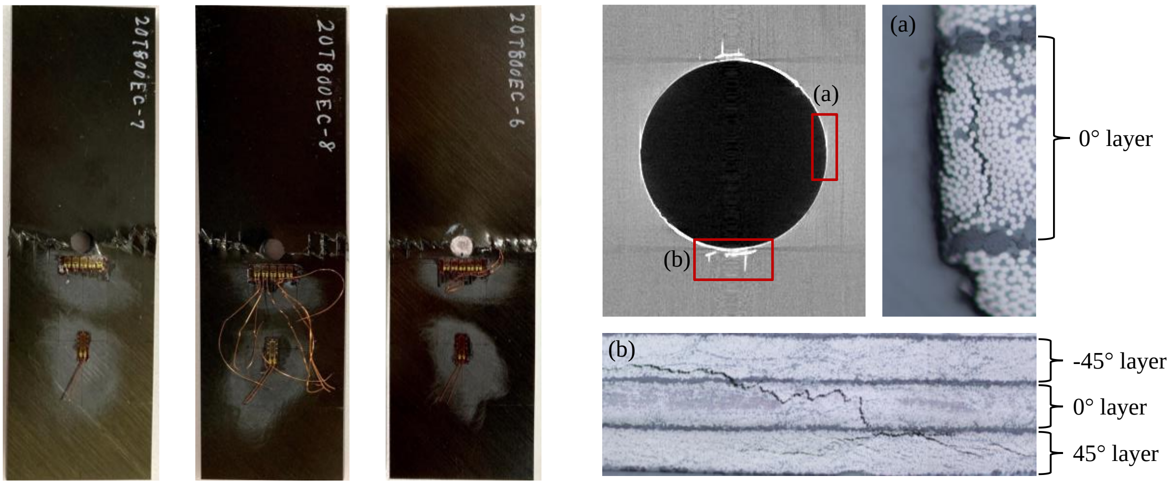


Figure 5. Samples of Failed Specimens and Fractography around the Hole of the Failed Specimen.

3 NUMERICAL ANALYSES

Finite element analyses were conducted to model the compression tests by using a nonlinear finite element code Marc (MSC software Inc.). Half model was created with 8-noded hexahedral elements according to symmetricity in the thickness direction as shown in Figure 6. Each ply of the specimens was modeled with different set of elements and a coordinate system of an orthotropic material. Contact condition between the specimen and pin were modeled by direct constraint method, in which nodes on a body are constrained on a surface of another body by multi-point constraint (MPC). To express the contact condition properly, the mesh around the hole was finely meshed, and contact surface of the pin was approximated as Coons surface that pass through all nodes on free surface of the body as seen in the right side of Figure 6, and it was regularly updated based on deformed surface of the body. Nodes in clamped area were rigidly connected to a representative node with MPC and boundary conditions were applied to the representative nodes to model the compressive load.

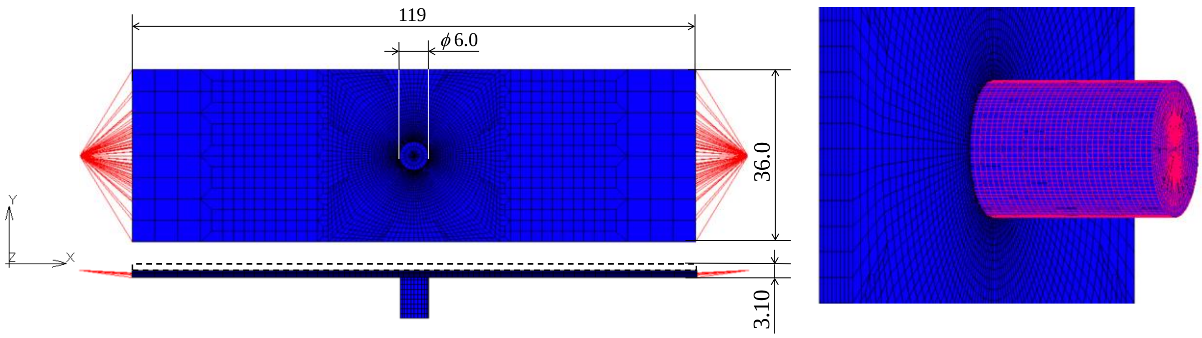


Figure 6. Finite Element Model of the FHC Test.

4 RESULTS AND DISCUSSION

To confirm validity of modeling of contact, numerical results related to the contact were firstly observed. Figure 7 shows contact pressure and contact area for cases of c=0.2% and 0.833%. The software outputs a result called Contact Status as 1 at nodes contacting to the surface of opposite side of the contact. In figure x, contact area was smoothly recognized by the software thanks to the capability of the approximation of the contacted surface. It was observed that 0° layers contacted with wider area and higher contact pressure because they have higher rigidity than other layers. Comparison between the results with different clearances demonstrated that the smaller clearance had effect to cause higher contact pressure. In addition, outer one of two 0° layers had higher contact pressure because the load was applied through outer free surface of the specimen and was indirectly transferred into the inner layers by shear stress.

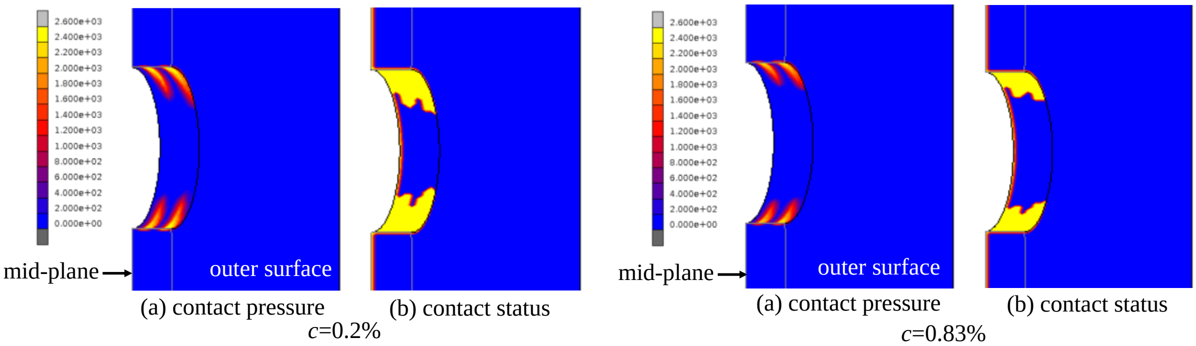


Figure 7. Numerical Results Related to Contact.

Figure 8 shows distributions of longitudinal stress in the outer 0° layer when nominal stress is 400 MPa. Stress concentration at lateral sides of the hole was observed in all specimens. The extent of the concentration was the maximum in the OHC specimen, and it reduced as clearance *c* decreased in the FHC specimens. Other stress concentrations were found at the top and bottom of the hole due to contact between the holes and pins in FHC specimens. It indicated that the reduction of the stress concentration at the sides of the hole in FHC specimens was attributed to the contact at the top and bottom of the hole.

Distributions of longitudinal stress along the center line of the outer 0° layer in transverse direction were evaluated as shown in Figure 9. It demonstrated that stress concentration was significantly reduced by existence of the pins. To further analyze the reduction of the stress concentration, the longitudinal stress was divided into two parts as shown in Figure 10. One is contribution to stress increase due to its concentration at the lateral sides of the hole $\sigma_{concentration}$ and the another is remaining nominal part of the stress $\sigma_{nominal}$. Load transferred in the layer was derived by integration of the stress over cross-sectional area of the layer, and it was divided into concentration part $F_{concentration}$ and nominal part $F_{nominal}$ as follows.

$$F_{total} = \int_A \sigma_{nominal}\, dA + \int_A \sigma_{concentration}\, dA \tag{2}$$

$$= F_{nominal} + F_{concentration} \tag{3}$$

As shown in Figure 11, $F_{concentration}$ was significantly reduced in all FHC cases compared to the OHC case. 84% and 63% decreases were observed in the cases of the steel pins with c=0.2% and 0.833%, respectively. This result agrees with the trend in the experiment that the failure load increases as the clearance of the pins decreases. The effect of the rigidity of the pins to the reduction of $F_{concentration}$ was not significant as same as the experimental results showed.

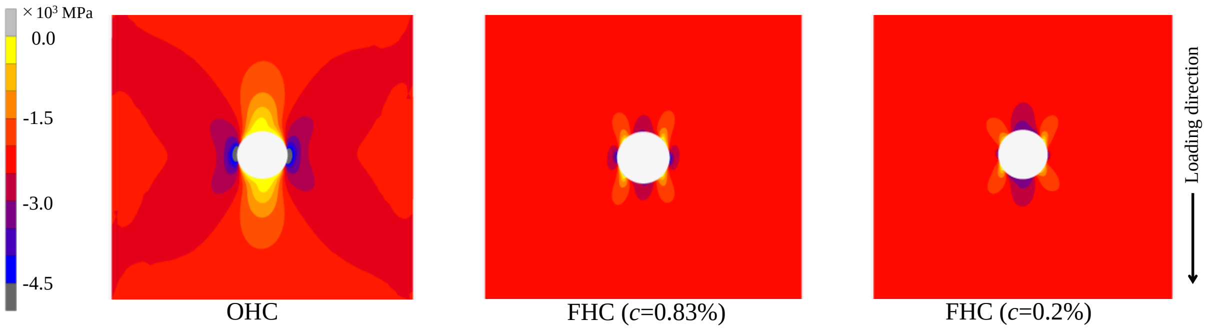


Figure 8. Comparison of Distributions of Longitudinal Stress Component around the Hole in 0° Layer.

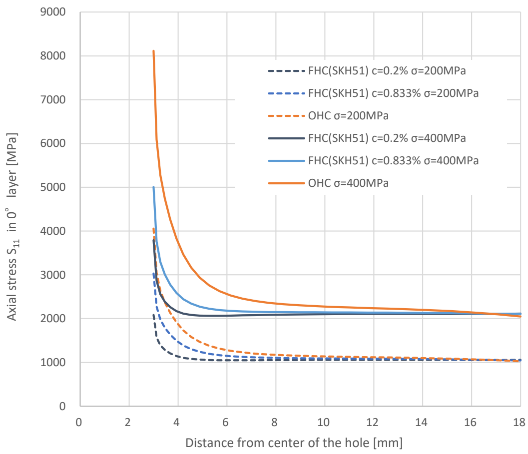


Figure 9. Stress Concentrations at Lateral Sides of the Hole with Different Clearances.

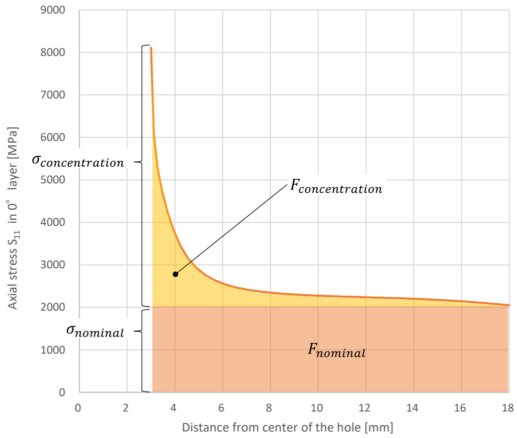


Figure 10. Derivation of Two Parts of Transferred Loads.

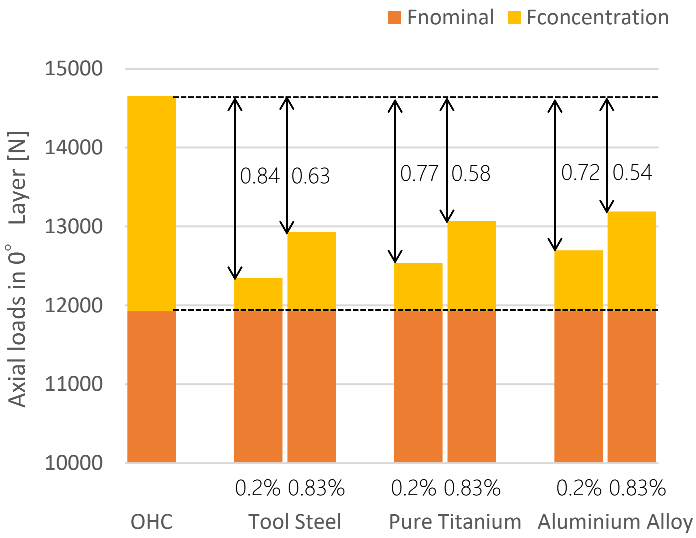


Figure 11. Effect of Different Inclusions and Clearances to Transferred Loads in 0° Layer.

To further investigate damage mechanisms, evolution of a failure index of compressive failure in 0° direction was observed as shown in figure 12. Table 3 shows average stress when events related to failure occurred in the experiments.

Under loading level with 100MPa of nominal stress σ where the pins started to touch the edges the hole in FHC specimens as shown in figure 12(a), the failure index at lateral sides of the hole in OHC specimen already became 1.0, which indicated initiation of the failure. FHC specimens showed less damage at the lateral sides of the hole than the OHC specimen, and the tighter the clearance between the hole and pin became, the smaller region of failure formed at the lateral sides of the hole. In addition, the failure index started to increase at top and bottom of the hole due to contact between the hole and pin.

With Loading level with 200MPa of nominal stress shown in figure 12(b), large region of failure was clearly observed in the OHC case, which corresponded to the failure stress obtained from the experiments.

Under 250MPa of compressive loading in figure 12(c), FHC with larger clearance clearly showed region of failure at lateral sides of holes, where failure was observed in the experiments. The same location of FHC with smaller clearance showed less damaged region and larger damaged region around the contact point instead.

With 300MPa of nominal stress in figure 12(d), lateral sides of the hole failed in all three cases. The region of failure in FHC was smaller than that of the OHC case. In the FHC cases, the tighter the clearance became, the smaller damaged region formed.

Stress in the experiments (MPa)	OHC	FHC (c=0.83%)	FHC (c=0.2%)
Contact to Pin	—	100	15
Failure at top and bottom of the hole	—	200	160
Failure at left and right sides of the hole	192.7	241.9	313.6

Table 3. Stress at Events Observed in the Experiments.

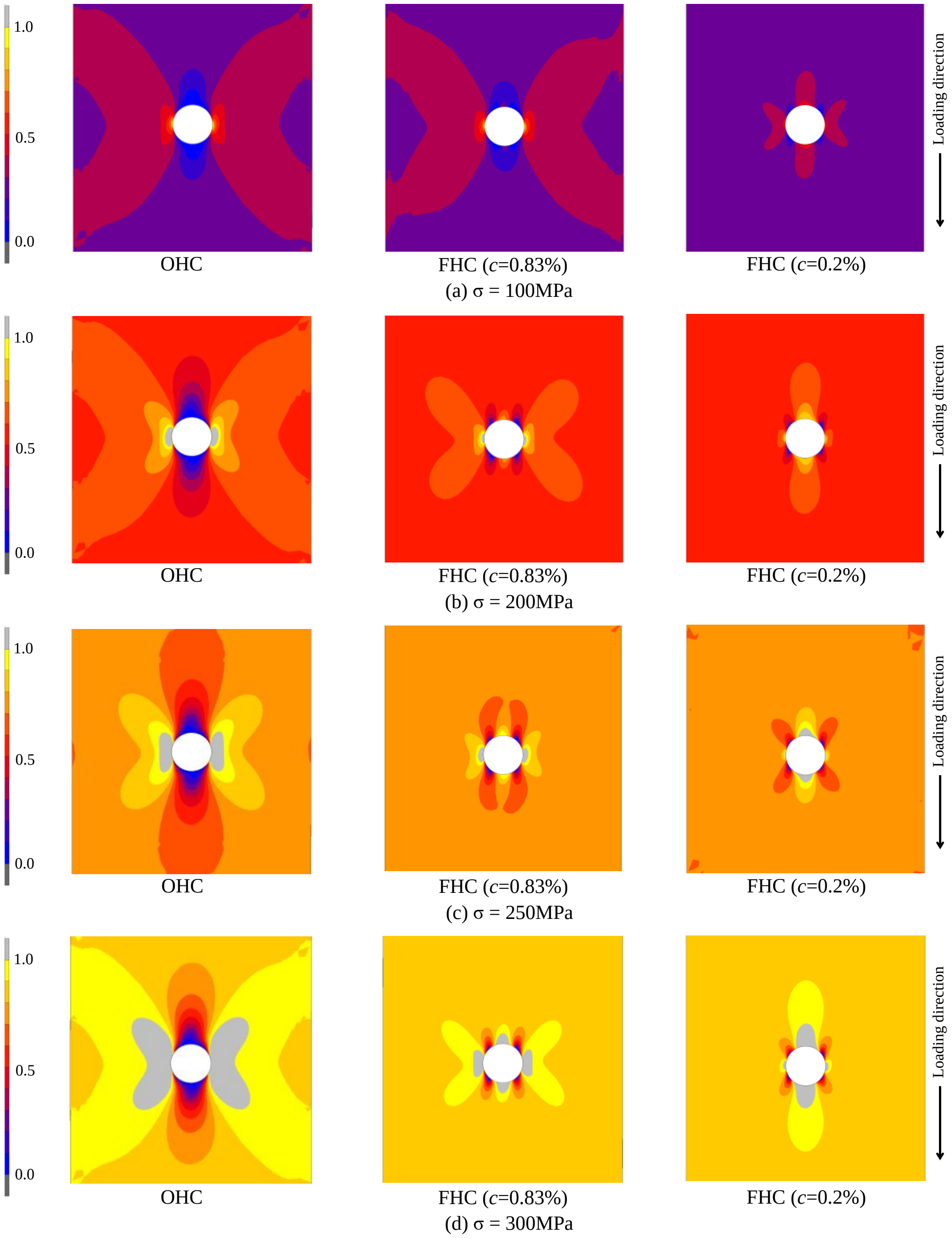


Figure 12. Evolution of Compressive Failure in 0° Direction in the 2nd Layer.

5 CONCLUSIONS

Finite element analyses of filled-hole compression tests with consideration of contact between holes and pins were conducted. Different materials and diameters of pins were adopted as parameters for cases of the analyses to investigate effects of rigidity of pins and clearances between the pins and holes on failure mechanisms. Key findings are summarized as follows.

- Increase of load transferred in the vicinity of the holes were suppressed about 80% by insertion of the pin.
- Progress of failure was delayed due to reduction of stress concentration at lateral sides of the holes by insertion of the pin.
- The tighter the clearance became, the more effect to delay the progress of damage was observed.
- Different materials of pins showed no significant effect to the progress of damage.

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