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Consideration of life prediction model for ceramic matrix composite(CMC) with cooling hole

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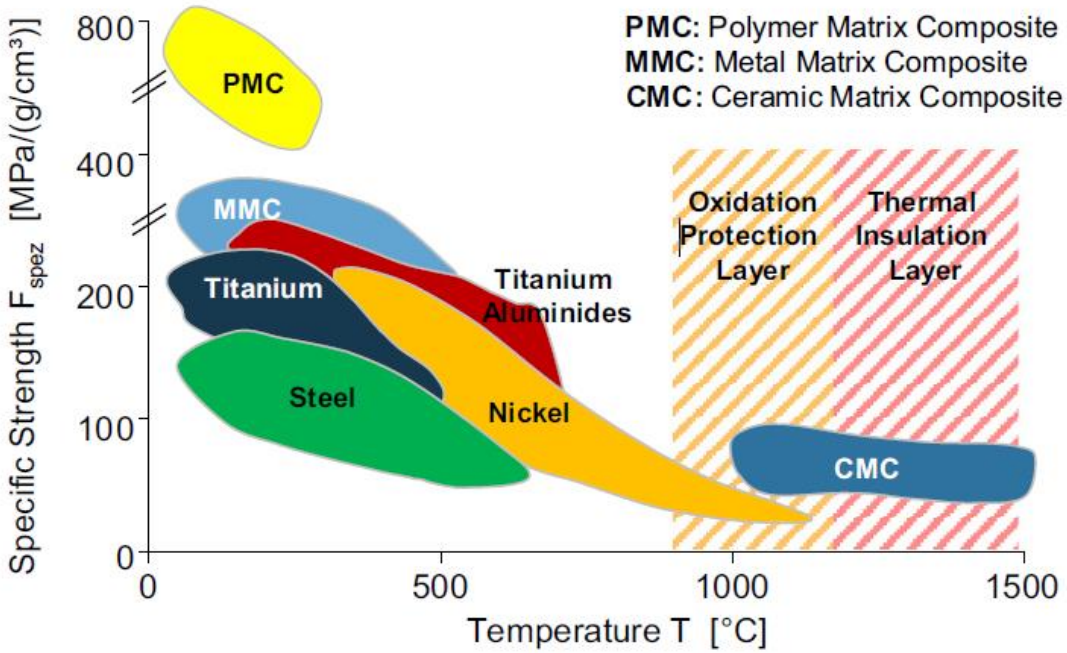
1. Introduction
1.1. Background

CMCs would contribute to ..

- Reducing cooling air and increasing turbine inlet temperature owing to high heat durability.
- Reducing parts weight owing to higher specific strength

CMCs have high potential to improve engine performance.



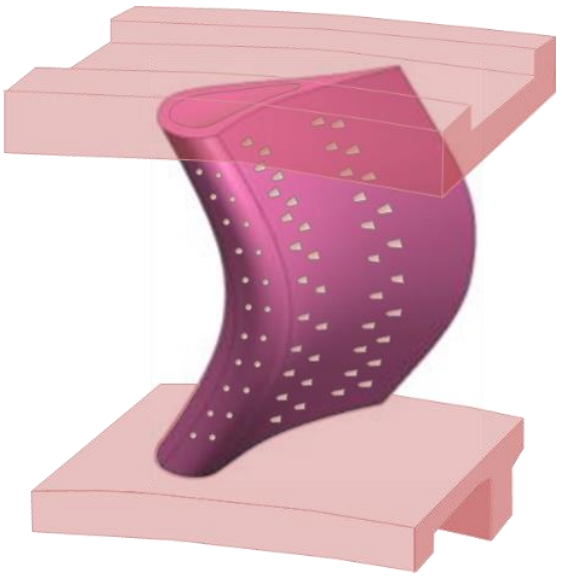
Material comparison chart [1]

[1] "Turbomachinery component manufacture by application of electrochemical, electro-physical and photonic processes ", Fritz Klocke ,etc, CIRP Annals - Manufacturing Technology, 2014

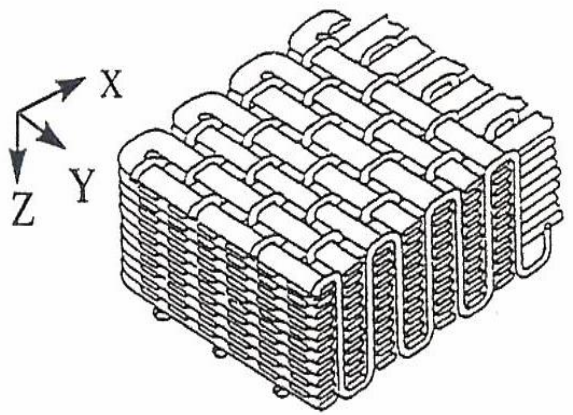
1. Introduction
1.2. Motivation

- High temperature parts are designed as hollow style with cooling hole.
- The CMC has 3D woven structure.
- There are few research about small hole effects of mechanical characteristics for composite material.

Life shortening effect of CMC caused by cooling hole was investigated.



Next generation turbine vane concept proposed in En-Core project [2]



Architecture image of 3D woven fabric

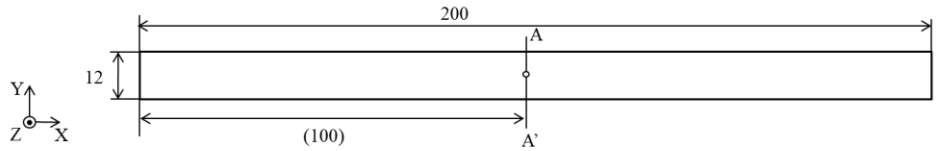
[2] https://www.aero.jaxa.jp/news/event/pdf/sympo190905/sympo19090503.pdf

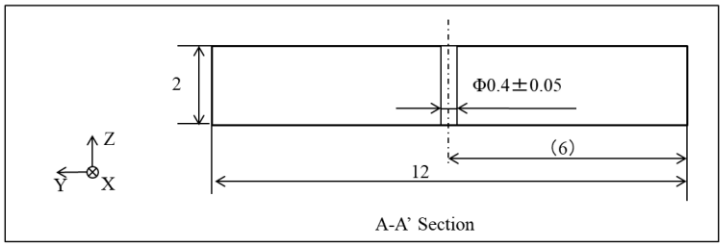
2. Test and measurement setup

2.1. Specimen setting

Simple plate specimens were designed to investigate the fatigue life of CMCs with various hole shape.

- The hole was manufactured by laser processing.
- 5 type of specimen were prepared.
- Hole was located on the center of the fiber bundle.





The number of holes	0	1	1	2	2
Projection hole shape	-	circle	ellipse	ellipse	trapezoid
Throat angle	—	90°	30°	30°	30°
Top and cross section view	A, Load direction, A, Top, A-A Section				
Meso-scopic structure	X fibre, Z fibre	Hole			

2. Test and measurement setup
2.2. Test condition and Measurement

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Strain survey have been conducted before LCF test.

- Strain survey test and fatigue test were conducted.
- Strain survey tests were conducted in room temp.
- Fatigue tests were conducted elevated temp at 1200 degree Celsius.

Test condition

Parameter	Strain test	Fatigue test
air/vaper	air	air
temperature	strain survey: RT	1200℃
load control system	load control	load control
stress rario	-	R=0.1
cyclic shape	-	sine wave
frequency	-	1 Hz

Measurement devices

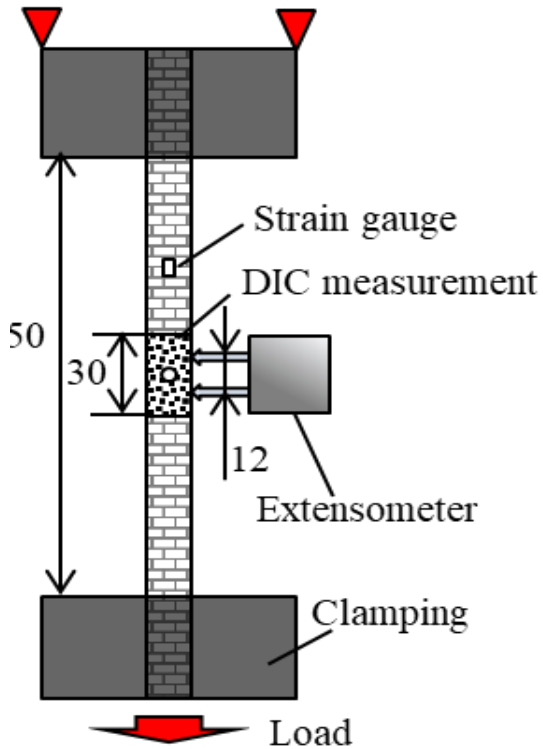
Device	Strain test	Fatigue test
extensometer	○	×
DIC	○	×
gauge	○	×
load cell	○	○

2. Test and measurement setup

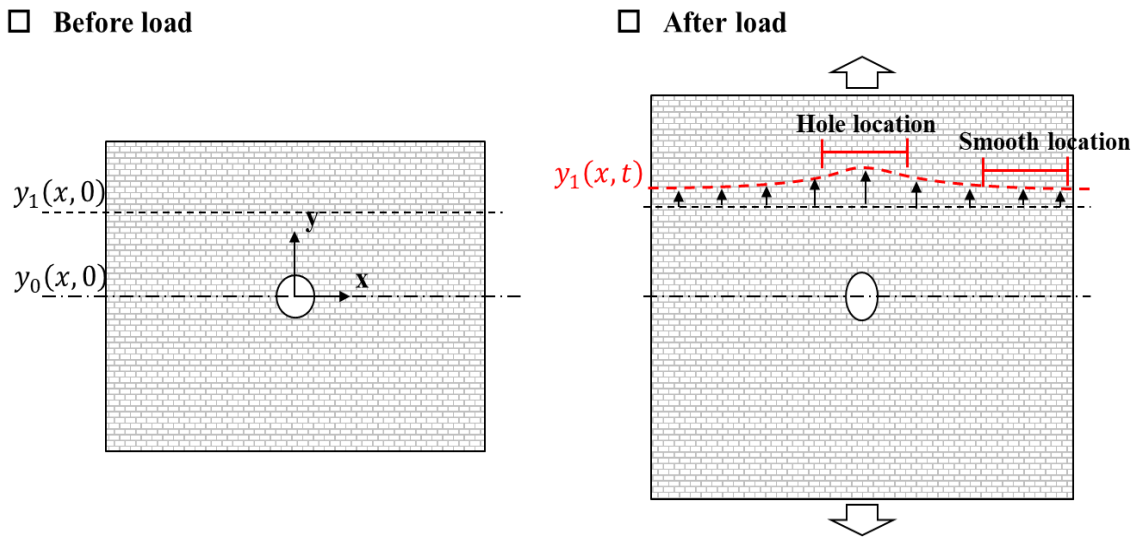
2.3. Measurement setup

Deformation was measured by 3 measurement devices.

- Displacement on the center of specimen was measured with extensometer.
- Strain on the specific point of specimen was measured with strain gauges.
- Displacement around hole was measured with DIC (Digital Image Correlation).



- Displacement was monitored on the line at near and far side from maximum strain location



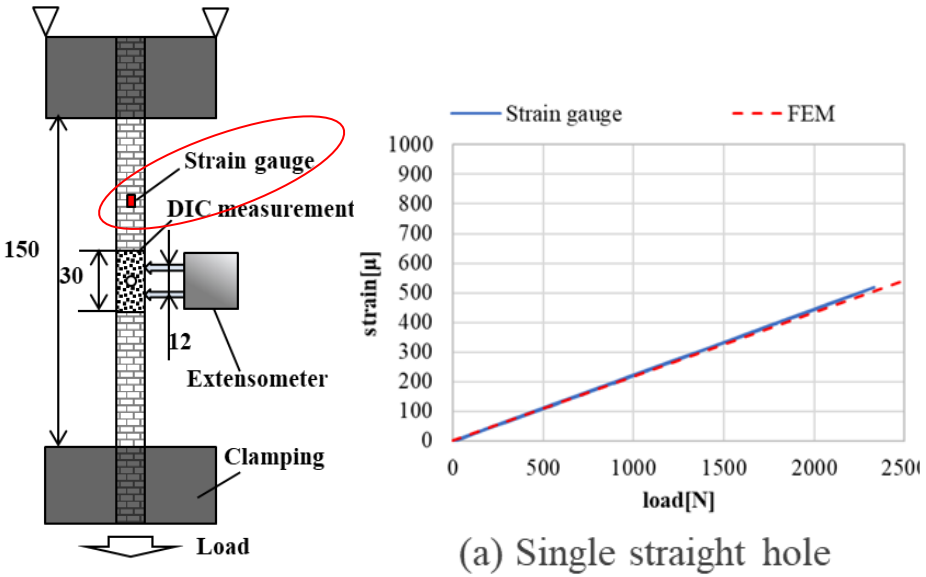
DIC calculation procedure

3. Test result

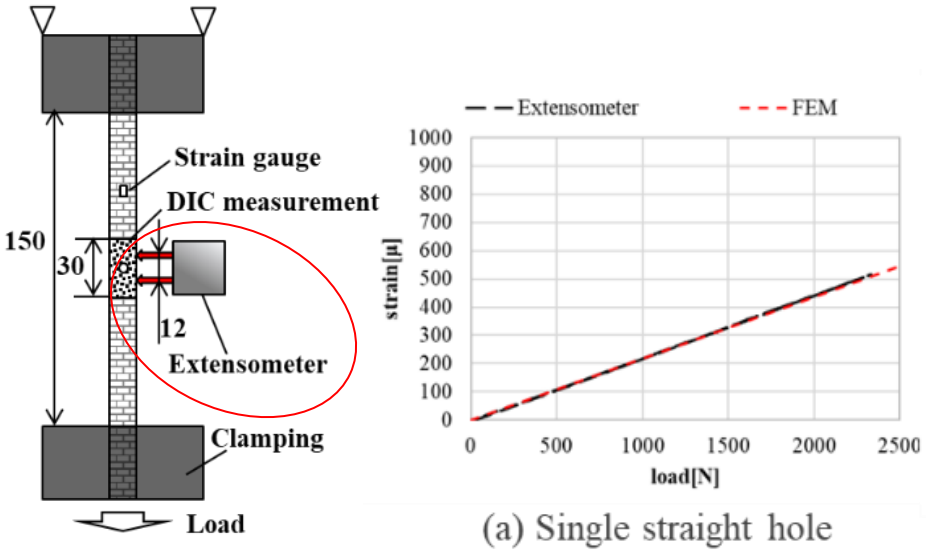
3.1. Measurement value of strain survey test

Measured strains on smooth area show good agreement with FEM

- Stains were measured with gauge and with extensometers.
- Both measured strains show good agreement with FEM. This means the material input of analysis is proper in low load condition.



Result of strain gauges



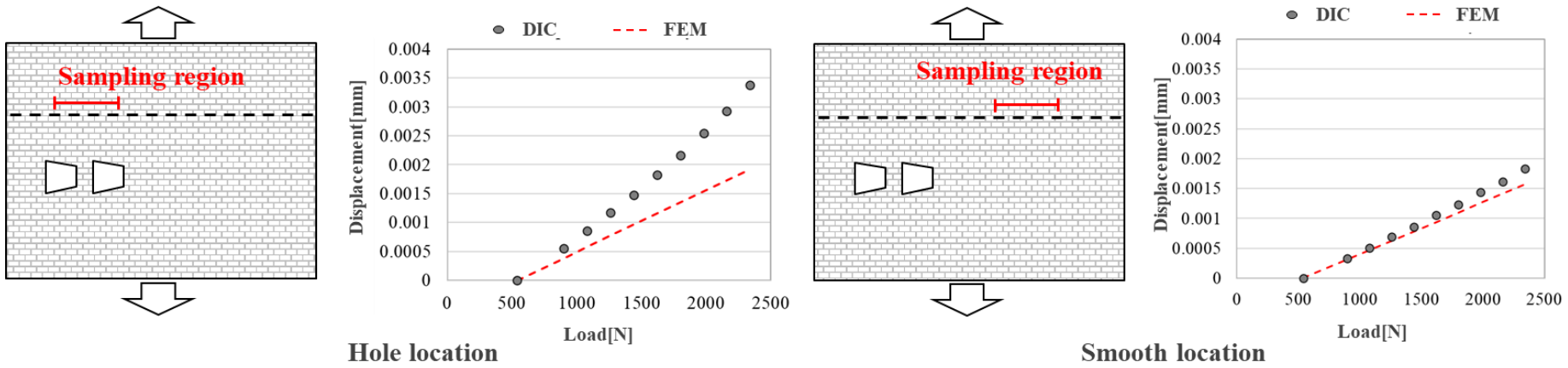
Result of extensometers

3. Test result

3.1. Measurement value of strain survey test

Displacement value measured by DIC show higher than FEM.

- Measured displacement per load around hole, indicated higher value than FEM assumption. Continuum material was assumed in FEM but the actual showed heterogeneous effect because hole was located on the center of fiber bundle.
- High resolution model and more zoomed measurement are effective to verify the hole region deformation.



Result of strain gauges

3. Test result
3.2. Fatigue test

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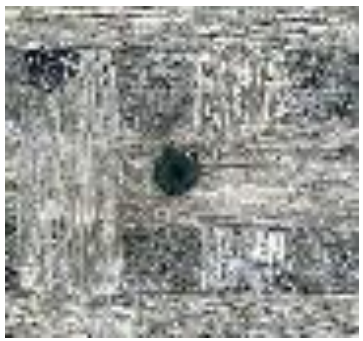
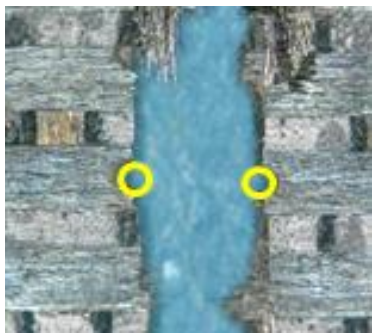
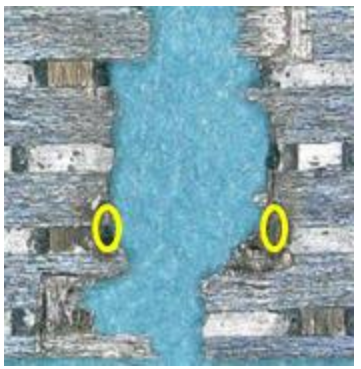
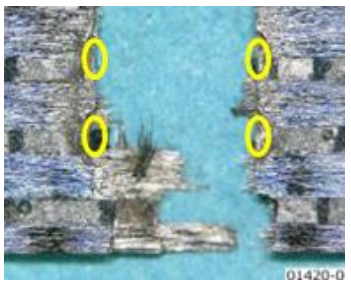
Fractured surface corresponds to cross-section through the hole for all type of specimens.

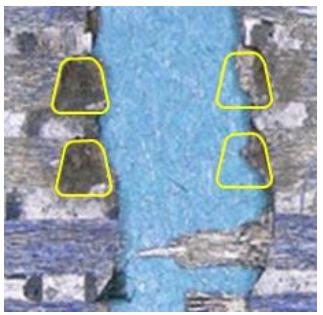
(a) Single straight hole

(b) Single slope hole

(c) Multiple slope holes

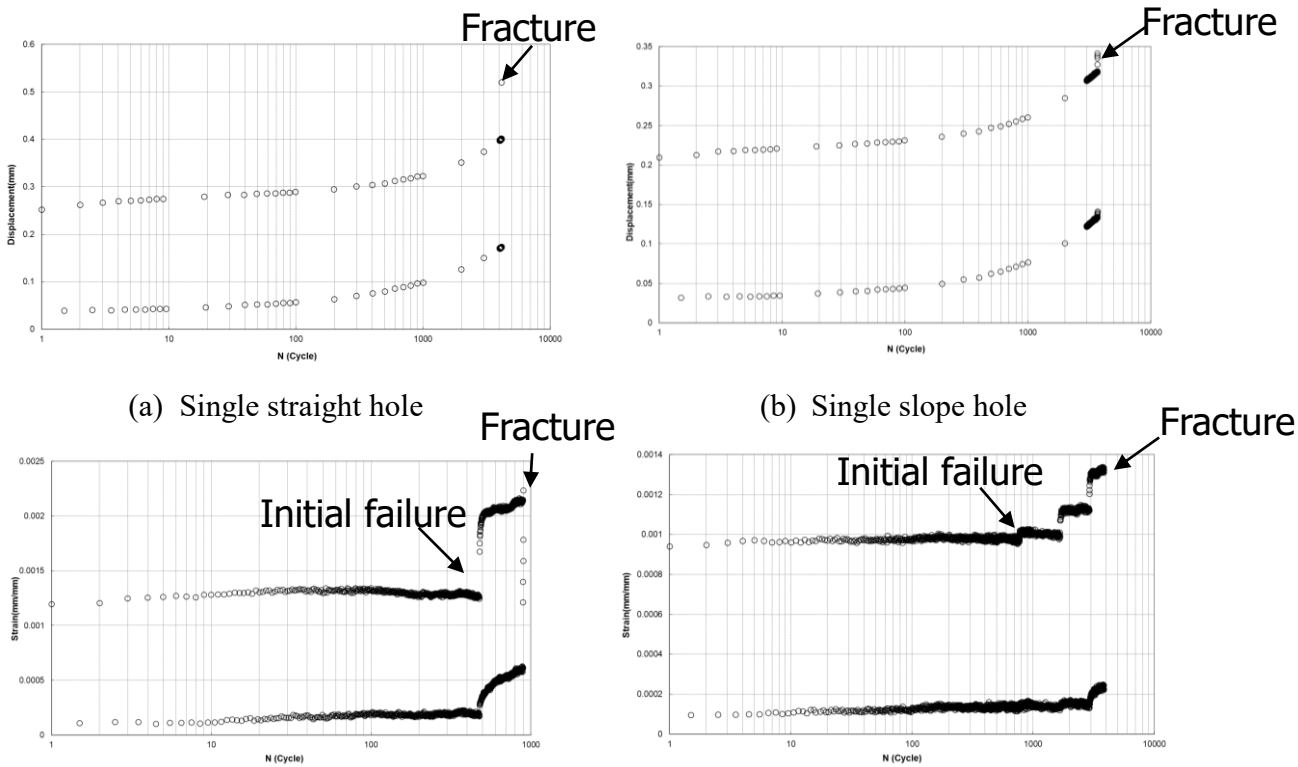
(d) Multiple diffuser holes

Figure 11: Fracture pattern after fatigue test

3. Test result
3.2. Fatigue test

Not only fracture but also failure timing were monitored in displacement history.

- Displacements of single hole type show the exponentially increase as time passes. But those of multiple hole type show discontinuous increment.
- Initial failure cycle was defined as this displacement initial jump.
- Fracture cycle was defined as load drop.



(a) Single straight hole

(b) Single slope hole

(c) Multiple slope holes

(d) Multiple diffuser holes

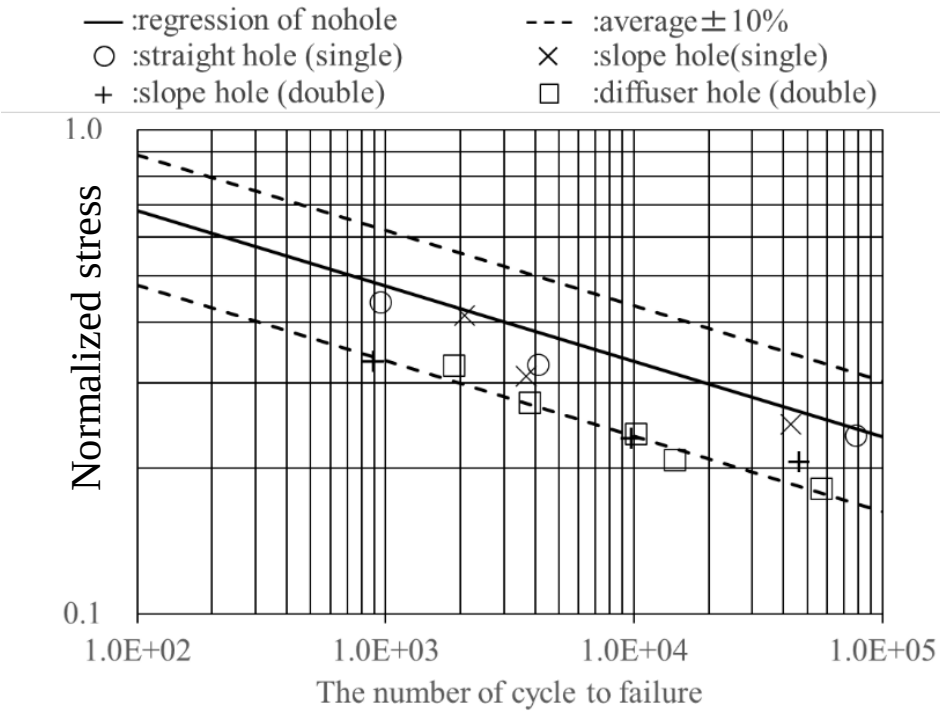
Figure 12: Displacement history

3. Test result
3.2. Fatigue test

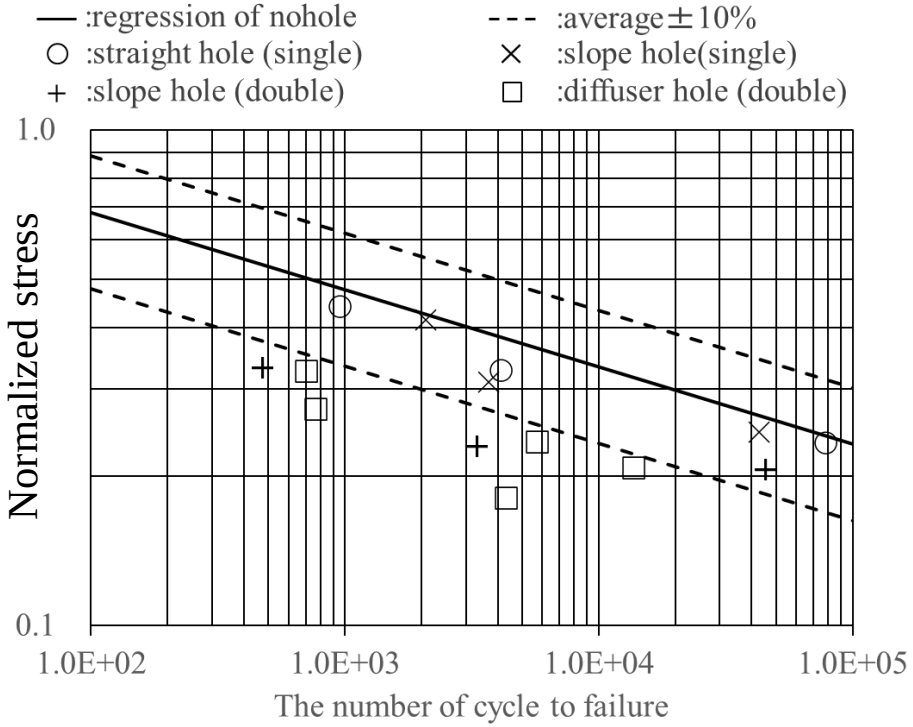
When Normalized stress was defined as nominal stress, strength was evaluated as shorter than smooth specimen in either case of using fracture cycle and failure cycle

- Life defined as initial failure cycle was more proper for engine design.
  →Normalized stress should be reconsidered to improve the prediction model.

- Life definition: Fracture cycle
- Stress countable size: Net cross-section



- Life definition: Initial failure cycle
- Stress countable size: Net cross-section

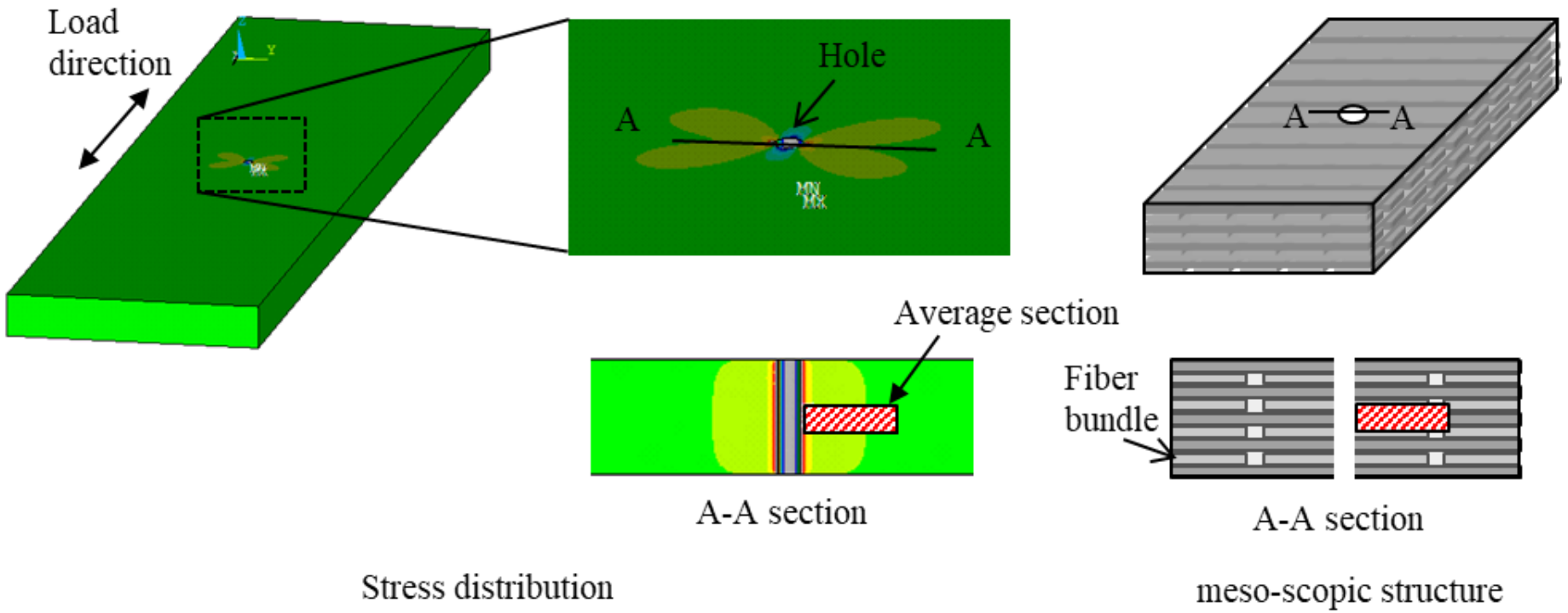


4. Consideration of life model

4.2. Recalculation of strength parameters

To improve the life prediction model, Normalized stresses were reconsidered as bellow.

- Normalized stresses for life calculation that are computed by averaging in one unit cell size.
- Unit cell is minimum unit size of CMC's periodic patterns.



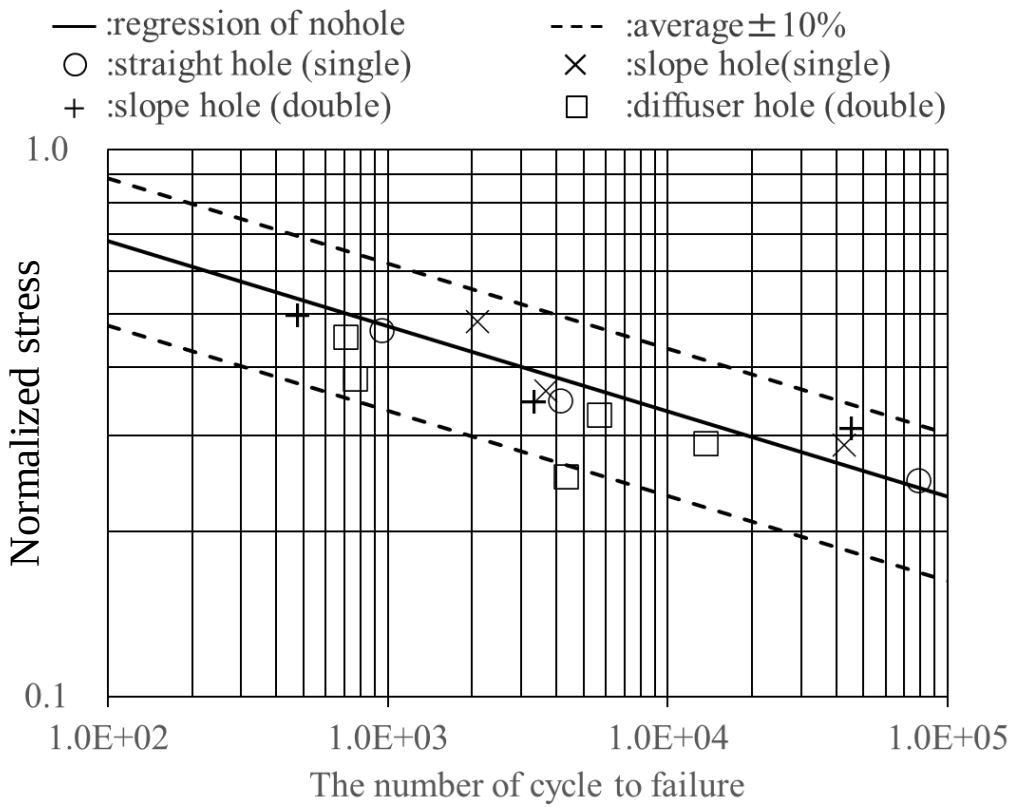
4. Consideration of life model

4.2. Recalculation of strength parameters

The life prediction model has improved by reconsideration of normalized stresses .

This chart shows the result after the reconsideration of normalized stress.
All specimen lives are explained by same curve and they are predicted within 20% to a regression curve generated by no hole specimen.

- Life definition: Initial failure cycle
- Stress countable size: One unit cell size



5. Conclusion

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- In this study, 4 type of holed specimen were designed to survey the relationship between hole specification and their failure lives. Failure life was determined as timing of displacement jump at displacement history diagram.

- The failure lives of diffuser hole that had most practical shape, were not shorter than the other type of holes.

- The damage processing mechanism was not clarified. Measurement and prediction of strain field around the hole was so complicated but understanding mechanism of this region is significant for verification of failure judgement. Higher resolution analysis and observation would be better to understand the mechanism of crack propagation for future work.

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