Research for thermal load and procedure to predict fatigue life up to form a fatigue crack on CFRP/Aluminium hybrid joints

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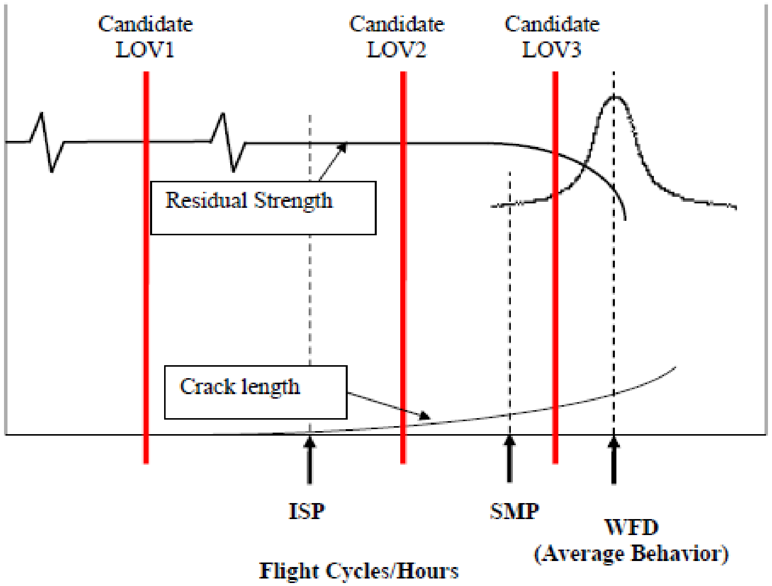
Background

WFD (Widespread Fatigue Damage): Simultaneous presence of multiple cracks, at multiple locations, that are of sufficient sizes and density in metal structure. And then in case the tensile fatigue load is applied to a metal structure with WFD, the structure will no longer meet the residual strength requirement.

For transport category aircraft, CFR (Code of Federal Register) currently demands aircraft manufacturer to develop LOV (Limit of validity) up to which WFD is unlikely to occur in an aircraft structure by virtue of its inherent design characteristics and maintenance actions.



LOV1: Inspection and repair for WFD are not required
LOV2: Inspection for WFD is required
LOV3: Inspection and repair for WFD are required

Comparison of WFD-Susceptible Structure to Airplane LOV (FAA AC 120-104)

Background

WFD in hybrid joint

The hybrid joint composed of the metal and CFRP (Carbon Fiber Reinforced Plastics) also have to be evaluated for the susceptibility of the WFD, in case its metal part carries the fatigue load. Because the thermal expansion is different between the metal and the CFRP, evaluation of WFD susceptibility has to be based on not only the external load but also the thermal load caused by the thermal experience during operation.

In 2015, ARAC (Aviation Rulemaking Advisory Committee) assigned TAMCSWG (Transport Airplane Metallic and Composite Structures Working Group) under TAE (Transport Airplane and Engine) Subcommittee in order to provide advice and recommendation on amendment of damage tolerant requirement in CFR and preparation of related guidance material. TAMCSWG proposes recommendations to apply the analysis supported by test evidence to WFD evaluation of hybrid joint.

Because the WFD evaluation under thermal load is time consuming comparing to that under external load, development of analytical procedure to evaluate the effect of the thermal load in hybrid joint is desired.

WFD prediction procedure for riveted joint

NRCC and JAXA Collaborative research work for WFD evaluation of a riveted lap joint (16×3) in 2010s)

Purpose:

Develop the procedure to predict the fatigue life up to first ink-up of the adjacent cracks on the riveted lap joint

Experiment (JAXA)

- Strain measurement under cyclic load
- Observation of Crack location and size
- Fracture surface observation

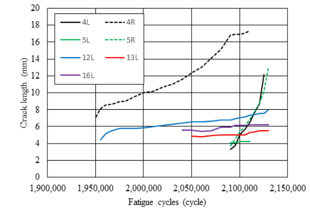
Numerical simulation (NRCC)

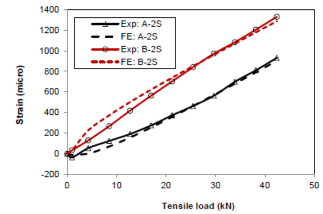
- Rivet squeezing by local FEM model
- Evaluation of stress and strain in lap joint by Global FEM model

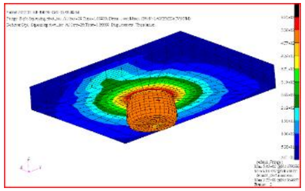
Result:

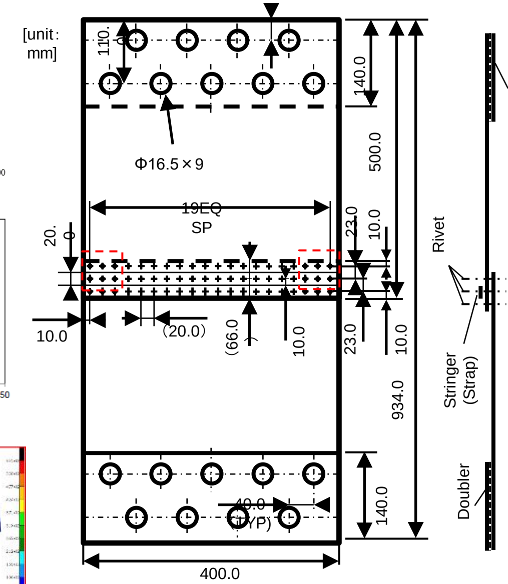
- Prediction of life to form certain size of fatigue crack based on SWT equation* substituting maximum stress and strain amplitude at critical location
- Prediction of fatigue life up to first link ups of adjacent cracks

*:Material data is obtained from the reference









Hole Dia (FEM)	Rivet Squeeze ratio (FEM)	s_{max} De / 2 (FEM)	Fatigue life based on SWT eq
4.115	1.507	0.5176	$2.434*10^6$
	1.527	0.4578	$4.590*10^6$
4.166	1.501	0.5300	$2.153*10^6$
	1.519	0.5147	$2.503*10^6$

WFD prediction procedure for riveted joint

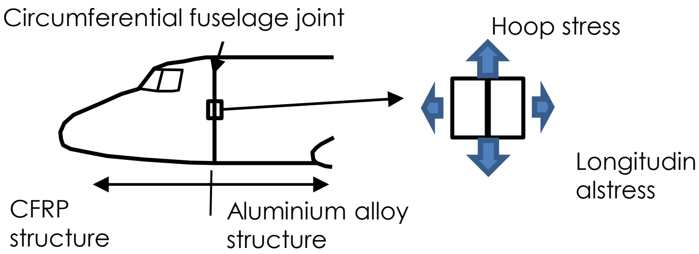
	Riveted joint (NRCC-JAXA)	Hybrid joint (This research)
Plate	Aluminum alloy	Aluminum alloy/CFRP
Fastening	Rivet	Bold
Load	External	External + Thermal
Loading condition	Ground-Air-Ground	Ground-Air-Ground
Fracture origin	Around rivet hole in Aluminum plate	Around bold hole in Aluminum plate (predict)
Cause of fracture origin formation	Stress concentration and wear	Stress concentration and wear (predict)
Material property	Stress-strain non-linearity	Temperature dependance, Homogeneous orthotropic elastic body (CFRP)
Finite deformation	During rivet squeezing	N/A
Fatigue life prediction	Crack formation (about 0.5mm) and Link ups of adjacent cracks	Crack formation (about 0.5mm)

Loading condition, fracture origin and cause of fracture origin formation are considered to be same for both joints and then WFD evaluation procedure for riveted joint proposed by NRCC and JAXA would be applicable to that for hybrid joint including the effect of thermal load

Objective

To develop prediction procedure for the fatigue life up to form a fatigue crack at certain size (0.5mm) in a metal/composite hybrid joint.

Candidate location of hybrid joint



Development of fatigue life prediction curve

- Evaluation of stress, strain and fatigue cycles by strain-controlled fatigue test (coupon)
- ↓
- Evaluation of parameters, σ'_f, ϵ'_f, b, c, used for SWT equation

Validation of FEM model（Thermal load）

- Evaluation of stress and strain on hybrid joint by thermal load test ⇔ Evaluation of stress and strain on hybrid joint by FEM analysis

↓

Evaluation of stress and strain of hybrid joint under thermal and external load

- Evaluation of stress and strain on hybrid joint under thermal and external load test ⇔ Evaluation of stress and strain on hybrid joint under thermal and external load by FEM analysis
- ↓
- Evaluation of maximum stress, σ_{max} and strain amplitude, $\Delta\varepsilon$ on hybrid joint under thermal and external load by FEM analysis

↓

Prediction of fatigue life to form fatigue crack

Substituting stress and strain obtain by FEM into SWT equation

$$\sigma_{max}\frac{\Delta\varepsilon}{2} = \frac{(\sigma'_f)^2}{E}(2N_f)^{2b} + \sigma'_f\,\epsilon'_f(2N_f)^{(b+c)}$$

Flow chart for fatigue life prediction up to form fatigue crack in hybrid joint under thermal and external load

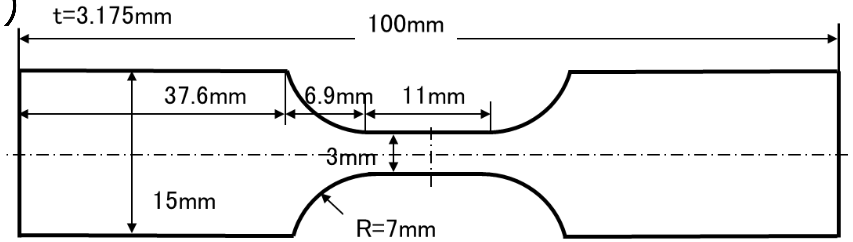
Experimental test to obtain material data used for SWT equation

Strain controlled fatigue test

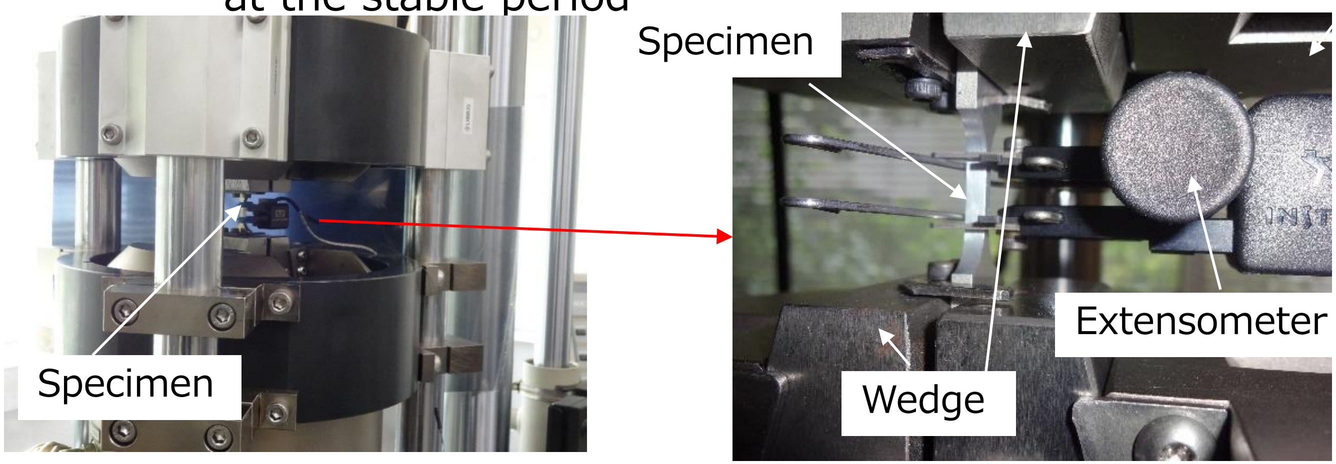
- Material: 2024-T3 bare
- Specimen: Rectangular section
- Test equipment: Instron 8802 series (100kN)
- Extensometer : Instron 2630-120 (gauge length 8mm)

Test condition :

- Frequency : 0.2Hz
- Average Strain : 0%
- Waveform: Sine shape
- Strain amp : ±0.8, 0.6, 0.4, 0.3, 0.25%
- Termination: maximum load decreases apparently to the maximum load at the stable period



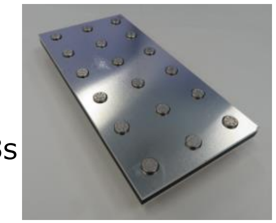
Specimen geometry

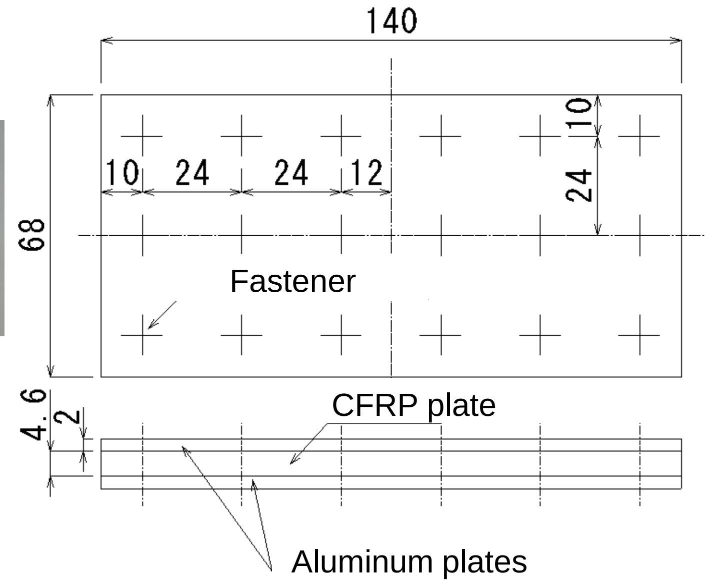


Test setup

Experimental test to obtain strain by thermal cycles in hybrid joint

Aluminum plate:
  2024-T3 Bare (t=2mm)
CFRP plate:
  T800S/3900-2B (t=4.56mm)
  Stacking sequence $[45/0/-45/90]_{3s}$
Fastener:
  Hole dia. 0.190-0.193 inch
  (4.83-4.90 mm)
  Hi-Lite fastener HST10-6-6 Pin(Ti),
  HST79CY6 Collar(Al)
  Torque 25-35 inch-pound
  (2.82-3.95 N-m)





Geometry of CFRP/Aluminum alloy hybrid joint

Experimental test to obtain strain by thermal cycles in hybrid joint

Test equipment: ESPEC TSD-100
Test condition(deg C): 25 → 60 → 85 → 60 → 0 → -20 → -55 → -20 → 0 → 25

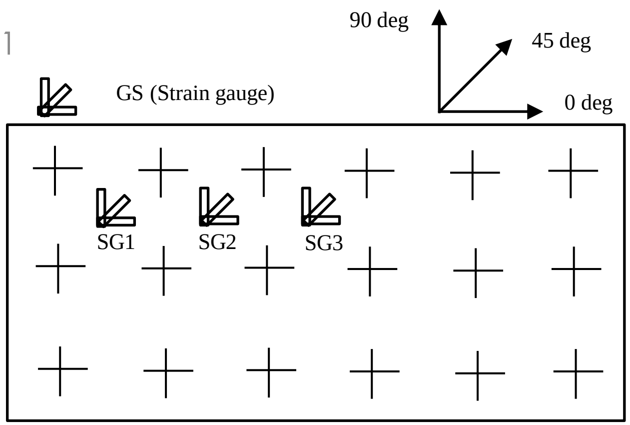
Thermal cycle test setup

Strain measurement:

$$\epsilon_{e(j)} = \epsilon_{t(j)} - \epsilon_{th(al)}$$

$\varepsilon_{e(j)}$: Elastic strain in aluminum alloy
$\varepsilon_{t(j)}$: Total strain in aluminum alloy
$\varepsilon_{th(al)}$: Unassembled Aluminum alloy

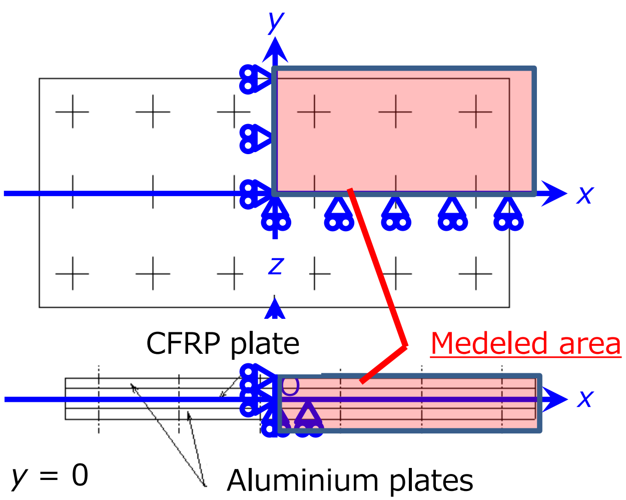
Out of plane deformation measurement:
KEYENCE VR-5000 (accuracy ±2.5μm)

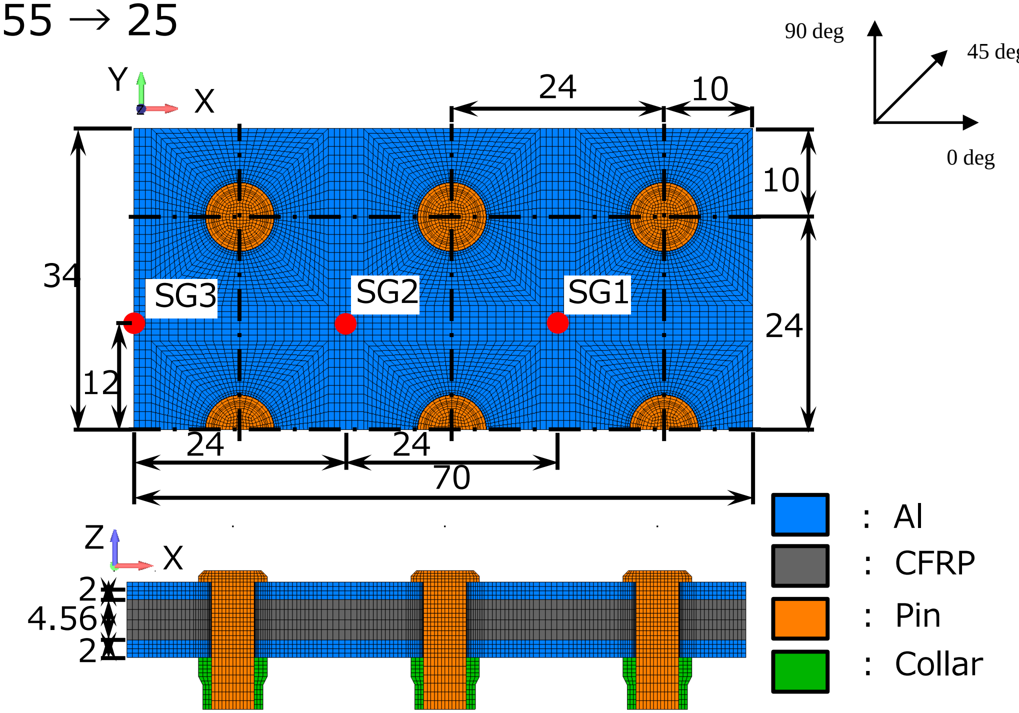


Strain gauge location

Numecircal simulation of hybrid joint under thermal cycles for verification of numerical procedure

Finite Element Analysis:
- Software: ABAQUS 2019
- Element: C3D8 (8 nodes and 6 surfaces)
- Material constant:
  - CFRP: homogeneous orthotropic elastic body (temperature dependent)
  - Metal: MMPDS
- Temperature(deg C): 25 → 85 → -55 → 25
- Friction coefficient: 0.2
- Fastening Force: 3559N (800lbs)

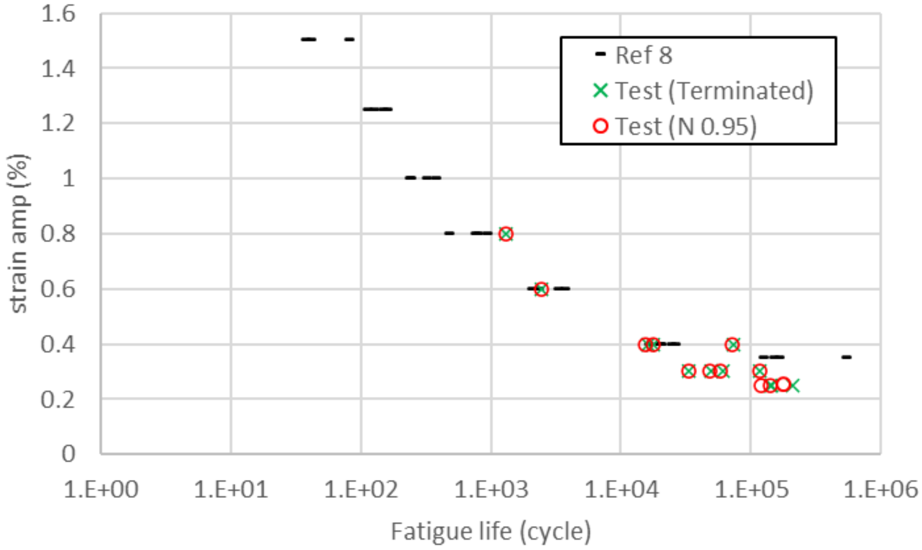


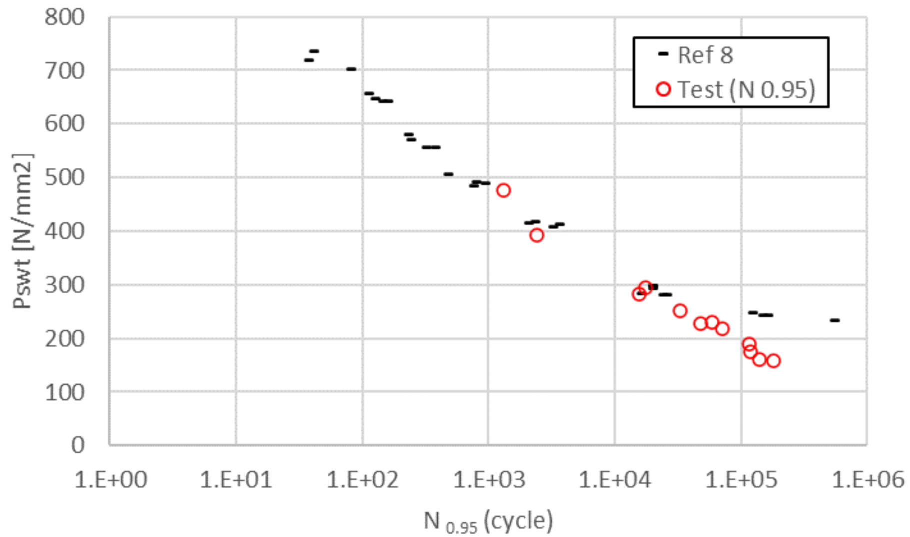


Area of FEM model and FEM mesh

Test results

Terminated: Fatigue cycles which test is stopped.
$N_{0.95}$: Fatigue cycles when maximum load decreases to 95 % of the Maximum load at the stable period

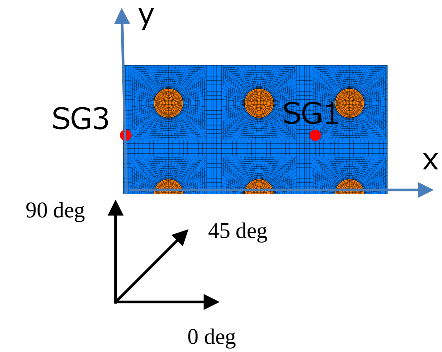


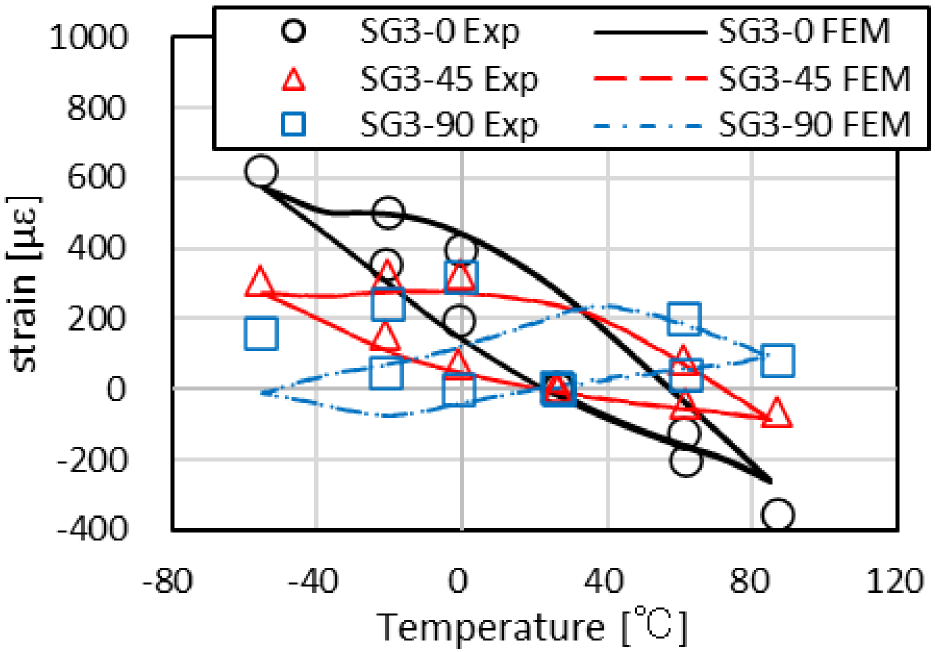


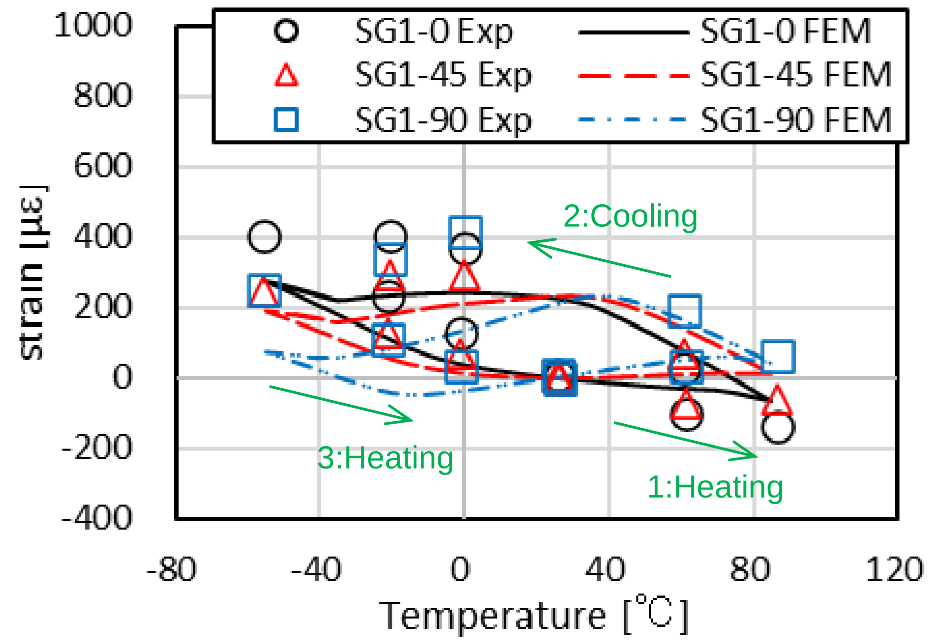
σ'_f : coefficient of fatigue limit	1279 MPa
e'_f : coefficient of plastic fatigue strain	0.118
b : fatigue strength exponent	-0.154
c : fatigue ductility exponent	-0.687

Test results

Hysteresis between elastic strain and temperature becomes stable after second cycle.
Irrespective to gauge location, strain variation along 0 degree is the largest and elastic strain changes nonlinearly around peak temperature.
Strain variation at gauge close to center of the specimen is larger.

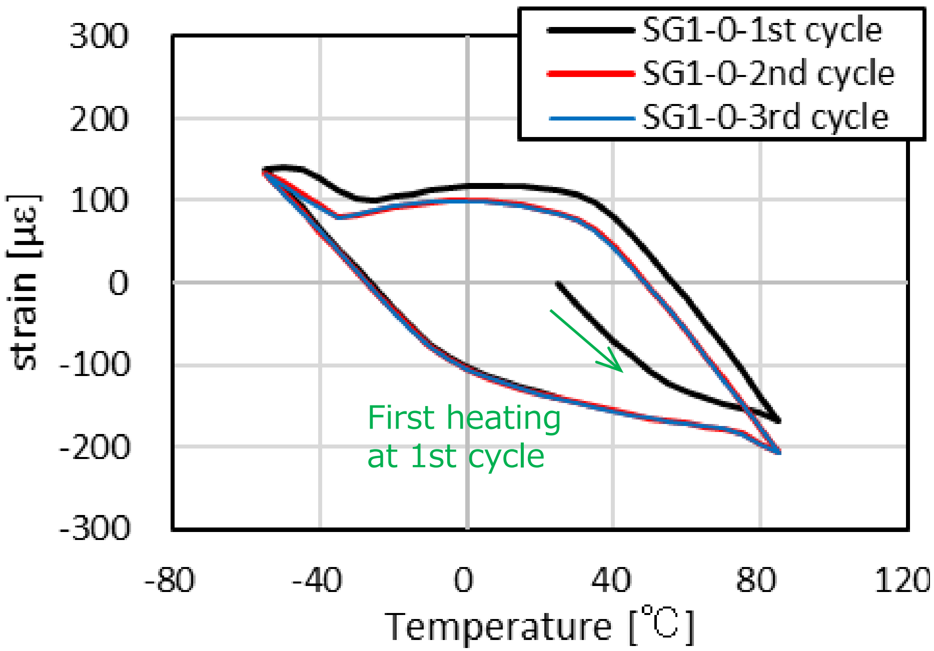


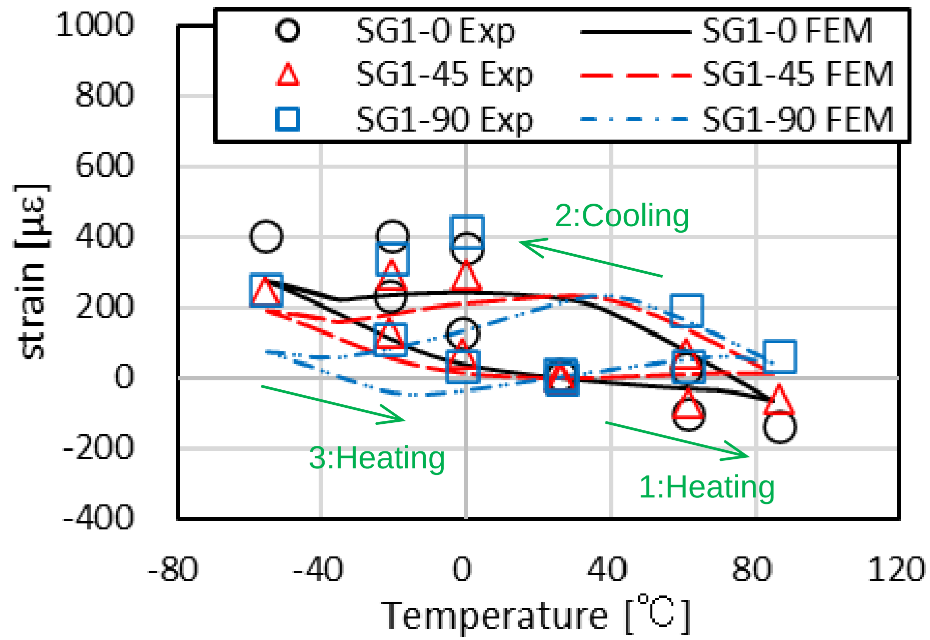




Hysterisis of elastic strain against temperature
(Left: Gauge No.3, Right: Gauge No.1)

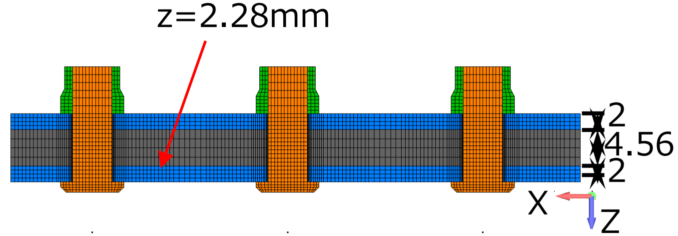
Numerical results

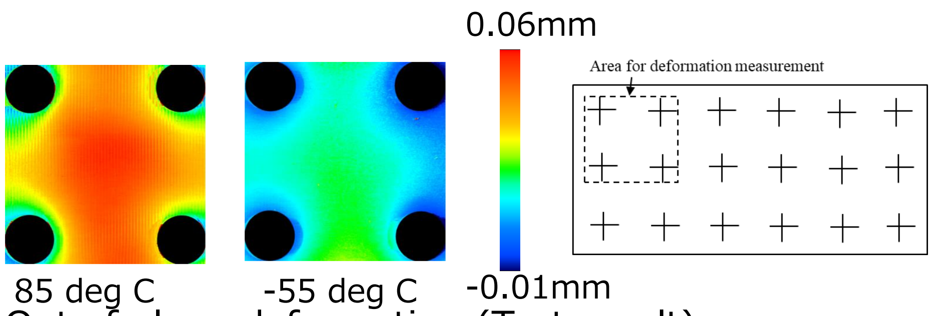




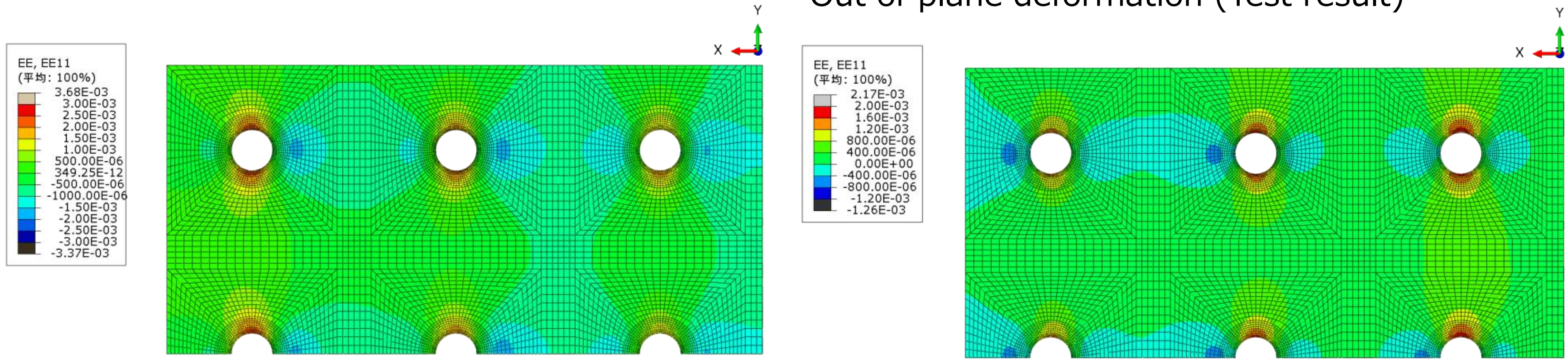
Hysterisis of elastic strain against temperature at Gauge No.1
(Left: Numerical, Right: Experimental and Numerical*)
*: Initial point is set at 25 deg C before temperature increase

Numerical results



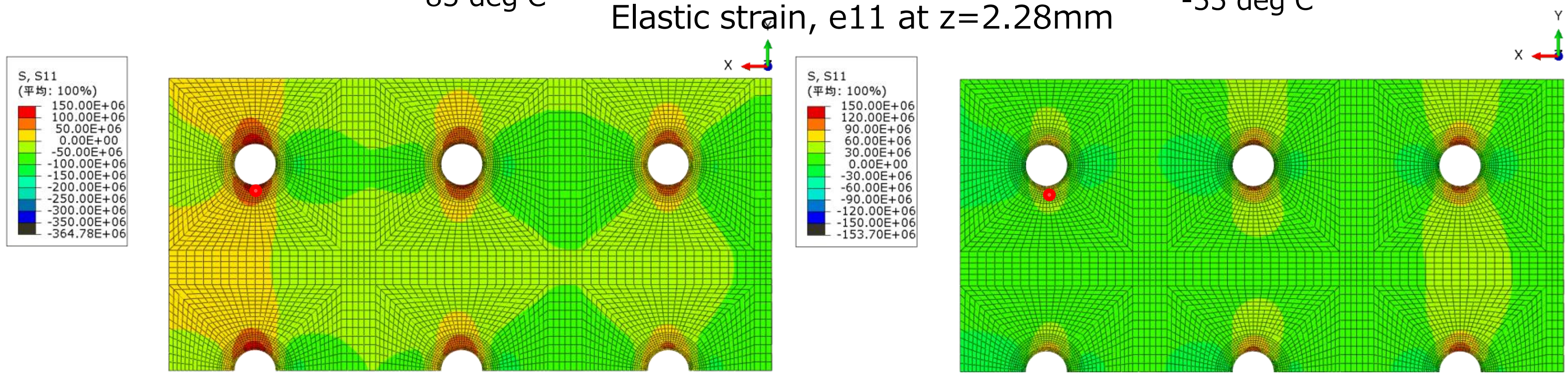


Out of plane deformation (Test result)



85 deg C -55 deg C

Elastic strain, e11 at z=2.28mm



85 deg C -55 deg C

Stress, s11 at z=2.28mm

Conclusions

The procedure to evaluate the life of fatigue crack formation in the CFRP/metal hybrid joint under thermal and external load is proposed based on the evaluation procedure for WFD on riveted lap joint.

Coupon test result indicates lower fatigue life at lower strain level comparing to the reference.

Thermal test for CFRP/Aluminium hybrid joint indiates the hysterisis between temperature and the elastic strain. FEM result identifies that the friction between CFRP and Aluminium plate would cause the hysterisis. Obtained thermal stress is about 100 MPa and is same order of one of the external stress planned for the fatigue test of the hybrid joint and then the thermal stress would affect the fatigue cycles to form the fatigue crack and WFD behavior of the hybrid joint.

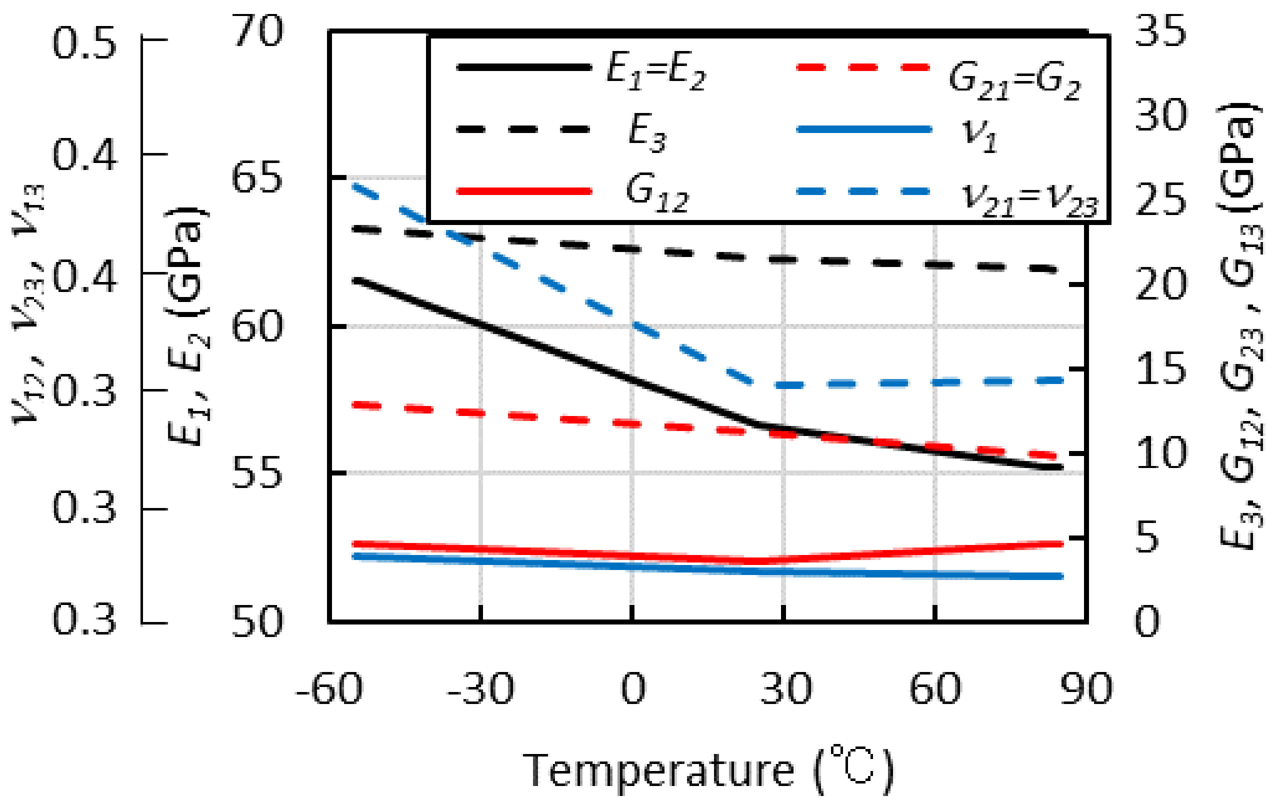
Thank you for your kind attention

Future Work

Additional coupon test to increase test sample and fracture surface observation to identify the cycles to form 0.5mm crack.

Thermal and external load test for CFRP/Aluminium hybrid joint to identify the effect of these loads to stress and strain on the joint

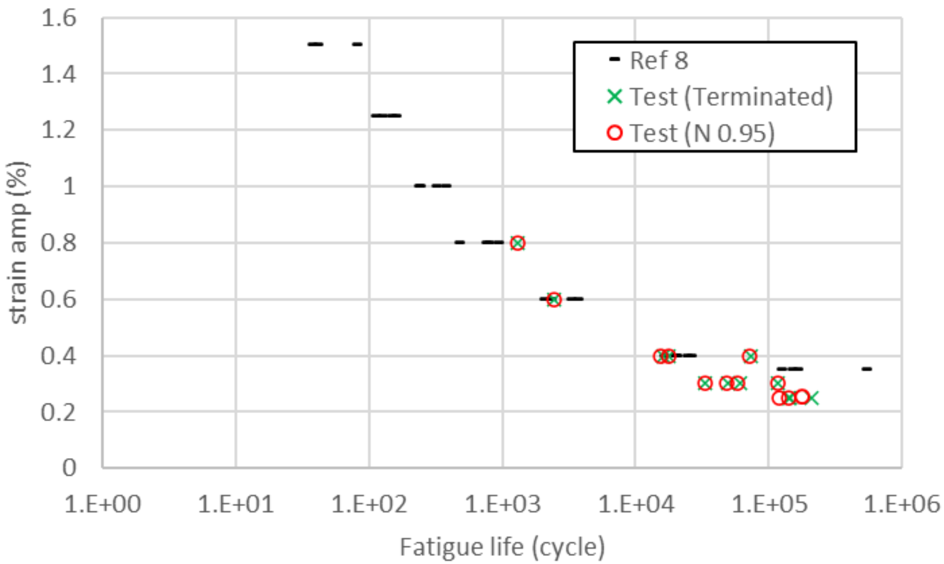
Rrelated FEM analysis to predict critical location in the joint and evaluation of proposed procedure.

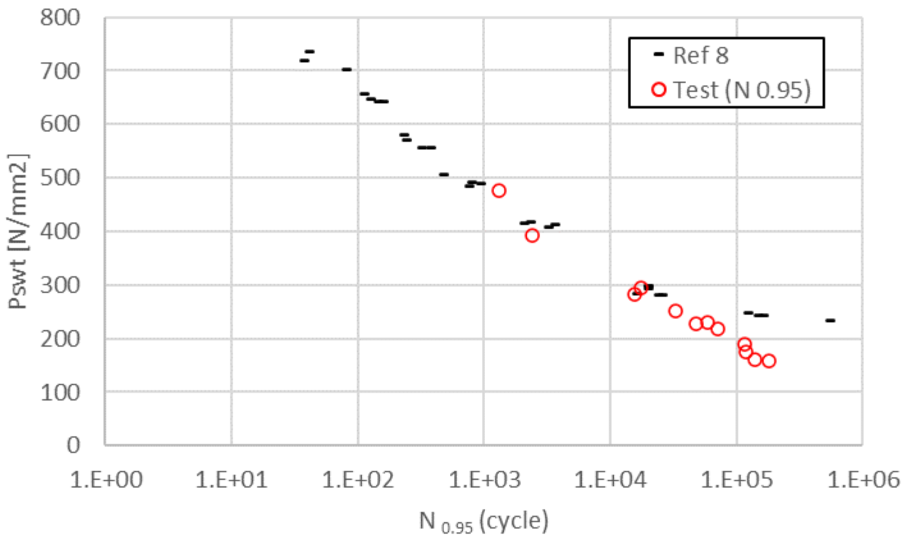


Material properties for CFRP

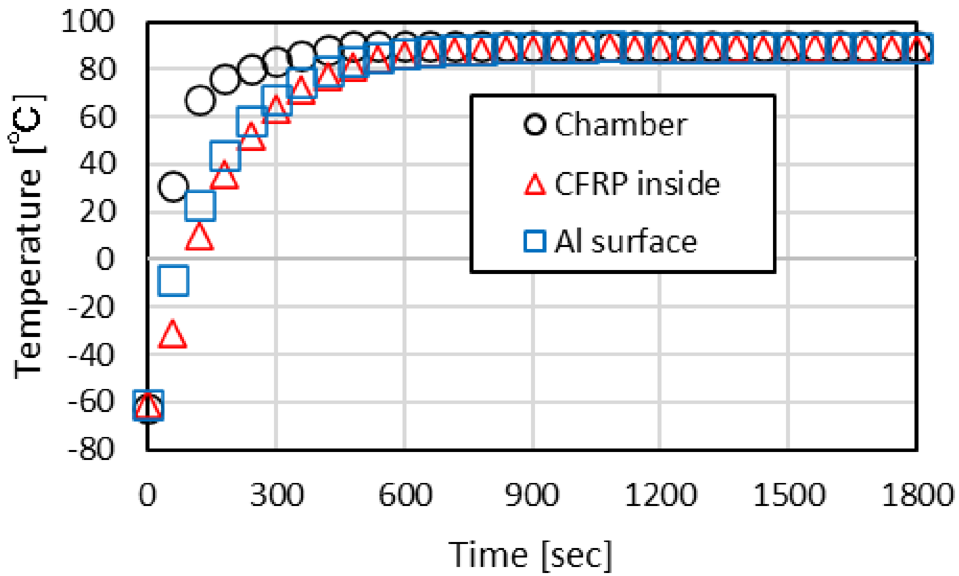
Test results

Terminated: Fatigue cycles which test is stopped.
$N_{0.95}$: Fatigue cycles when maximum load decrease to 95 % of the Maximum load at the stable period

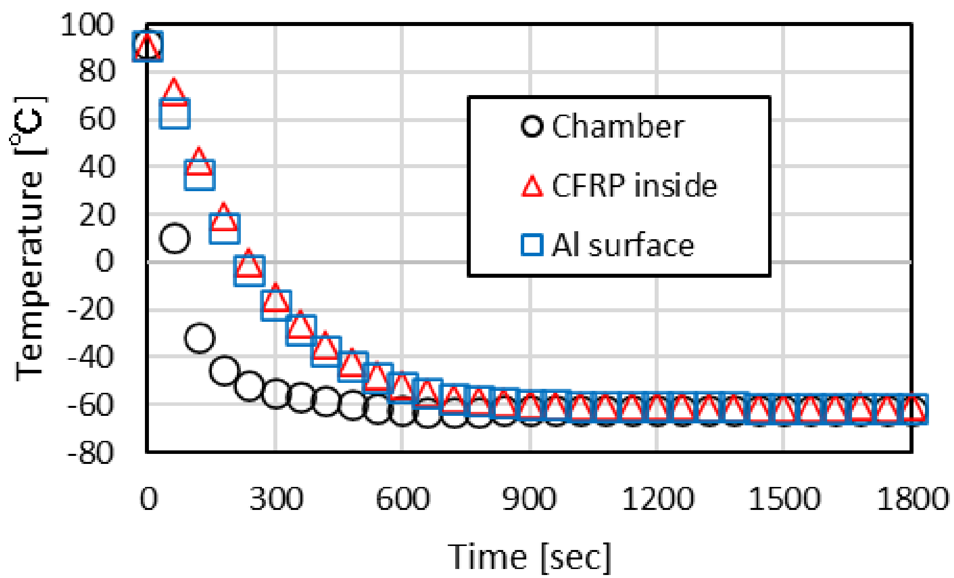




	Ref.8	This result
s'_f : coefficient of fatigue limit	835MPa	1279 MPa
e'_f : coefficient of plastic fatigue strain	0.174	0.118
b : fatigue strength exponent	-0.096	-0.154
c : fatigue ductility exponent	-0.644	-0.687

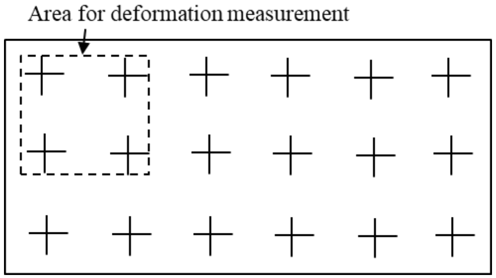


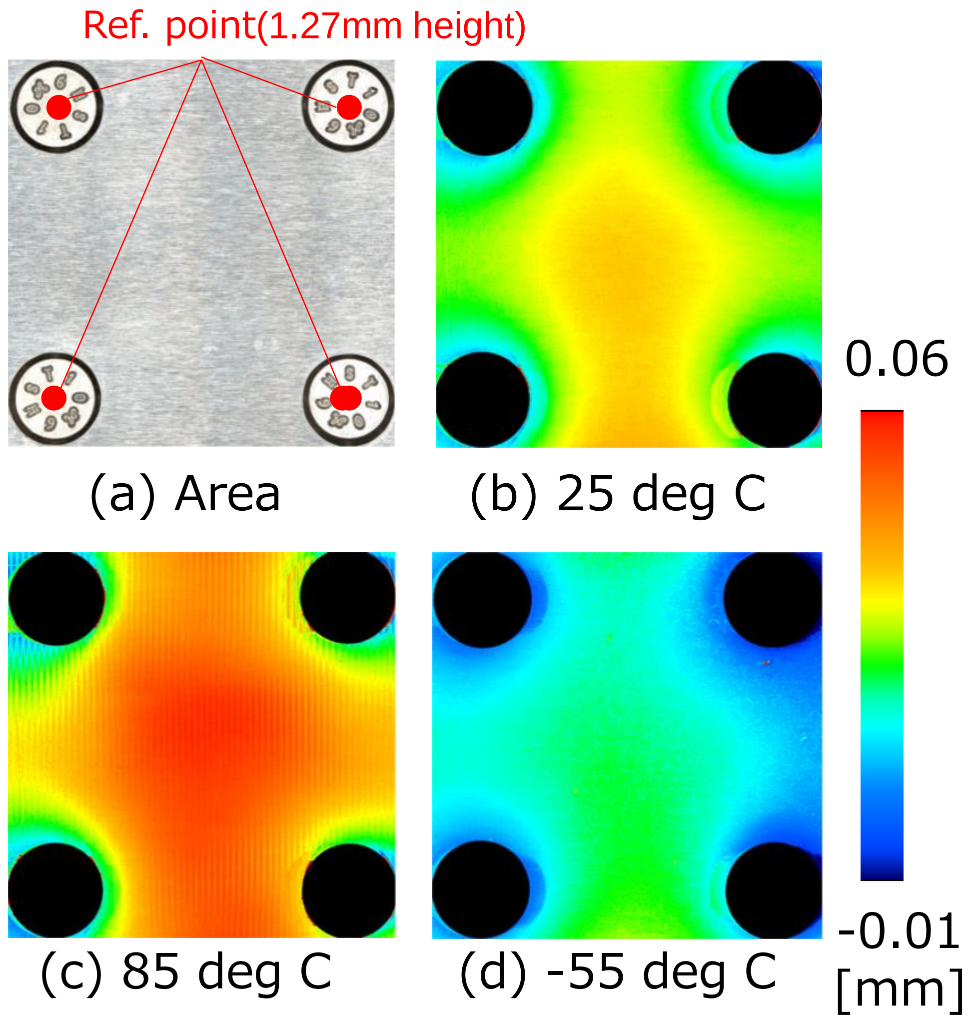
Temperature [℃]
100
80
60
40
20
0
-20
-40
-60
-80
0
300
600
900
1200
1500
1800
Time [sec]
Chamber
CFRP inside
Al surface



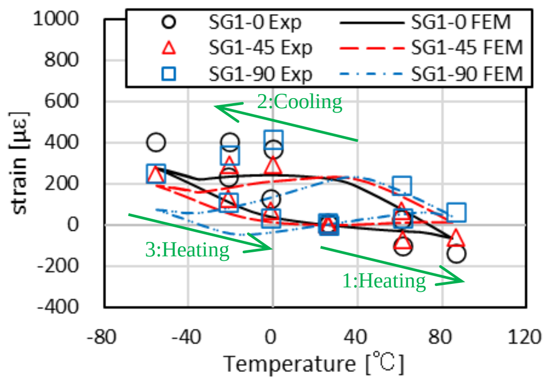
Temperature [℃]
100
80
60
40
20
0
-20
-40
-60
-80
0
300
600
900
1200
1500
1800
Time [sec]
Chamber
CFRP inside
Al surface

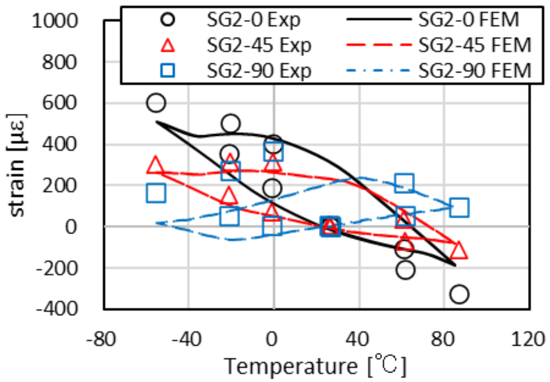
Test results

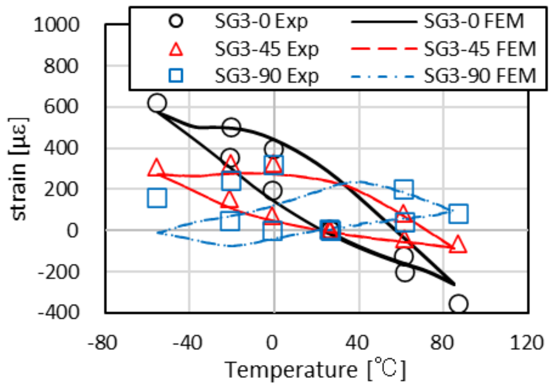


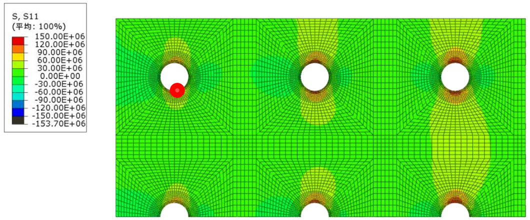


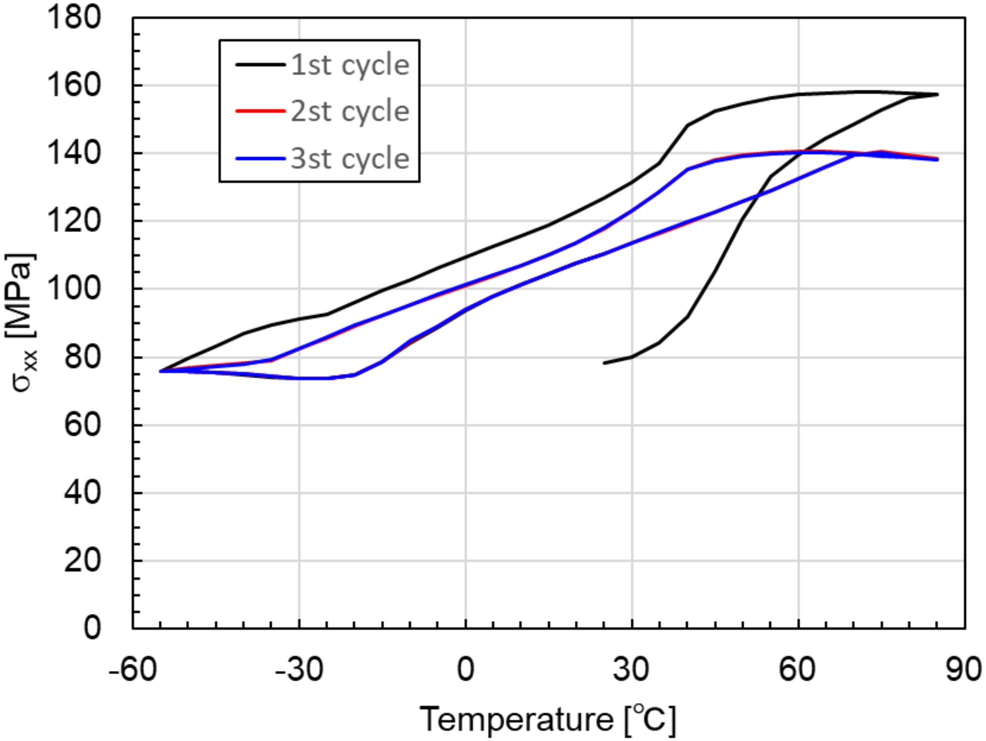
Test results



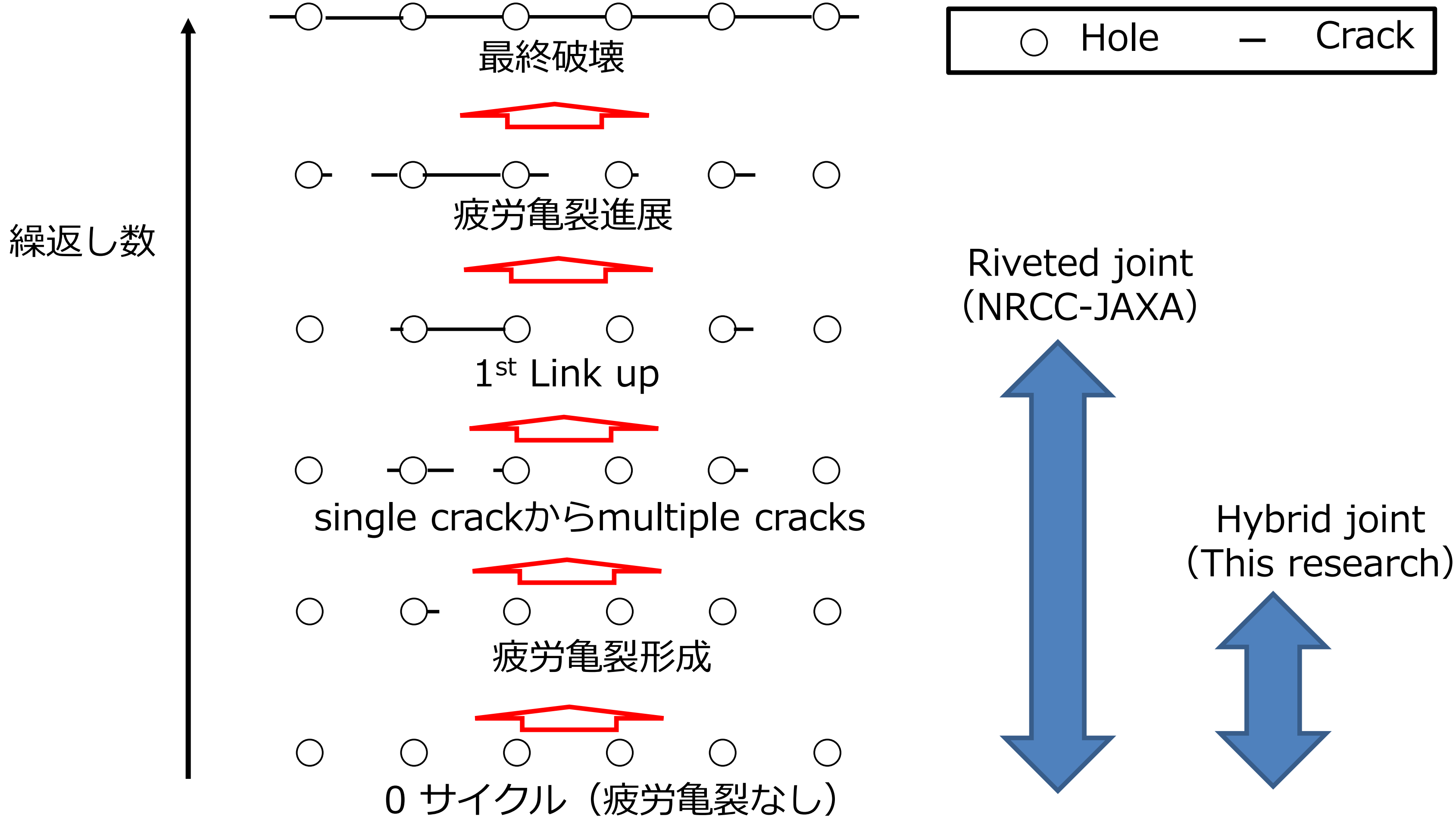





S, S11
(平均: 100%)
150.00E+06
120.00E+06
90.00E+06
60.00E+06
30.00E+06
0.00E+00
-30.00E+06
-60.00E+06
-90.00E+06
-120.00E+06
-150.00E+06
-153.70E+06


1st cycle
2st cycle
3st cycle
σxx [MPa]
Temperature [℃]
180
160
140
120
100
80
60
40
20
0
-60
-30
0
30
60
90

WFD評価手法の検討



繰返し数と損傷形態の変遷の模式図

WFD prediction for riveted joint (NRCC and JAXA)

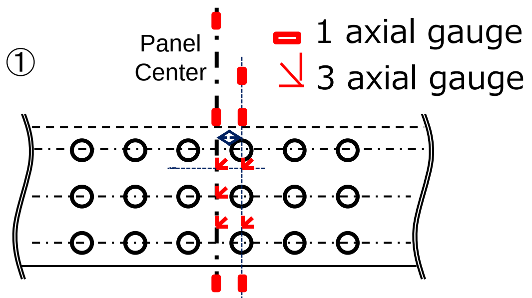
Experiment (JAXA)

Fatigue test of riveted joint (16×3)

①Strain measurement under cyclic load

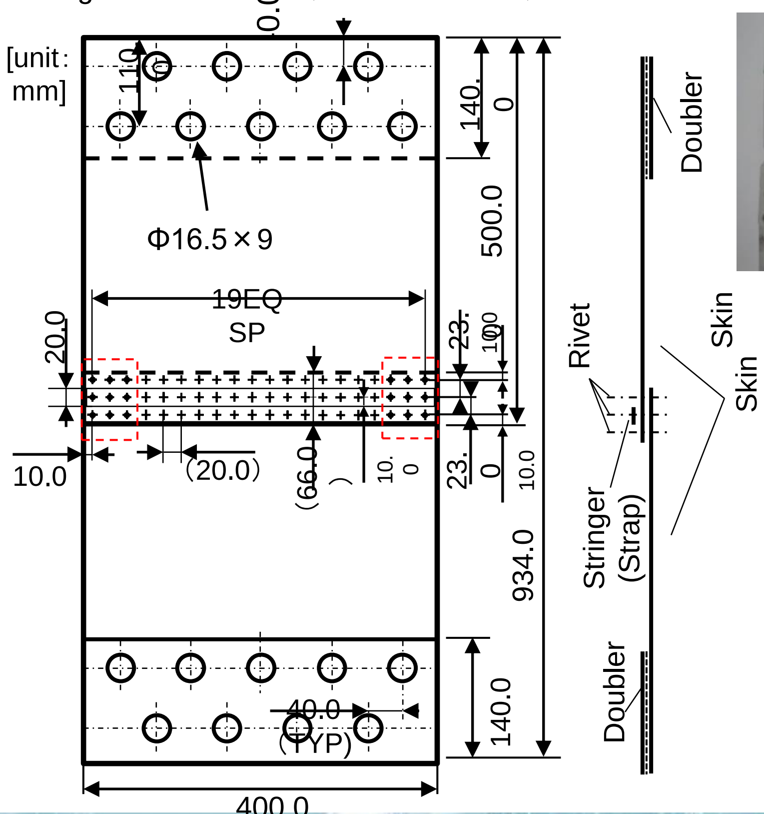
②Observation of Crack location and size by CCD

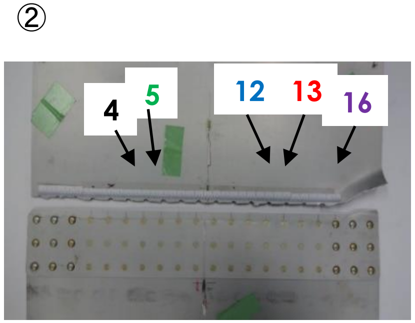
③Fracture surface observation

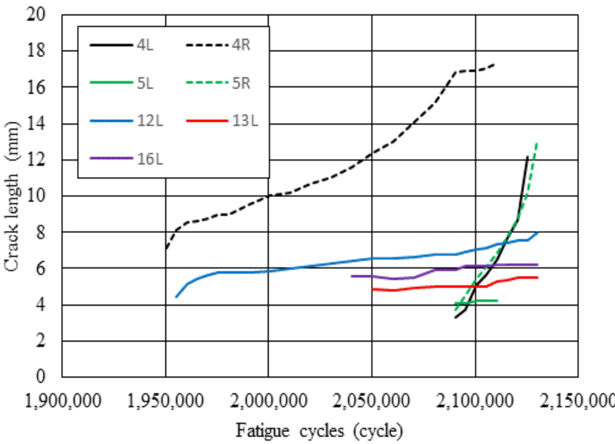


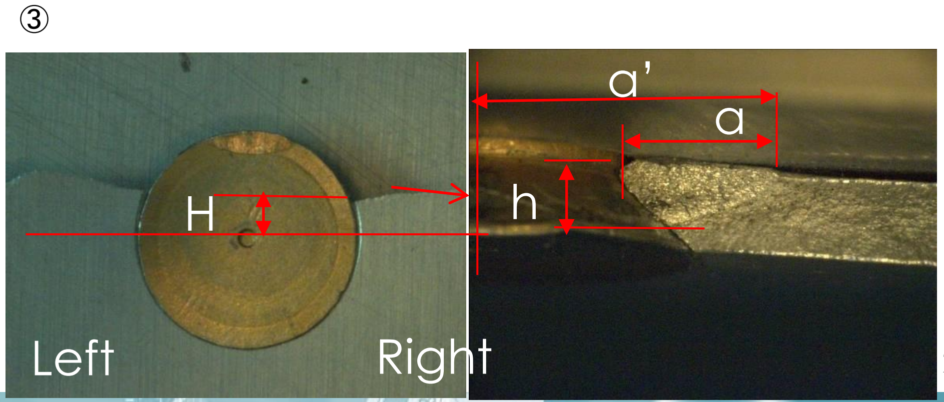
Skin, Doubler t:0.050 inch（Material: 2024C）

Stringer t: 0.063 inch（Material: 2024C）

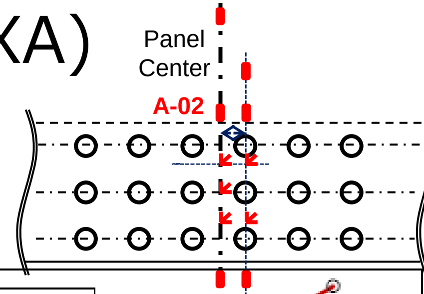








WFD prediction for riveted joint (NRCC and JAXA)



Numerical analysis (NRCC)

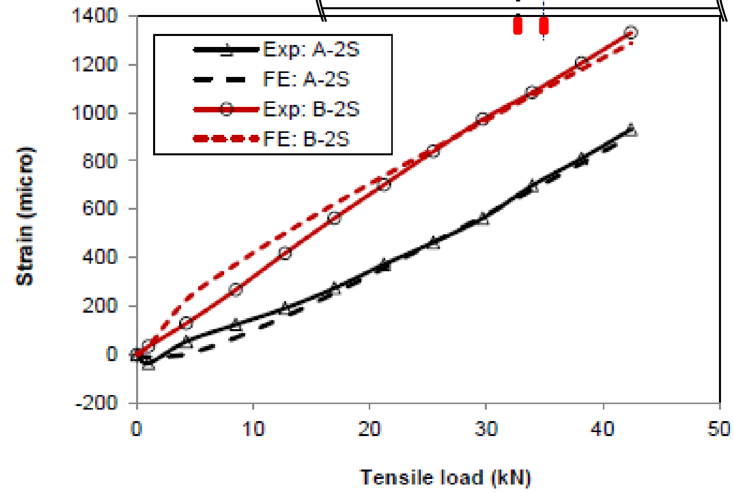
①Rivet squeezing by local FEM model

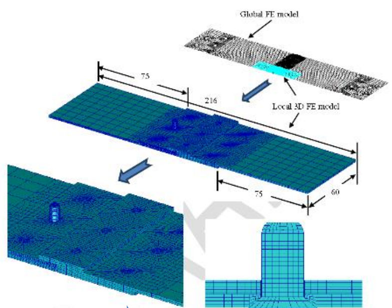
②Evaluation of stress and strain in lap joint by Global FEM model

③Prediction of life to form certain size of fatigue crack based on SWT equation substituting maximum stress and strain amplitude in Global FEM model

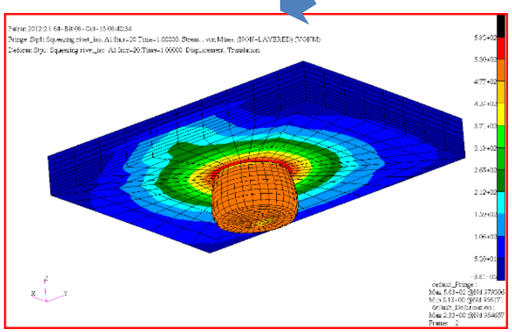
④Prediction of fatigue life up to first link ups using In-house code

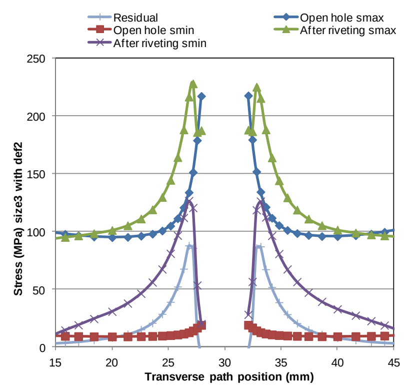
②





①





③ SWT[*1] Equation :

$$\sigma_{max}\ (\Delta\varepsilon/2) = (\sigma'_f)^2/E\ (2N_f)^{2b} + \sigma'_f\epsilon'_f\ (2N_f)^{(b+c)}$$

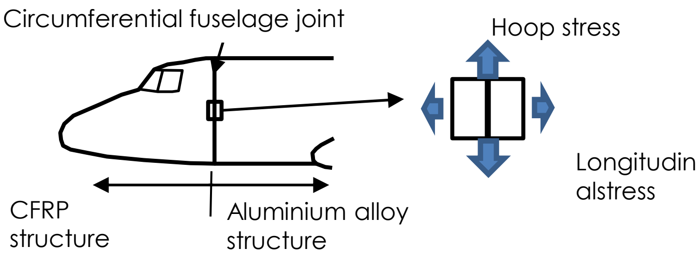
Hole Dia (FEM)	Rivet Squeeze ratio (FEM)	s_{max} De / 2 (FEM)	Fatigue life based on SWT eq.[*2]
4.115	1.507	0.5176	$2.434*10^6$
	1.527	0.4578	$4.590*10^6$
4.166	1.501	0.5300	$2.153*10^6$
	1.519	0.5147	$2.503*10^6$

Objective

To develop prediction procedure for the fatigue life up to form a fatigue crack at certain size (0.5mm) in a metal/composite hybrid joint.

- Experimental test to obtain material data used for SWT equation
- Experimental test to obtain strain by thermal cycles in hybrid joint
- Numecircal simulation of hybrid joint under thermal cycles for verification of numerical procedure

Candidate location of hybrid joint



Development of fatigue life prediction curve

Evaluation of stress, strain and fatigue cycles by strain-controlled fatigue test (coupon)

↓

Evaluation of parameters, σ'_f, ϵ'_f, b, c, used for SWT equation

Validation of FEM model（Thermal load）

Evaluation of stress and strain on hybrid joint by thermal load test ⟷ Evaluation of stress and strain on hybrid joint by FEM analysis

↓

Evaluation of stress and strain of hybrid joint under thermal and external load

Evaluation of stress and strain on hybrid joint under thermal and external load test ⟷ Evaluation of stress and strain on hybrid joint under thermal and external load by FEM analysis

↓

Evaluation of maximum stress, σ_{max} and strain amplitude, $\Delta\varepsilon$ on hybrid joint under thermal and external load by FEM analysis

↓

Prediction of fatigue life to form fatigue crack

Substituting stress and strain obtain by FEM into SWT equation

$$\sigma_{max}\frac{\Delta\varepsilon}{2} = \frac{(\sigma'_f)^2}{E}(2N_f)^{2b} + \sigma'_f\,\epsilon'_f(2N_f)^{(b+c)}$$

Flow chart for fatigue life prediction up to form fatigue crack in hybrid joint under thermal and external load

Background

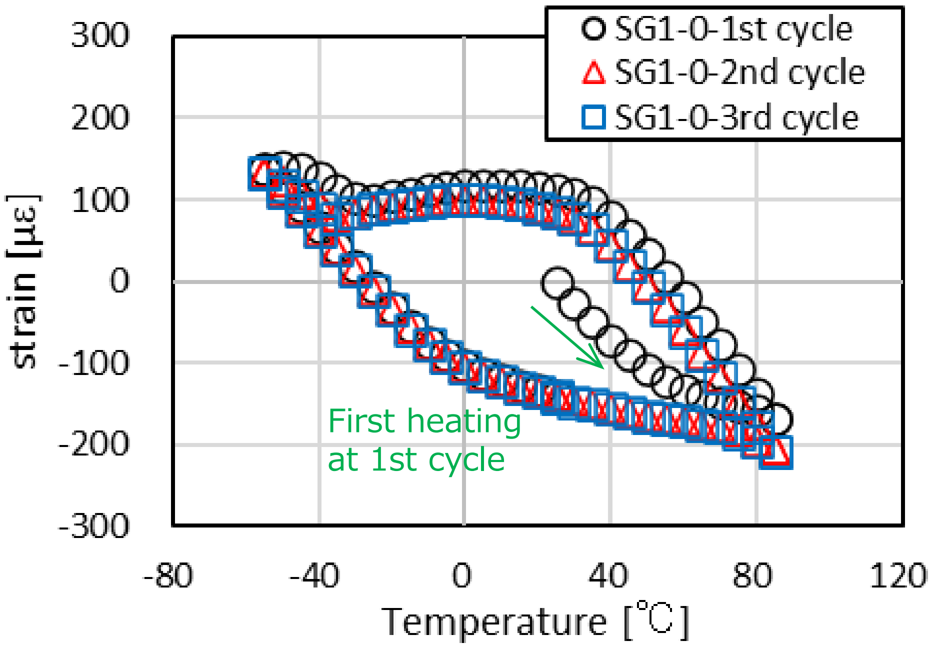
TAMCSWG recommendations:

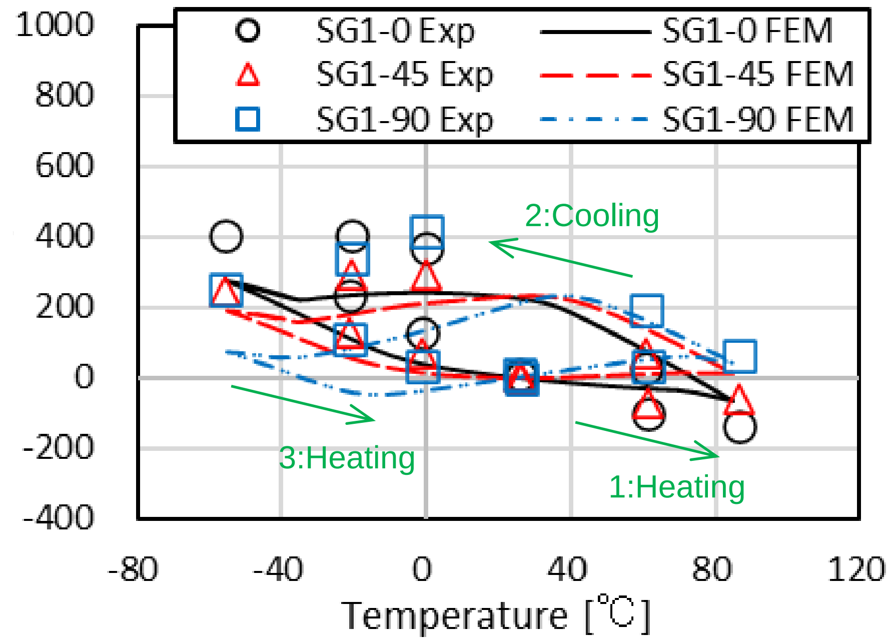
Attempts to simulate the self-balancing thermal loads by an increase in mechanical loads in full scale tests is not acceptable since the resulting total loads will not adequately represent internal load distributions.
Simulation of certain loading conditions in the full-scale testing is not necessary, if it can be shown impractical and accurately addressed by analysis supported by test evidence.

For damage tolerance evaluation of metallic structure, certain loads, such as thermal fatigue loads, will use analysis supported by test evidence, typically with lower level test articles (e.g., component, sub-component, and coupons).
For demonstration of freedom from WFD, the particular loads, which cannot be applied in the full-scale fatigue test (e.g., thermal effect), can be incorporated in the existing acceptable means of compliance-- that is, a combination of crack growth analysis and a tear down inspection.

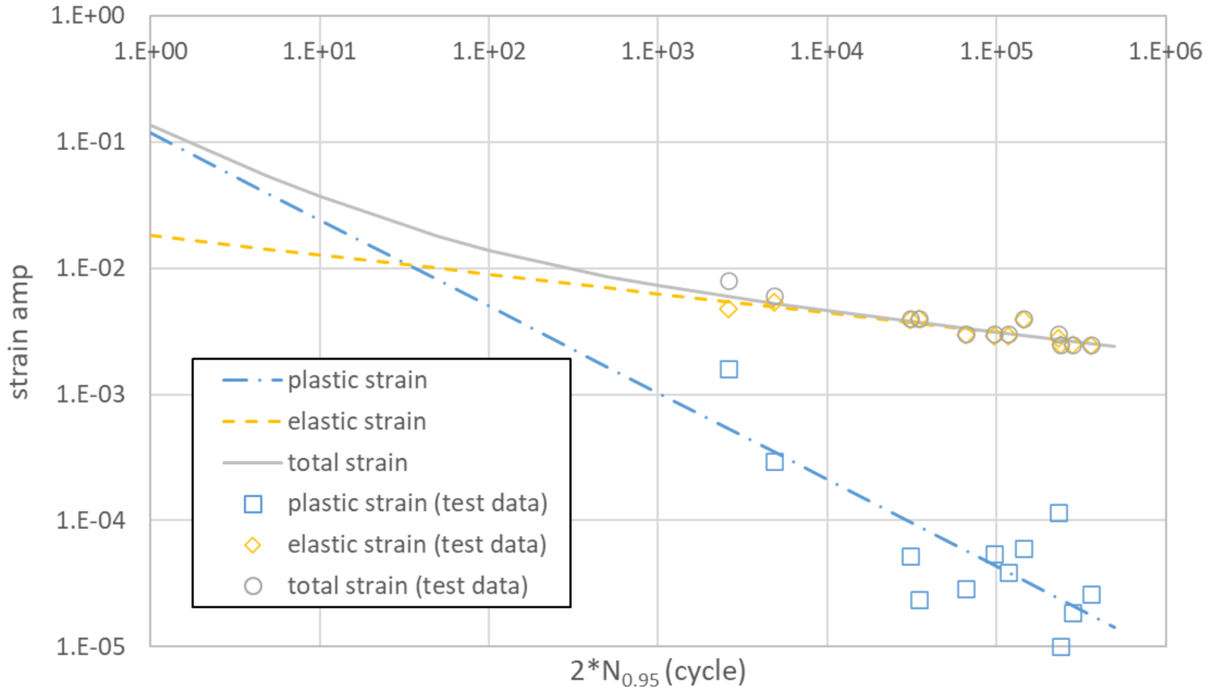
Fatigue test including cyclic thermal load is time consuming comparing to that for external load and then development of analytical procedure for thermal load is desired.

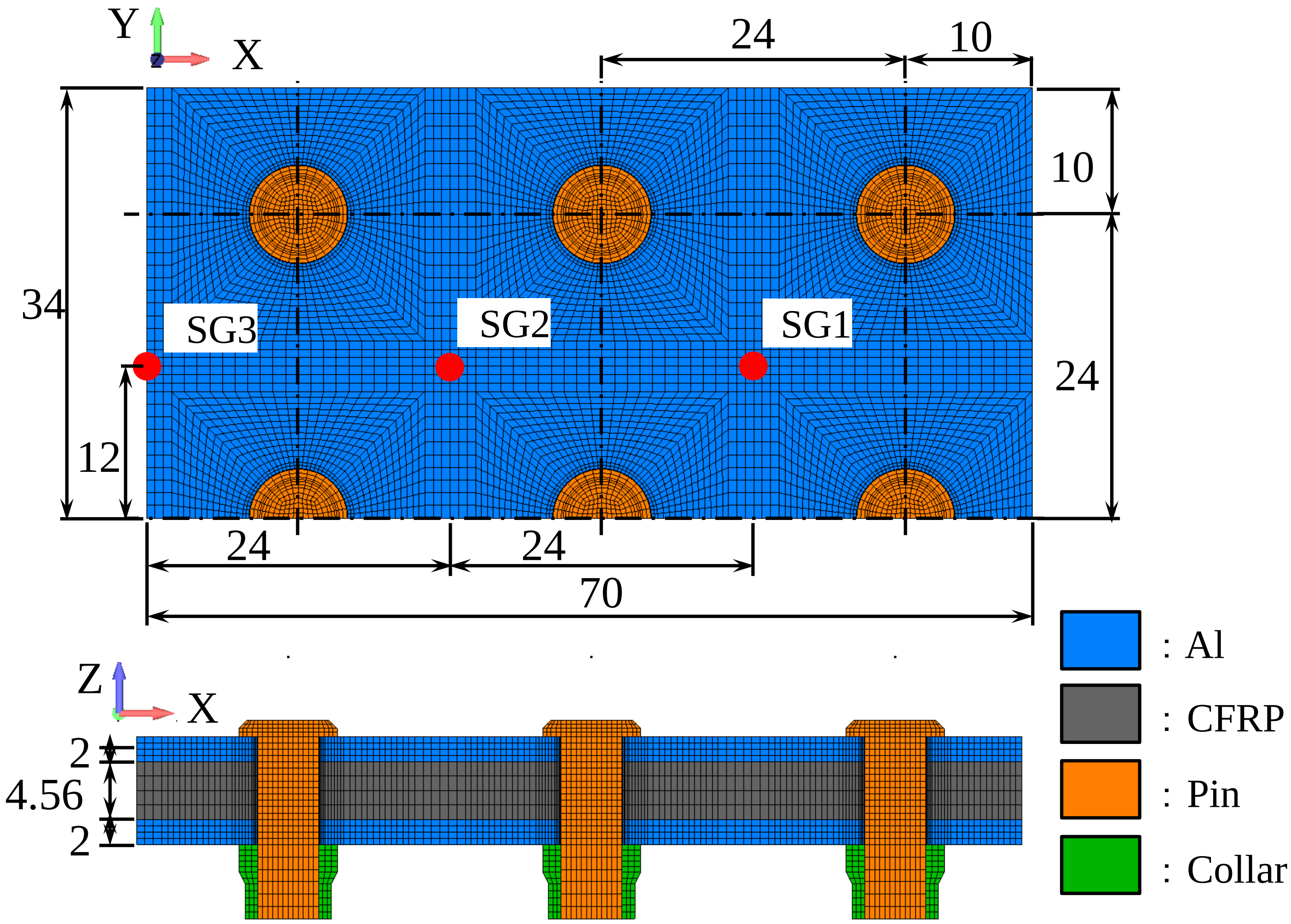
Numerical results





Hysterisis of elastic strain against temperature at Gauge No.1
(Left: Numerical, Right: Experimental and Numerical)


1.E+00
1.E-01
1.E-02
1.E-03
1.E-04
1.E-05
1.E+00
1.E+01
1.E+02
1.E+03
1.E+04
1.E+05
1.E+06
strain amp
2*N0.95 (cycle)
plastic strain
elastic strain
total strain
plastic strain (test data)
elastic strain (test data)
total strain (test data)


Y
X
24
10
10
34
SG3
SG2
SG1
24
12
24
24
70
Z
X
2
4.56
2
: Al
: CFRP
: Pin
: Collar

背景ー航空機構造の設計思想（WFD）

WFDを生じる可能性がある構造部位の例

STRUCTURAL AREA
Longitudinal Skin Joints, Frames, and Tear Straps (MSD/MED)
Circumferential Joints and Stringers (MSD/MED)
Lap Joints with Milled, Chem-milled or Bonded Radius (MSD)
Fuselage Frames (MED)
Stringer to Frame Attachments (MED)
Shear Clip End Fasteners on Shear Tied Fuselage Frames (MSD/MED)
Aft Pressure Dome Outer Ring and Dome Web Splices (MSD/MED)
Skin Splice at Aft Pressure Bulkhead (MSD)
Abrupt Changes in Web or Skin Thickness — Pressurized or Unpressurized Structure (MSD/MED)
Window Surround Structure (MSD, MED)
Over-Wing Fuselage Attachments (MED)
Latches and Hinges of Non-plug Doors (MSD/MED)
Skin at Runout of Large Doubler (MSD)—Fuselage, Wing or Empennage
Wing or Empennage Chordwise Splices (MSD/MED)
Rib-to-Skin Attachments (MSD/MED)
Typical Wing and Empennage Construction (MSD/MED)

- Monte Carlo Simulation (CanGROW)
  - 45,000 trials
  - POF combination for 28 crack sites