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Investigation of Steam Turbine blade failure

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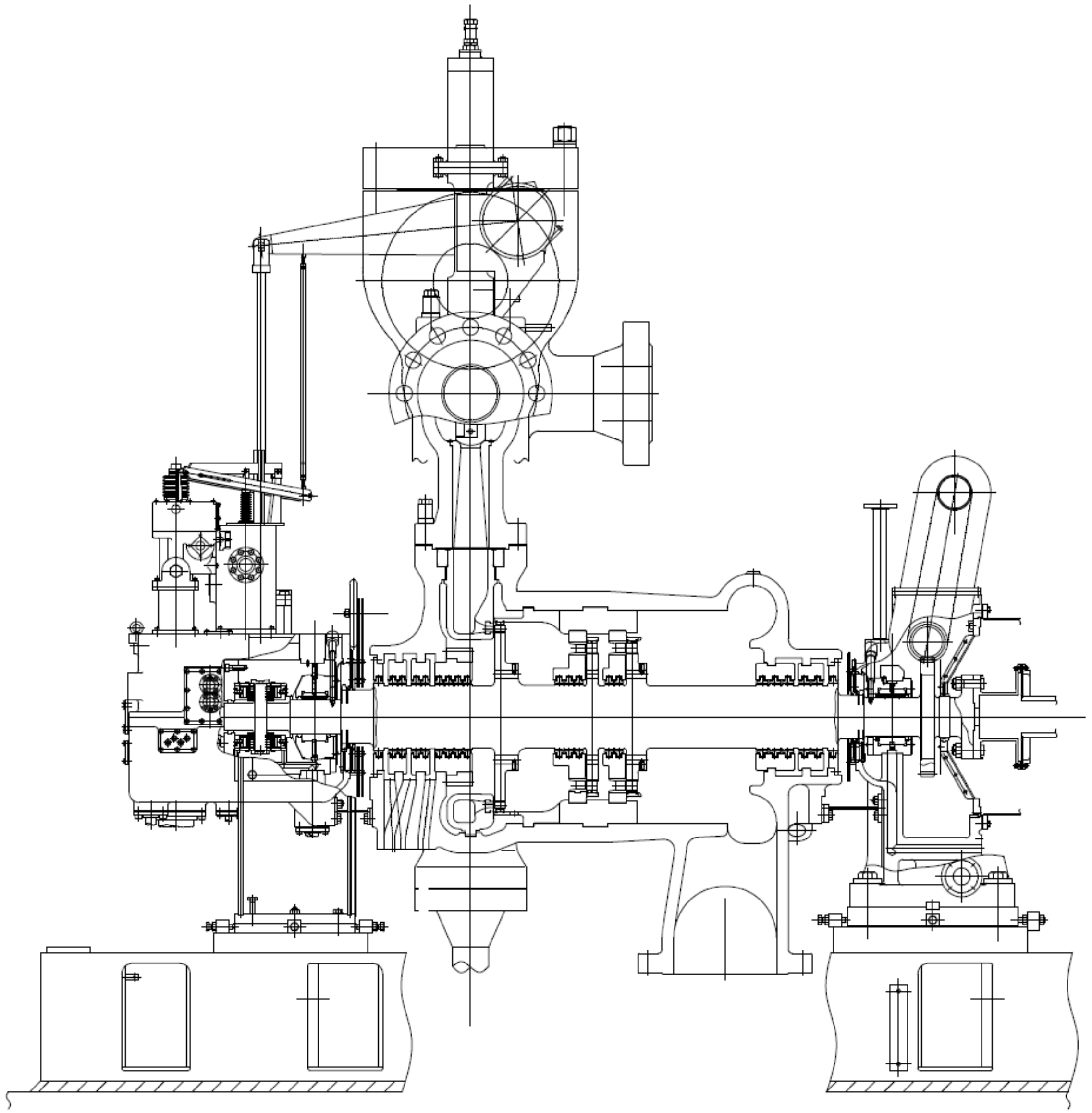
Abstract

Blade failure was observed on a backpressure steam turbine (driving a centrifugal compressor) after it was in service for more than one year.

This paper presents details of observations, inspections carried out and root cause analysis of the turbine blade failure.

Contents

1. Turbine Specification



Turbine Cross Section

- Turbine specification
  - Back pressure turbine driving ethylene compressor in a cracker plant
  - Power : 17MW
  - Speed : 4117 – 5085 rpm
  - Normal steam inlet condition
    - Inlet : 103 kg/cm^2G , 503℃
    - Outlet : 45 kg/cm^2G

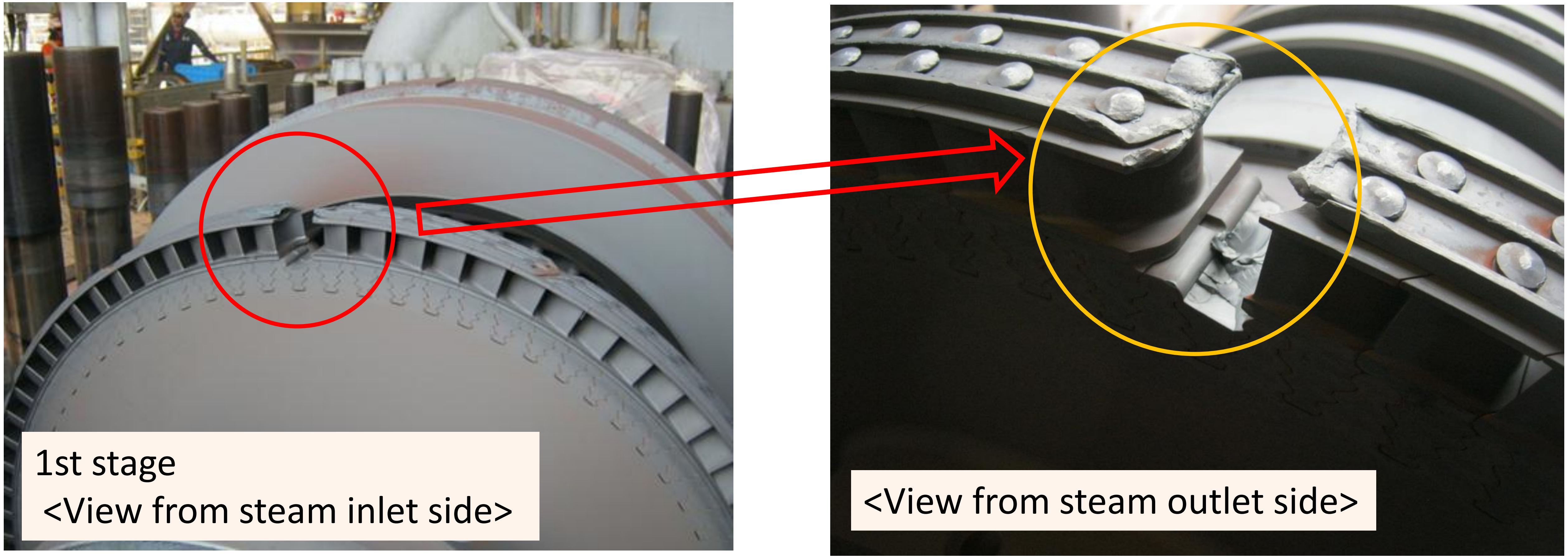
- History

2013
Plant Start

March 2014
Turbine trips on high vibrations

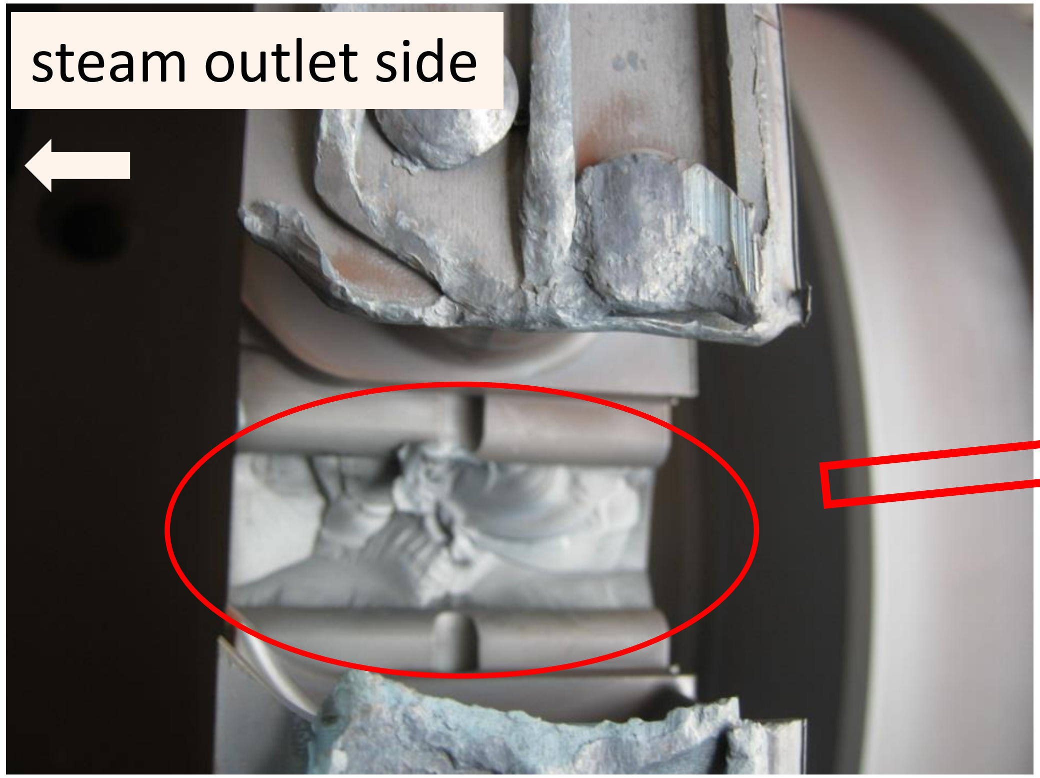
Restart attempted and unsuccessful due to high vibrations at low speeds. Decided to overhaul turbine.

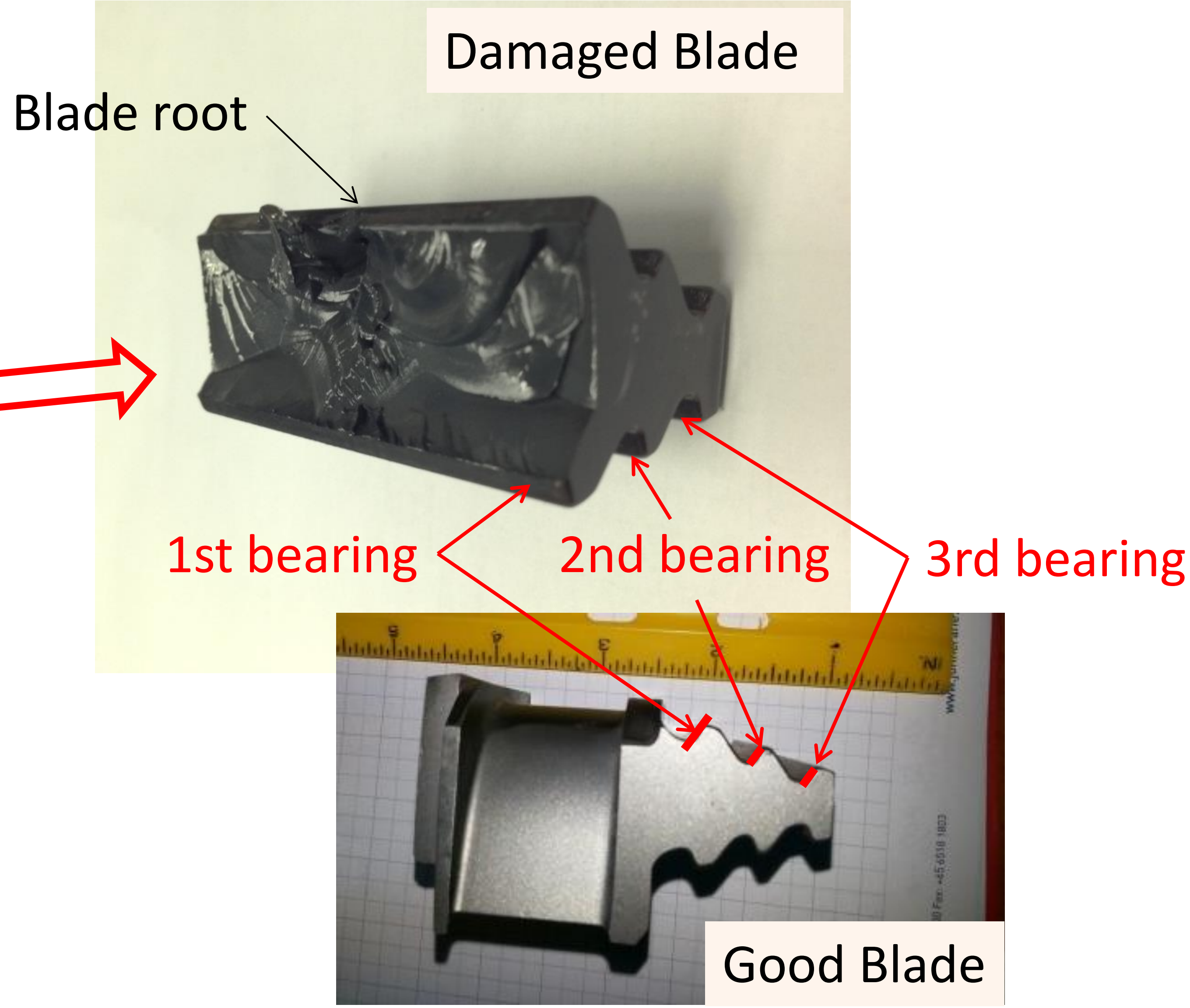
2. Observations during overhaul (1/3)



First stage wheel : Broken blade at one location. No damage on other components.

2. Observations during overhaul (2/3)

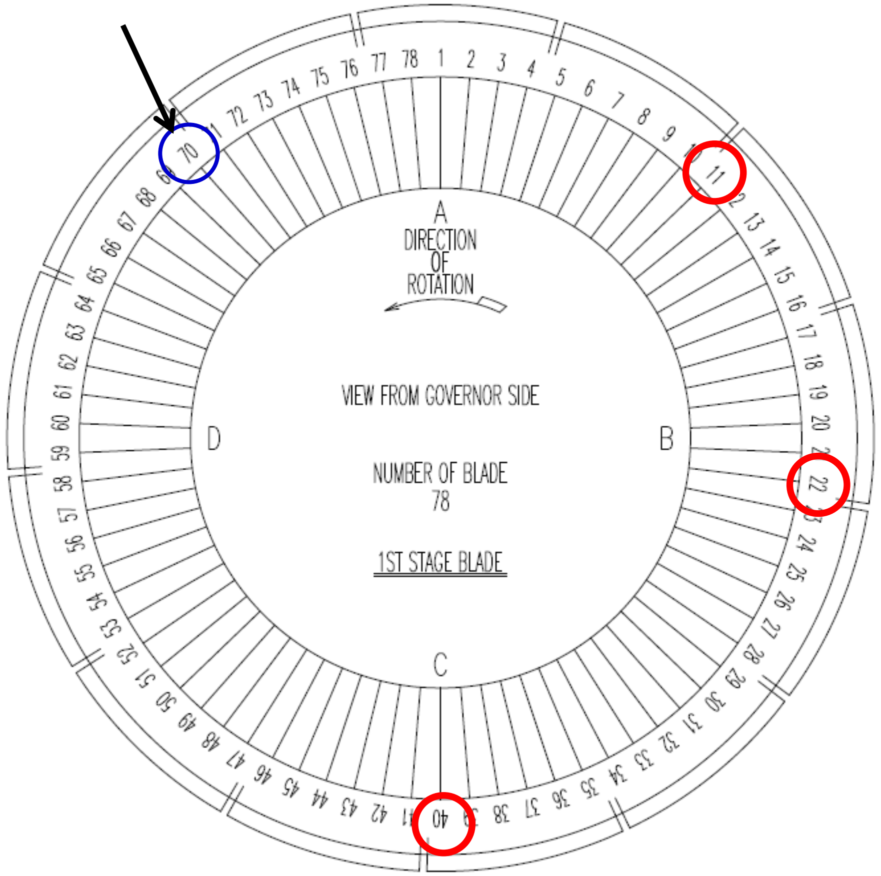




One blade damaged out of 78 blades, and fracture was located at the 1st bearing portion of blade root. Other components (2nd and 3rd stage) not damaged

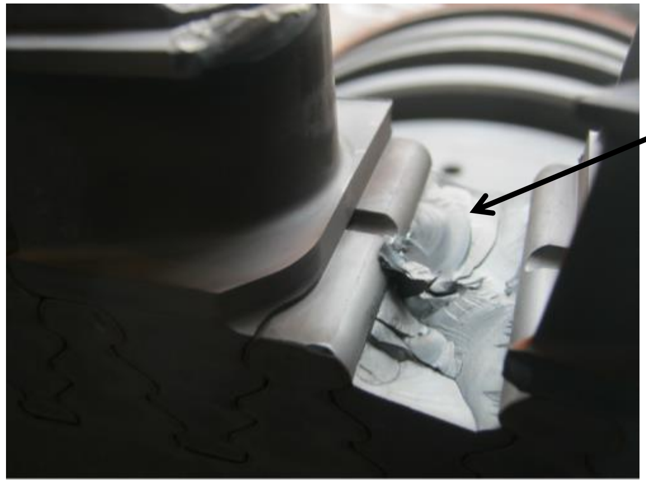
2. Observations during overhaul (3/3)

Failed blade



○ : Crack indication

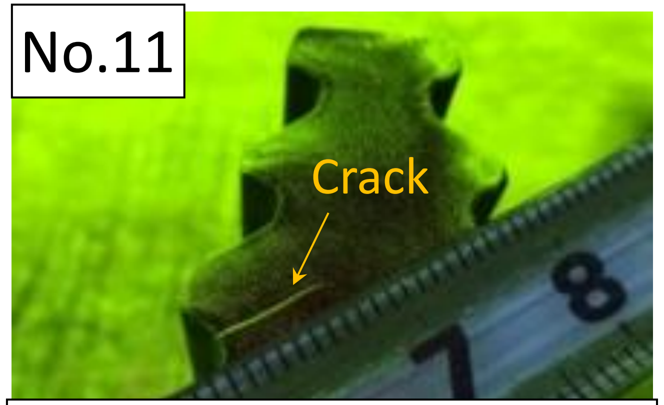
Failed blade and crack indicated blades were located on the first/last of shroud.



No.70 blade root

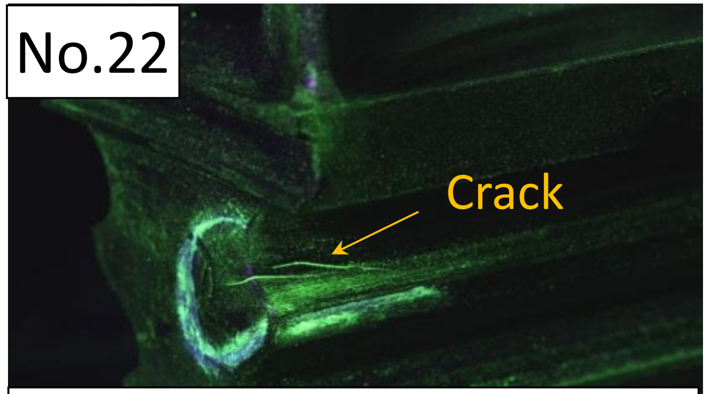
Failed blade was No.70 on blue colored circle part.

No.11



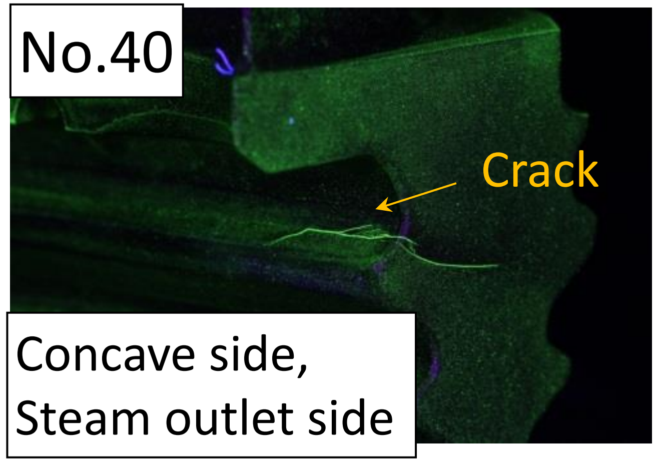
Convex side, Steam inlet side

No.22



Concave side, Steam inlet side

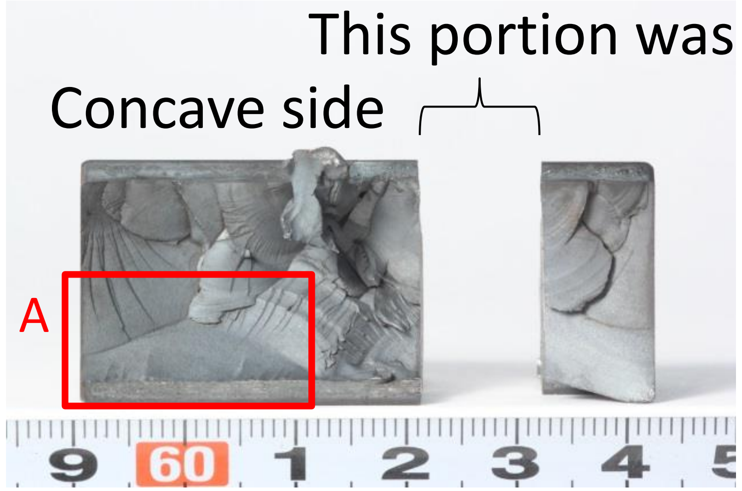
No.40



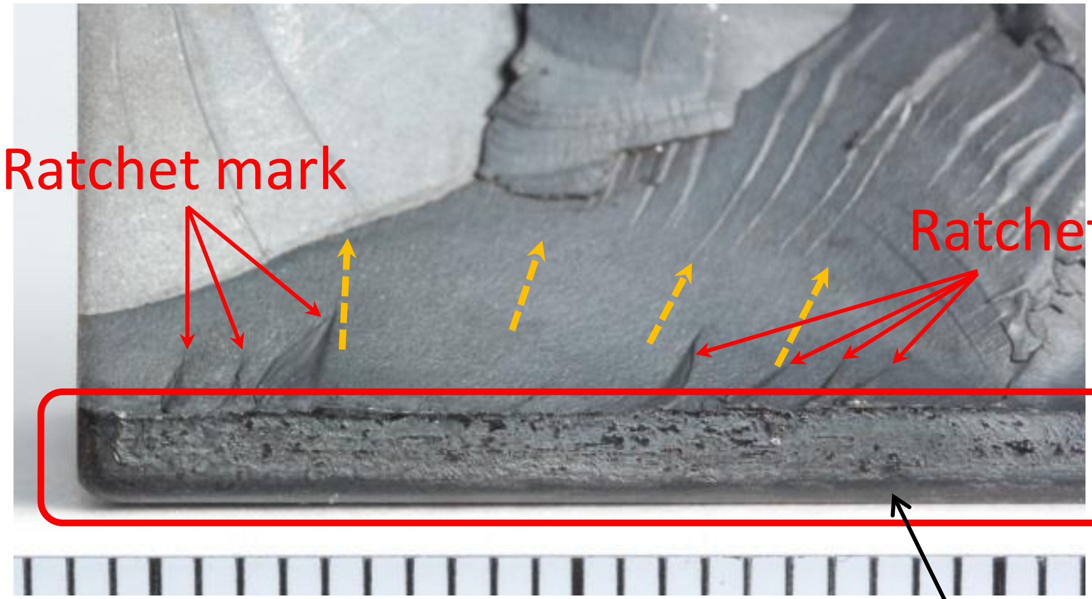
Concave side,
Steam outlet side

Crack indication was detected on No.11, No.22 and No.40 blade root in MT inspection.

3-1. Fracture surface observations



Overview of fracture surface



Magnification of A area

- Ratchet mark was observed on fracture surface, so the crack has multiple origin.
- Rough surface was observed around crack origin.
- Crack was started from rough surface.
- No corrosion pit was observed.
- Chemical components and hardness were satisfied the required specification.

Initial crack was initiated by fretting fatigue, and blade failed from high cycle low stress fatigue.

3-2. Fracture surface observation result

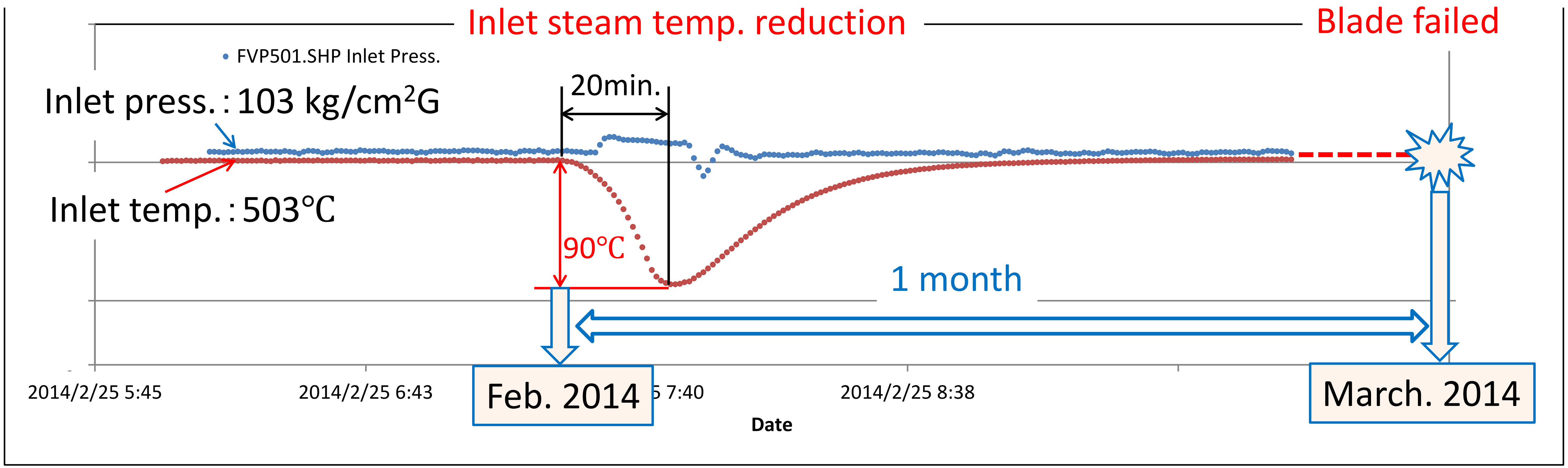
The followings are observed from fracture surface of No.70 blade.

1) The blade failed from high cycle fatigue.
2) Fatigue cracks start in 4 areas on both sides of the blade root.
   This and the presence of ratchet marks support a high cycle low stress fatigue mode.
3) In the fatigue crack initiation locations multiple fretting marks are present.
   Fretting fatigue cracks start from these locations.
4) The failed blade steel is made of good quality.
5) No evidence of an external factor related to steam quality was found.

Fig.1 Fracture surface of No.70 blade

4. Review of operation data

- <u>Review of Operation data</u>



The temperature changed from approximately from 500 degree C to 410 degree C in roughly 20 minutes and then recovered to rated temperatures in approximately 30 minutes.
This event had occurred approximately 1 month before the failure of the turbine blade.

5. Possible cause (1/2)

PHENOMENON	ANALYSIS OF FAILURE PHENOMENON		HOW TO VERIFICATION	Result & Assessment	
Blade failure on 1st stage of Comp. drive steam turbine	Excessive static stress	Out of allowable operation	Review of operation data	Inlet steam temperature goes down from 500℃ to 410℃ in 20 min.	△
		Unexpected damage	Observation of nozzle and blade surface	No indication of contact with other parts was observed by visual.	×
	Excessive vibration stress	Excessive exciting force	Re-check of 1st stage blade strength by using 3D FEM analysis	1st stage blade stress due to NPF, 2×NPF and shock load are satisfied with our design criteria. However, valve sequence is different from PRC turbine.(ERC turbine is 2 shock road condition)	△
		Large stress concentration by improper machining and/or assembly	Observation of blade outline	Blade root dimension is within design. Groove dimension is within design.	×
	Corrosive environment	Insufficient quality of steam	Observation of fracture surface	Failed blade material is made of good quality. No evidence of an external factor related to steam quality was found.	×
	Inferior material	Defects of material	Observation of fracture surface		
		Insufficient mechanical property	Inspection of blade material		

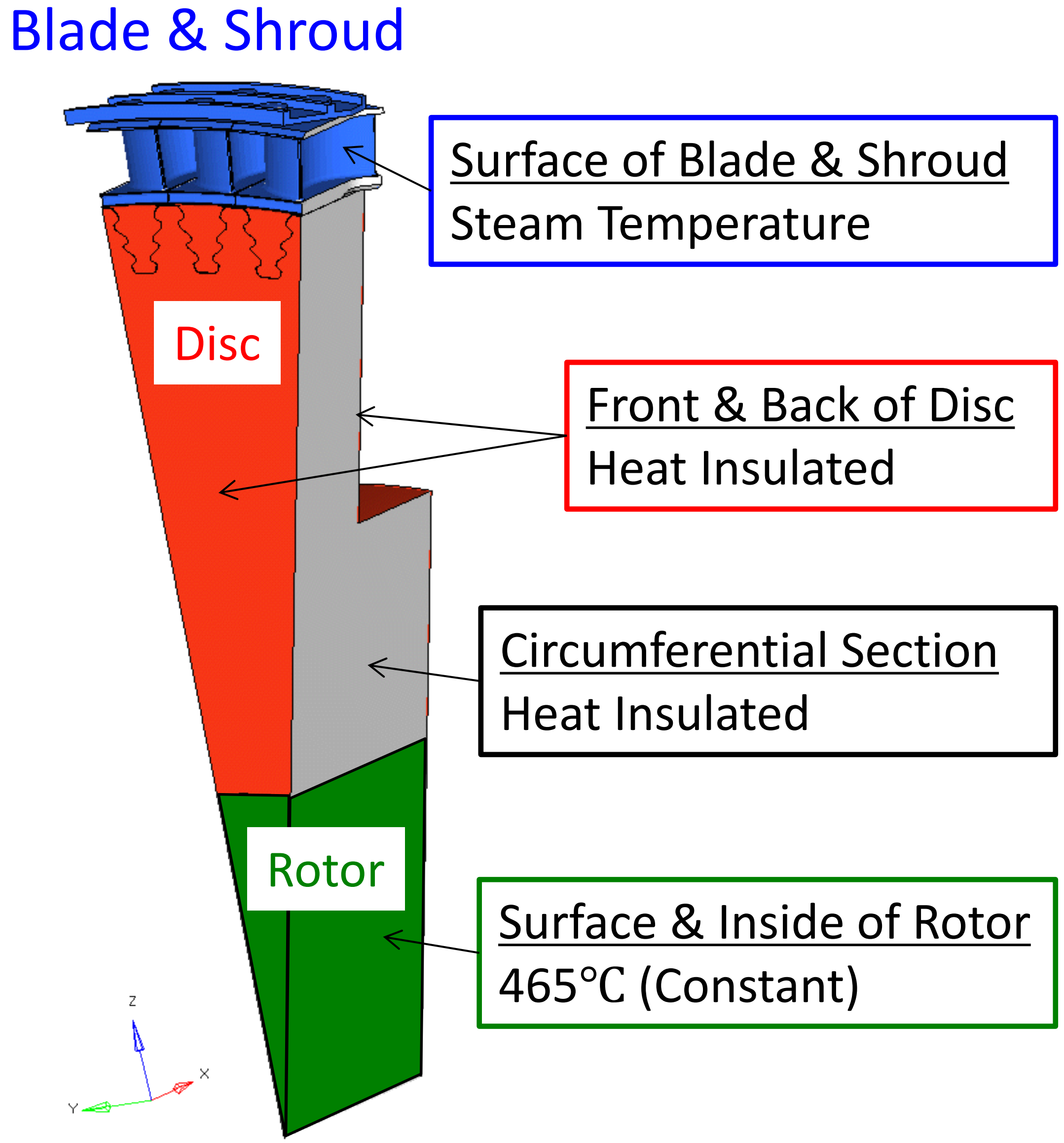
△ : Possibility × : Low possibility

5. Possible cause (2/2)

	Operation	Stress	Fracture
Step 1	Steam inlet temp. 90℃ reduction (-4℃/min)	Vibratory stress (Shock) ⇒ Slip on blade root	Number of cycles exceed fretting thresh-hold for crack initiation ⇒ initial cracks formed
Step 2	Rated Operation	High cycle low stress fatigue	Vibratory stress ⇒ cause crack propagation even with no slip

6. Heat transfer stress analysis (1/2)

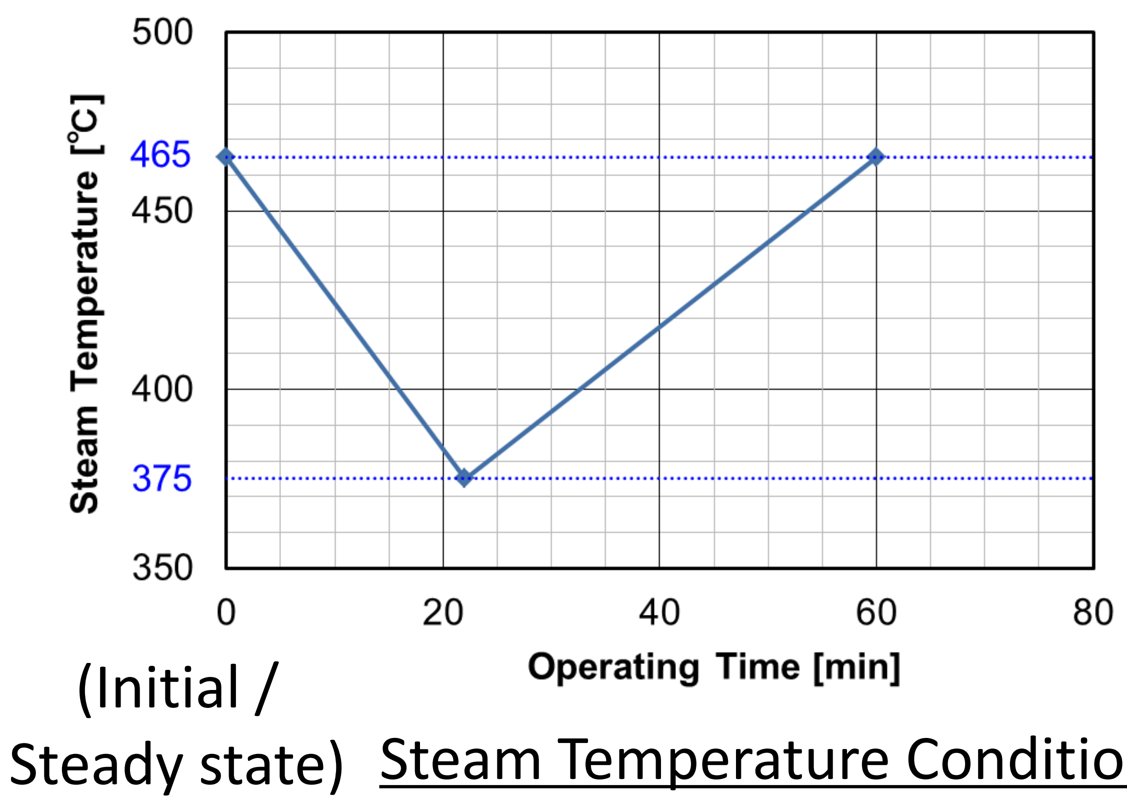
<Analysis Model>



Analysis Model & Thermal Boundary Condition

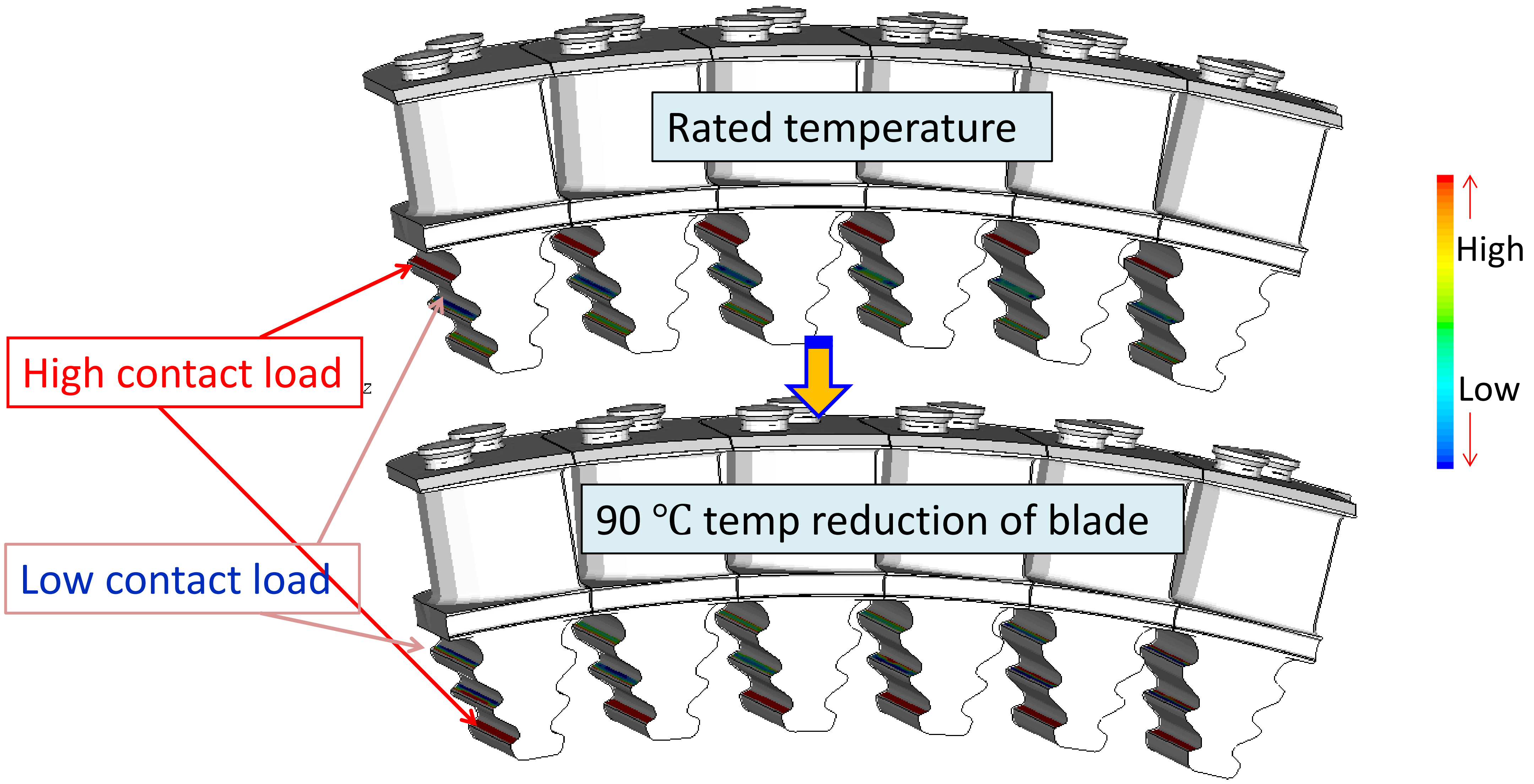
<Analysis condition table>

Steam Temp.		Operating Time			Operating Speed
Reduction	Reheating	Reduction	Reheating	Total	
-4 ℃/min	+2.4 ℃/min	22 min	38 min	60 min	Nor. (4700 rpm)



Steam Temperature Condition

6. Heat transfer stress analysis (2/2)

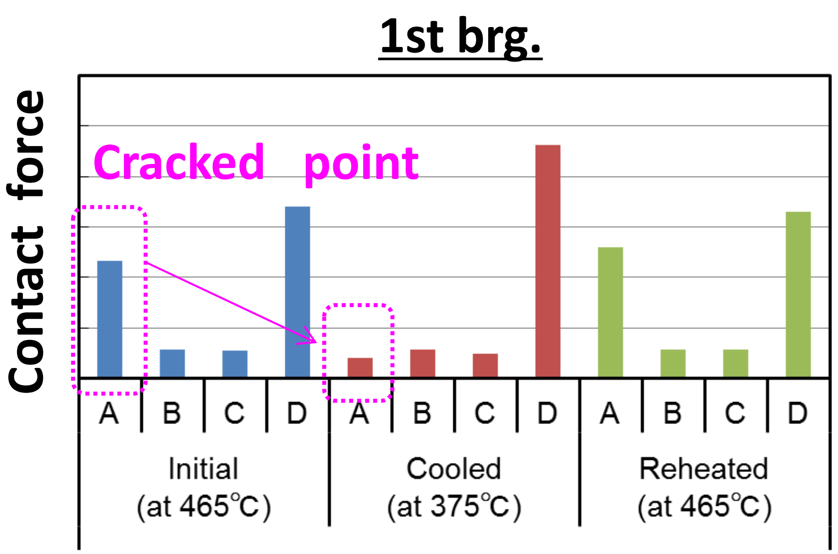


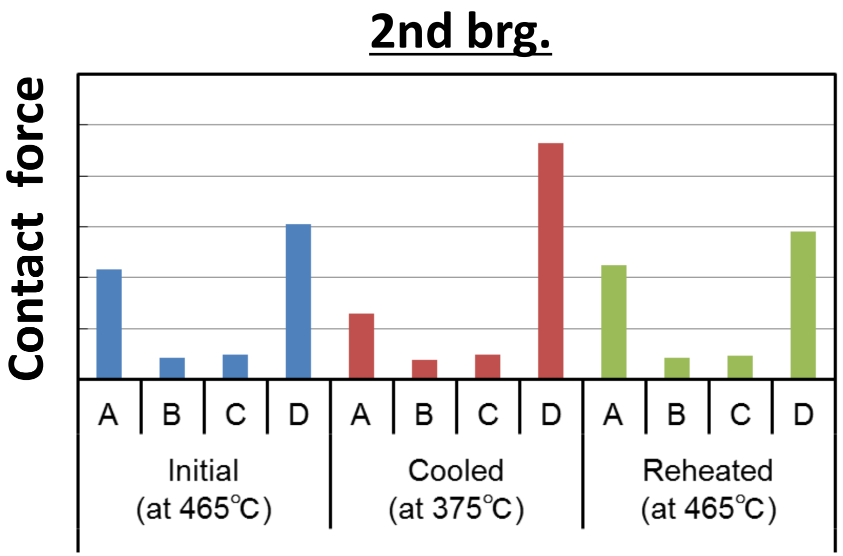
The contact area shifts from 1st bearing surface to 3rd bearing surface on end blades as temperature is reduced. Makes the end blades susceptible to vibrations.

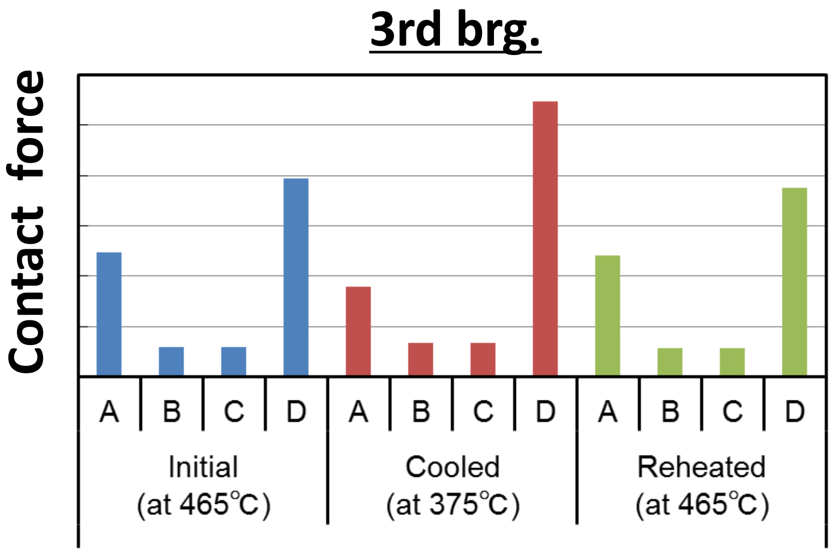
Contact force reduction

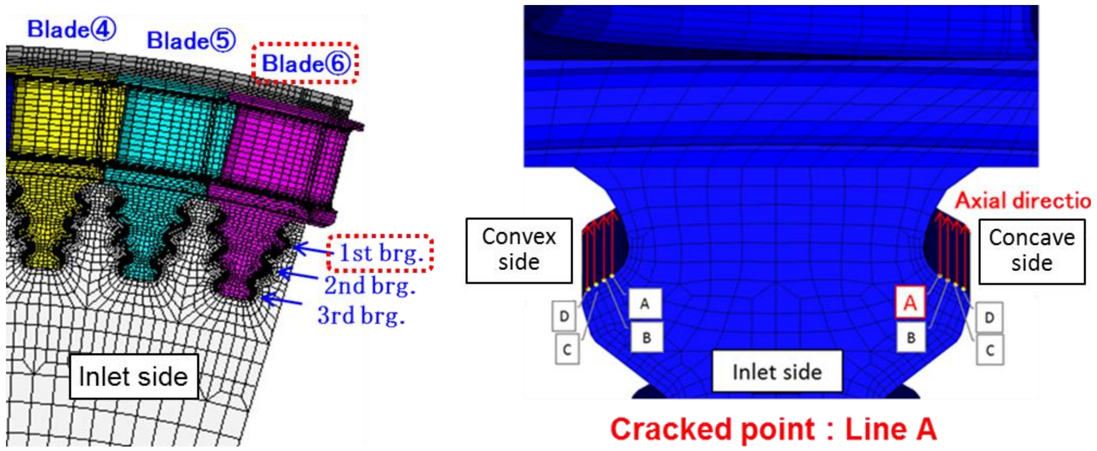
(Focused on first or last blade of shroud group)

- ✓ *At the 1st brg. Line A (cracked point), the contact pressure significantly reduce after steam cooled.*
- ✓ *After steam reheated, the contact pressure become nearly equal to initial condition again.*







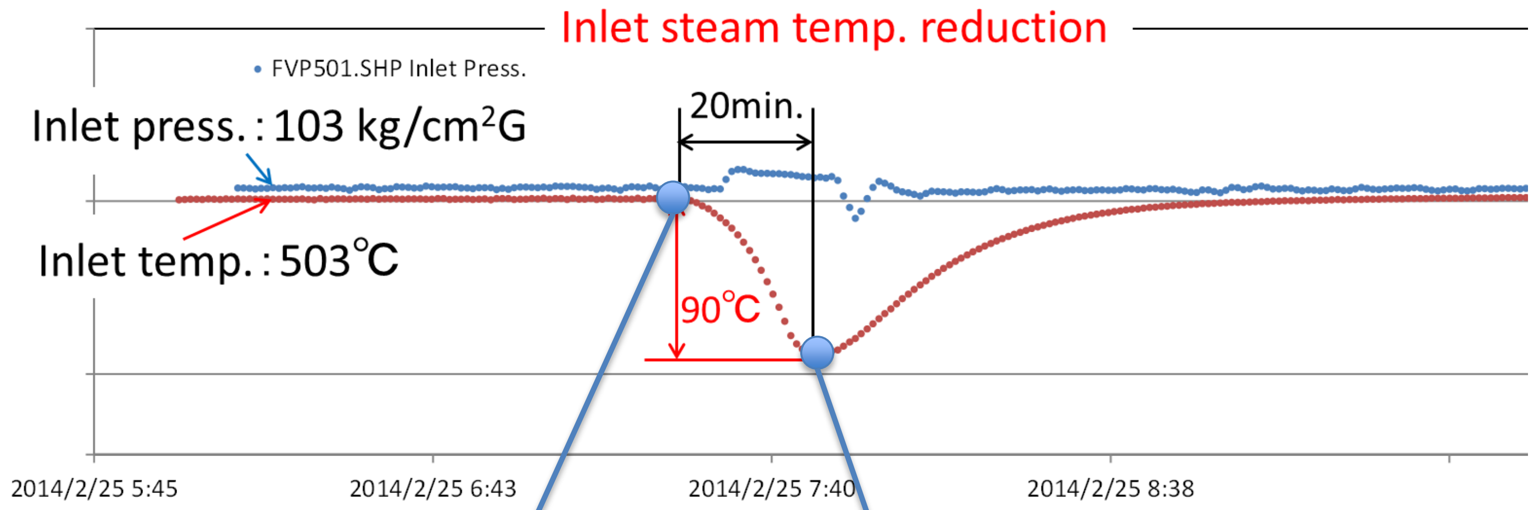


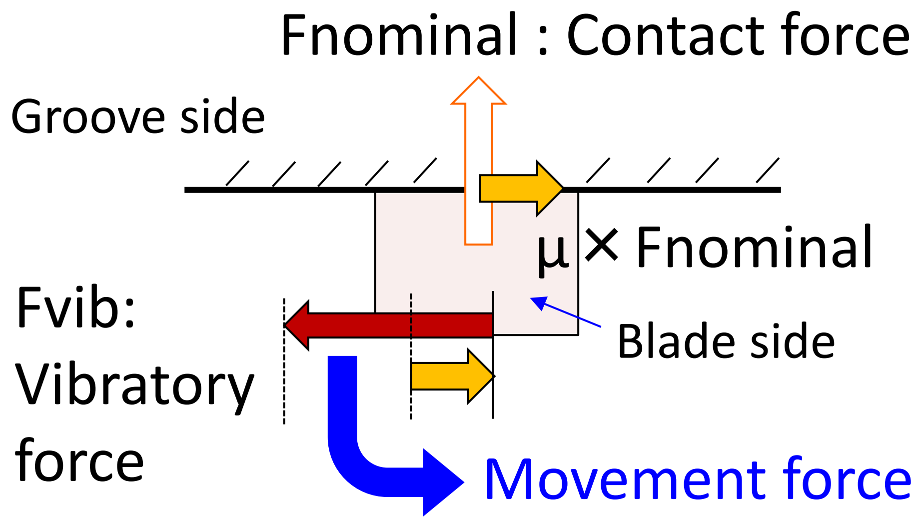
Average of contact pressure (at Blade⑥ / Concave side)

Slip evaluation result

(Focused on first or last blade of shroud group / 1st bearing)

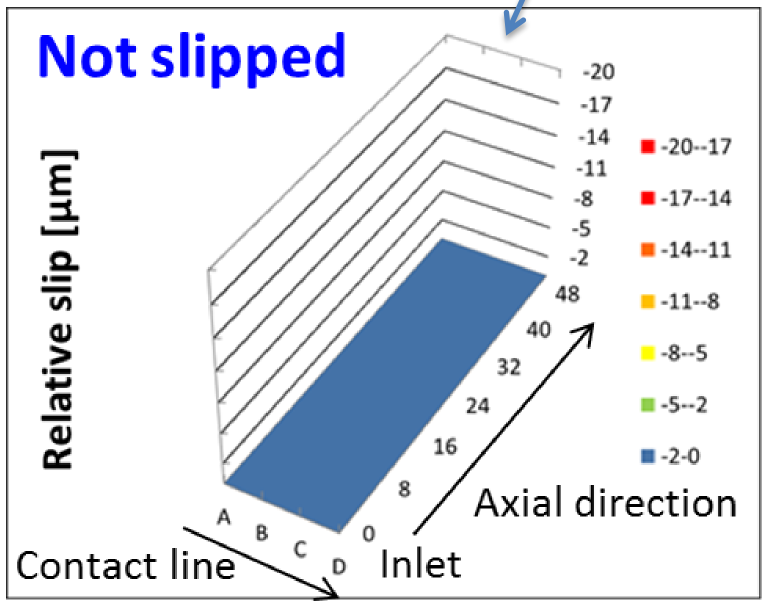
✓ *Slip between rotor groove and blade was possible as the vibratory forces exceeded contact force on blade root during temperature excursion event*



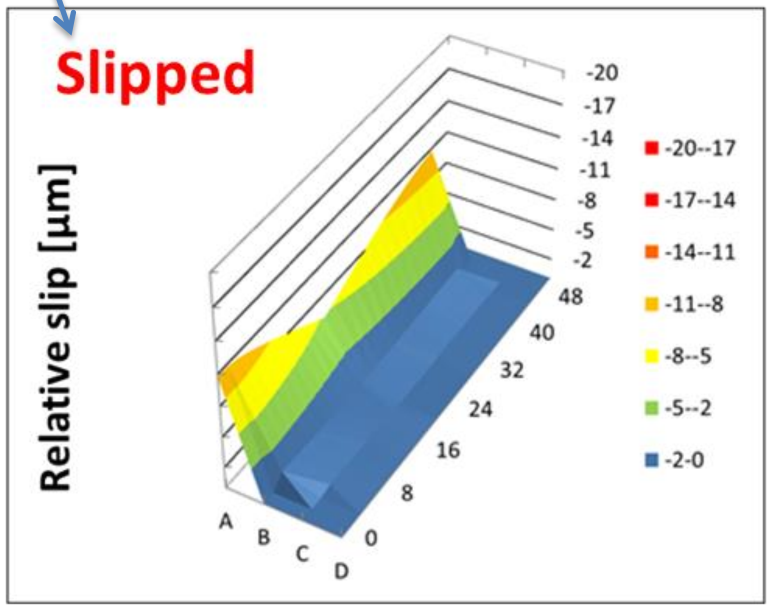


Fvib > μ × Fnominal ⇒	Slipped
Fvib < μ × Fnominal ⇒	Not Slipped

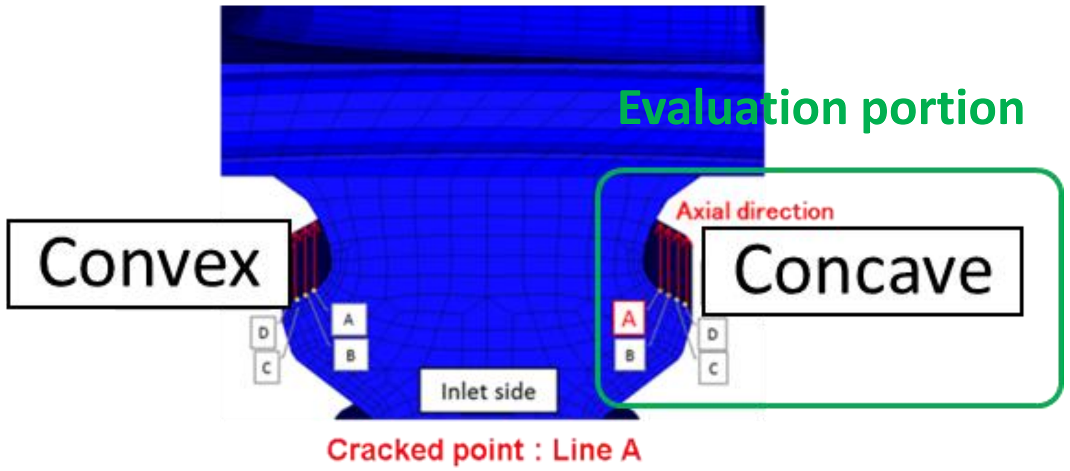
Steady state (0 sec)



90°C Reduction (1320sec)



Slip level of contact area



7. Fretting stress analysis (1/2)

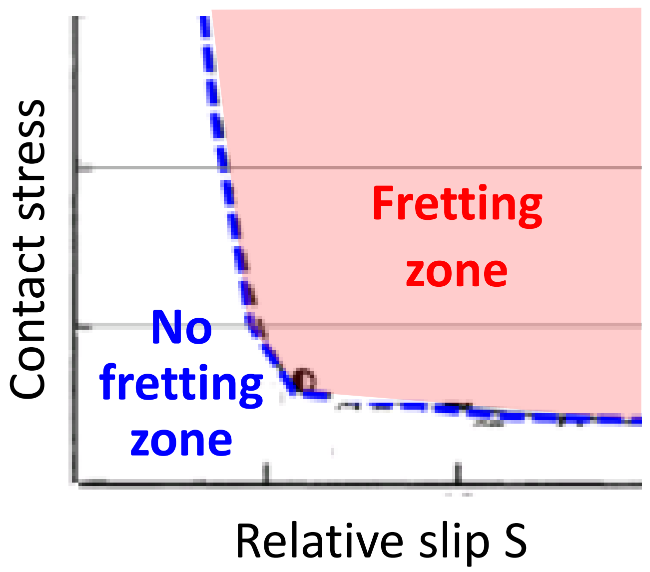
Fretting evaluation

Relative slip & contact stress is plotted on fretting criteria (based on experimental data in OEM).

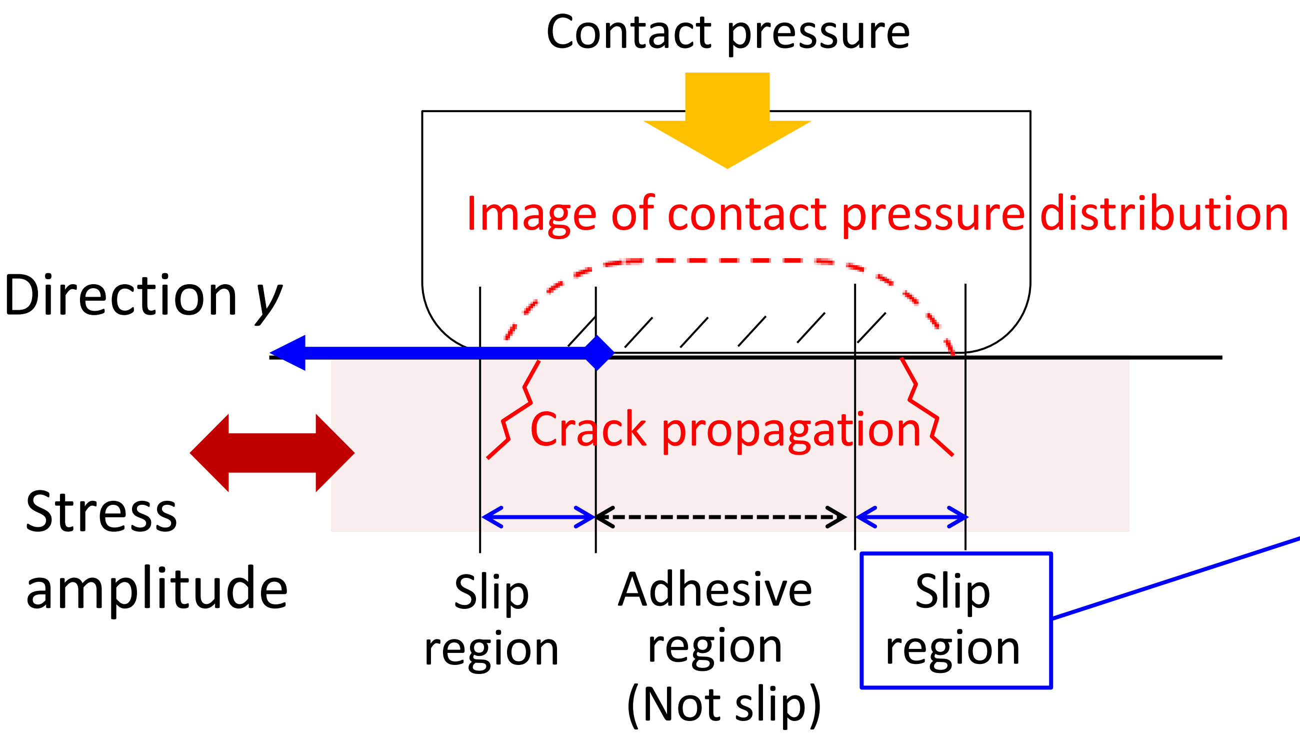
Relative slip S is,

$$S = \frac{(1-\nu^2)}{E}\int \frac{Fvib-\mu Fnominal}{Area}\,dy$$

Fretting map

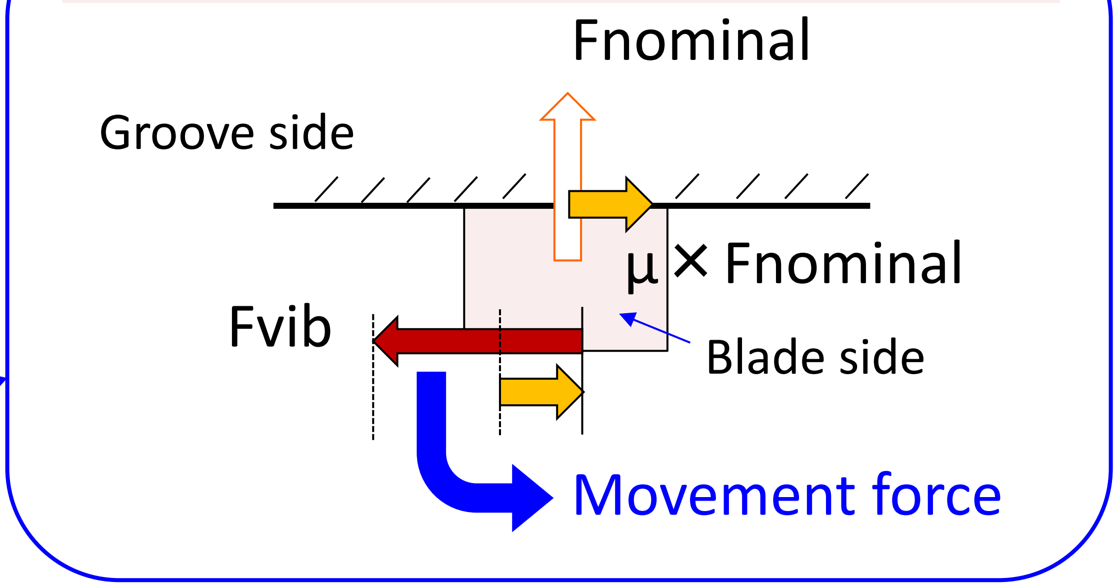


Schematic of fretting crack



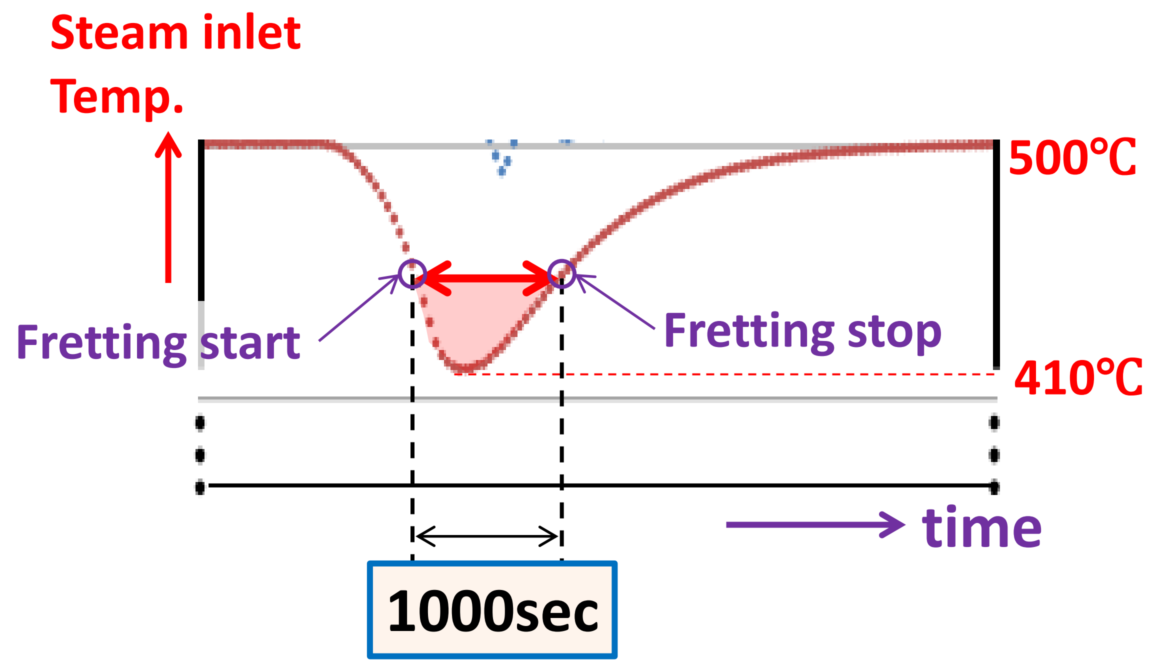
Fvib > μ × Fnominal ⇒ Slipped

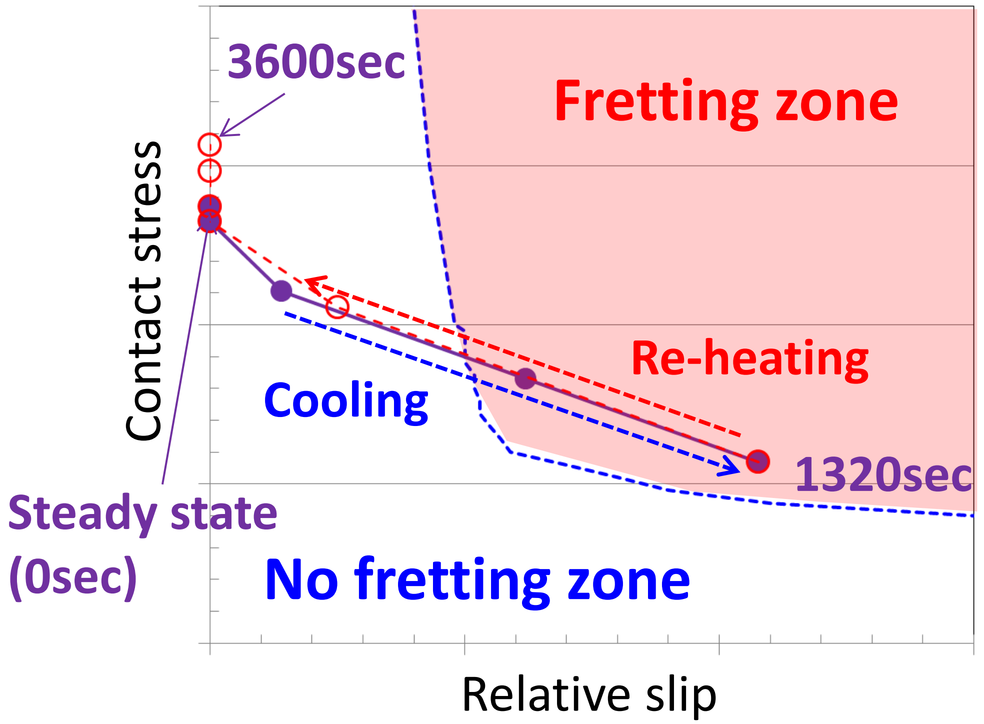
Fvib < μ × Fnominal ⇒ Not Slipped



7. Fretting stress analysis (2/2)

Result





Fretting estimated time : 1000sec

Dominant cycle : 157Hz = 4700rpm/60 × 2shock/round

⇒ Cyclic number : 1.6×10^5 cycles = 157Hz × 1000sec

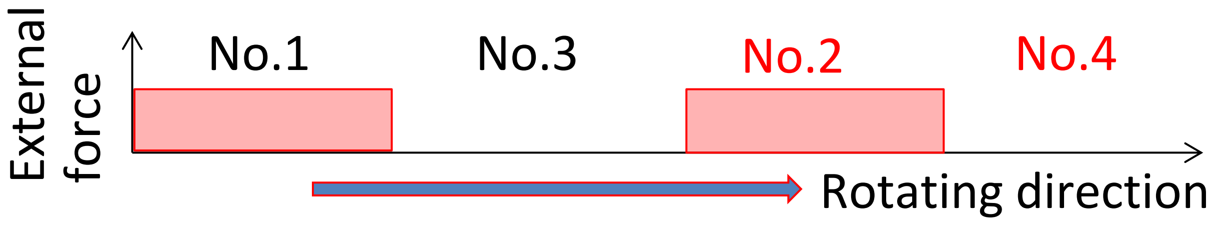
Commonly, cyclic number for fretting fatigue crack initiation is 10^4 ~ 10^5 cycle.

➡ Enough time to initiate fretting crack

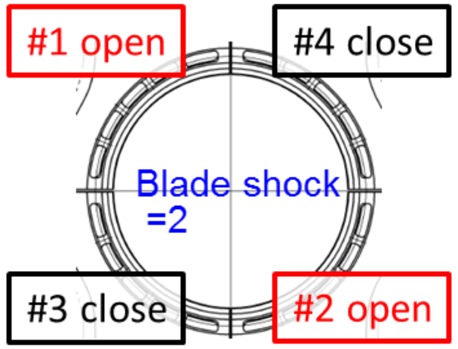
8. Solution to avoid fretting (1/2)

Vibratory stress can be reduced about 50% due to GV opening location change for No,2 and 4.

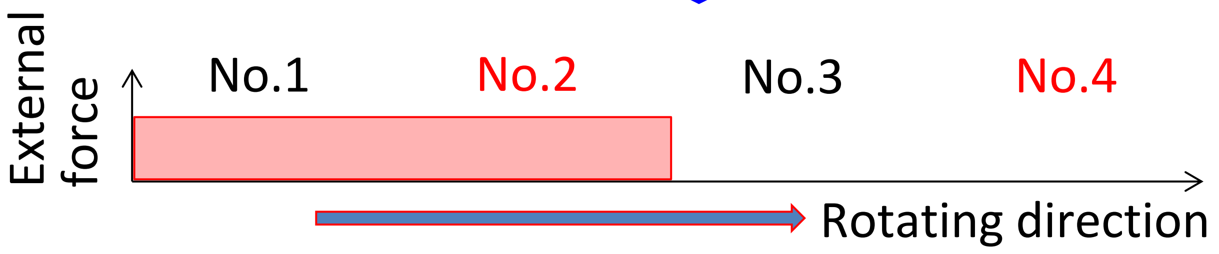
Original



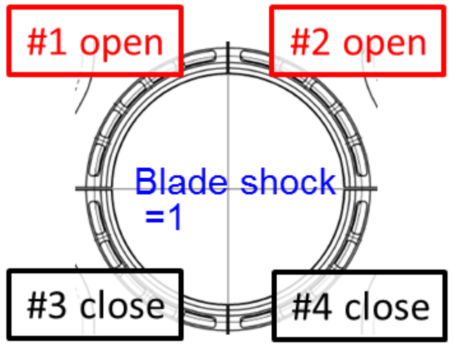
2 time external force occurs on blade during one rotation

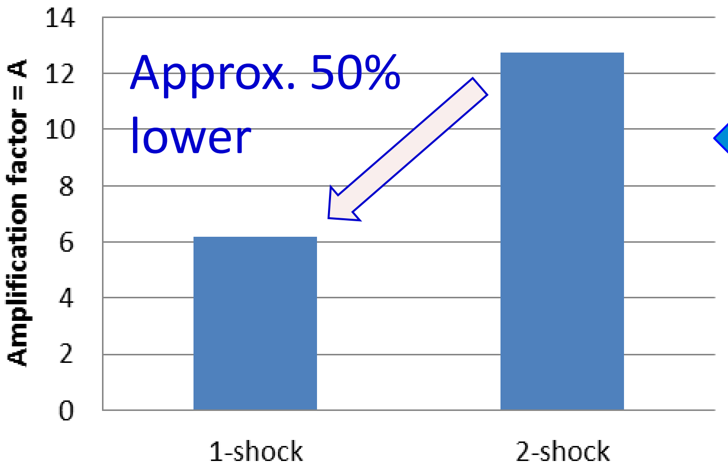


After modification



1 time external force occurs on blade during one rotation





FFT (Fast Fourier Transform) is applied to above stepped force

$\sigma v = A \times \sigma b$

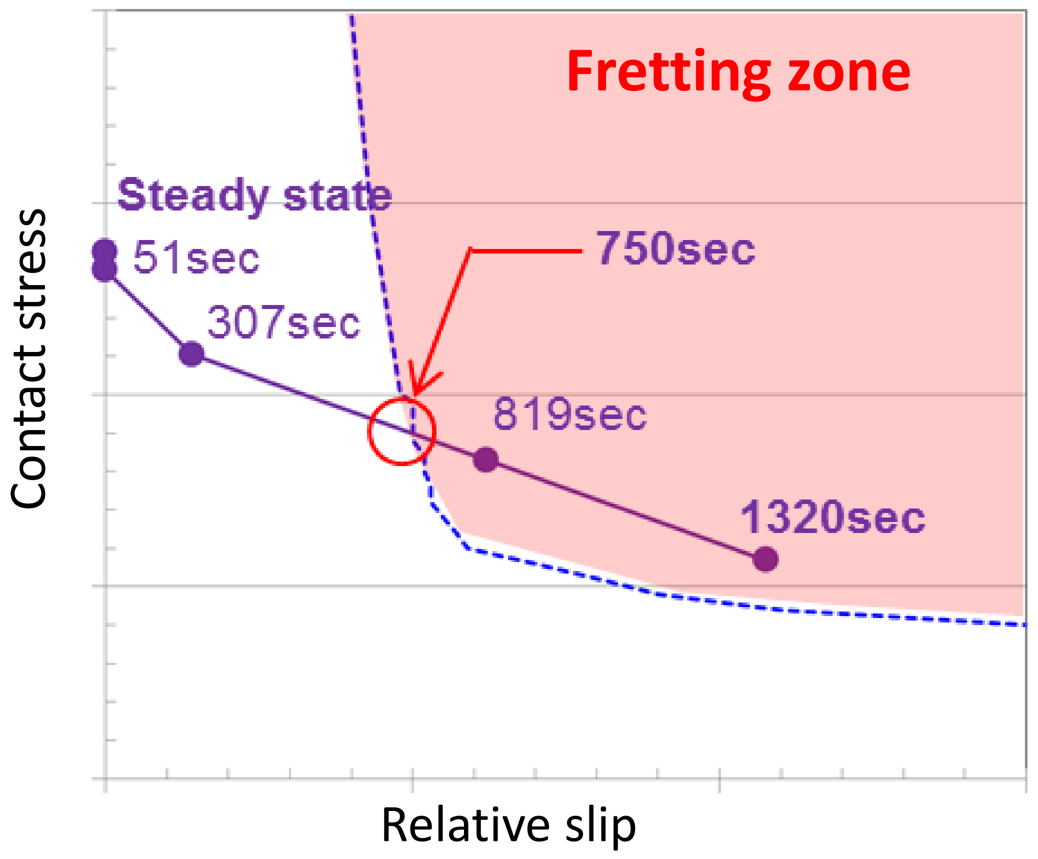
σv: Shock stress

σb: Bending stress

8. Solution to avoid fretting (2/2)

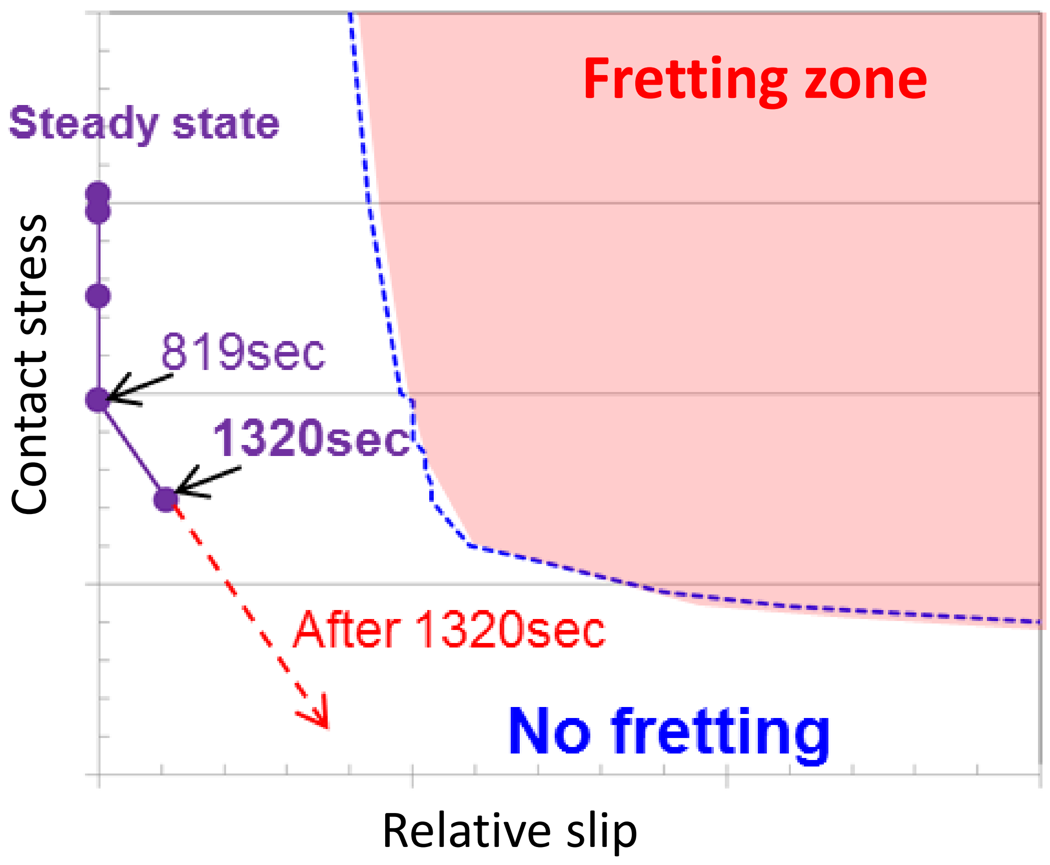
● Comparison of fretting evaluation

Fretting analysis result
Original case



Fretting occurs from 750sec

Fretting analysis result
Improvement case



Fretting does not occur.

9. Conclusion

1. Contact pressure at the origin of crack changed significantly during inlet steam temperature excursion.

2. Slip between rotor disk and blade was possible as the vibratory forces exceeded contact pressure on blade root during temperature excursion event.

3. Temperature event combined with number of cycles during low temperature excursion was adequate to cause fretting and to initiate fretting cracks.

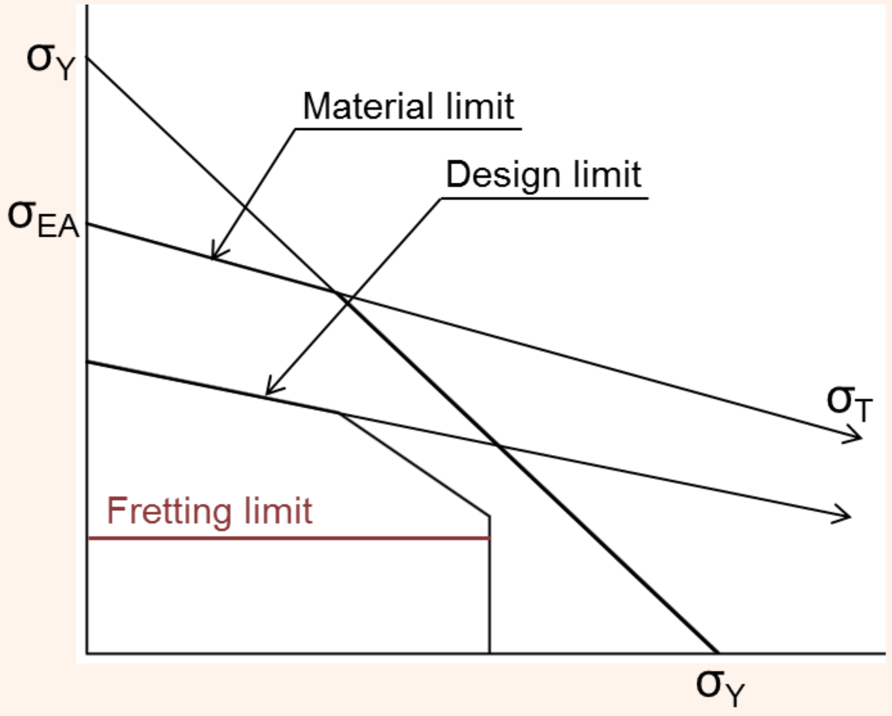
4. Reduction of contact pressure at the first/last blade of shroud group due to temperature change, and crack location are matching with the analysis result.

5. Vibratory stresses have to be reduced to be lower than contact pressure as a solution to avoid fretting. This was possible by modification of governing valve sequence in case of this turbine. Effect of change has been studied and model results show that fretting can be avoided even in case of temperature excursions by reducing vibratory stresses.

10. Lessons Learned

- Operation
  - ✓ Plant operation can have significant impact on performance of steam turbines. Stable temperature must be maintained for long term reliability.
- Design
  - ✓ Robust design should consider potential operation out of normal operating ranges.
  - ✓ Establish guideline for fretting on Goodman diagram to avoid fretting

Guideline for fretting on Goodman diagram



Where:

σY - Yield strength

σEA - Fatigue limit in pure steam

σT – Actual breaking stress

Thank you for your attention