ASIA TURBOMACHINERY & PUMP SYMPOSIUM
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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.

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1. Background and abstract information
2. Turbine specification and history
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7. Heat transfer stress analysis
8. Fretting stress analysis
9. Solution to avoid fretting
10. Conclusion
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1. Background information

Investigation of Steam Turbine blade failure

- First stage turbine blade failure was experienced in the Compressor drive steam turbine. This steam turbine is a back pressure turbine driving ethylene compressor in a cracker plant. Power rating is 17MW and normal operating speed is 4454rpm. Steam inlet conditions are 103 kg/cm^{2}G and 503 degree C with exhaust at 45 kg/cm^{2}G.

- Blade failure was found after the turbine has been in service about one year. The first stage blade root is a Fir tree design and fracture was located at the 1st bearing portion of blade root. This fracture surface showed high cycle low stress fatigue failure and multiple fretting marks were observed around the crack.

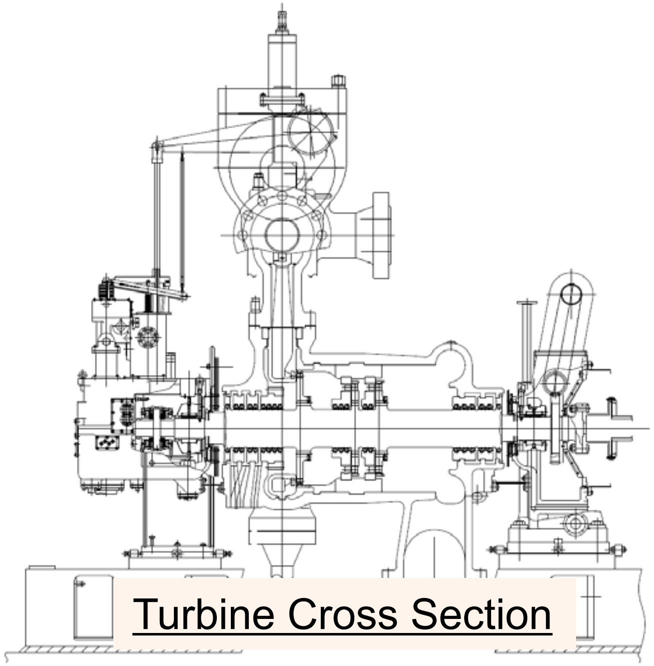
- Detailed analysis of design and review of operating conditions carried out. The operational data indicated that steam temperature went down significantly during one of the operating incidences. The temperature changed from approximately from 500 degree C to 410 degree C in roughly 20 minutes and then recovered to rated temperatures in approximately 30 minutes. This event had occurred approximately 1 month before the failure of the turbine blade.

- Detailed review of blade design was carried out. The effect of temperature excursion was studied in detail by FEM tools. Blade model and packeted design of the blades were developed. Analytical tools and methods were adopted to study impact of temperature change on the blade roots. Most of the tools focus on steady state conditions of operations; in this case rate of temperature change was modeled in the FEM analysis. The result show that contact pressure at the origin of crack changed significantly during inlet steam temperature excursion due to differential expansion between disk and blades. It was also found that micron level blade movement was possible as the vibratory force exceeded contact pressure on blade root during temperature change event. This was considered adequate to cause fretting and to initiate fretting cracks. Reduction of contact pressure at the first/last blade of shroud group, and crack location is good agreement with the analysis result.

- Vibratory stresses have to be reduced to be lower than contact pressure as a solution to prevent 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 blade slippage can be avoided even in case of temperature excursions. The turbine has been successfully operated for more than 1 year after modification.

- This presentation shows the detail analysis results and introduces method of resolving fretting fatigue issues in turbine blade.

2. Turbine Specification and history



Turbine Cross Section

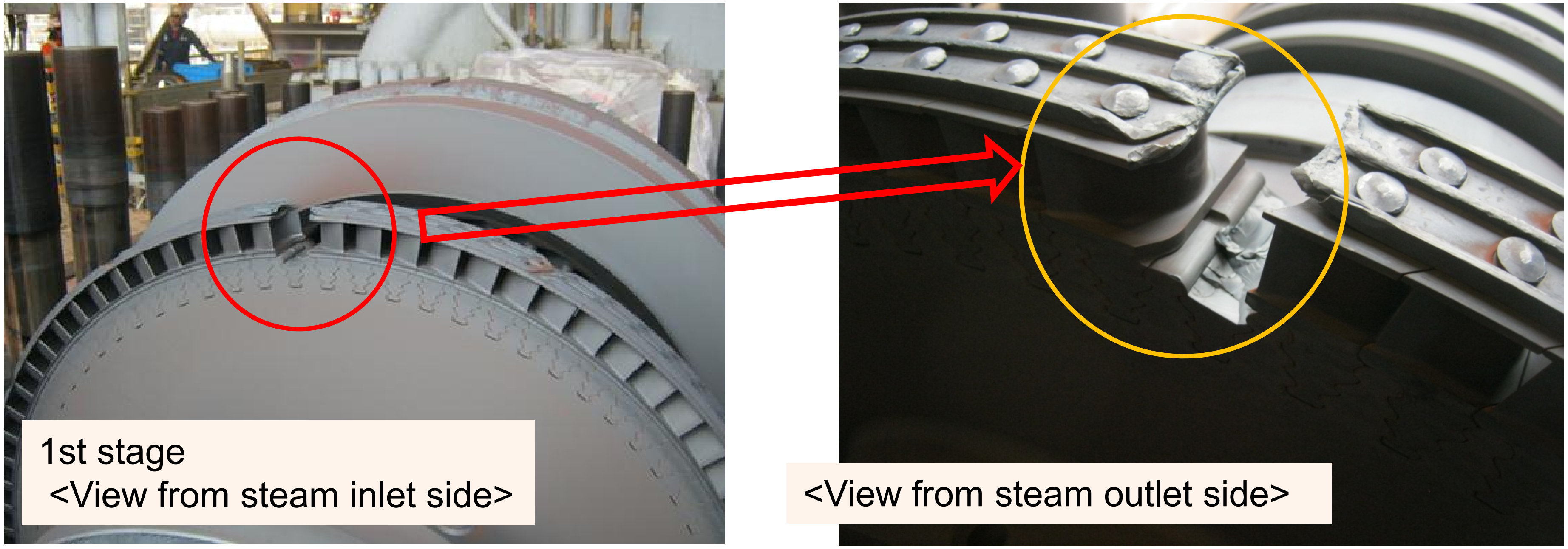
- Turbine specification
  - Back pressure turbine driving ethylene compressor in a cracker plant
  - Power : 17MW
  - Speed : 4117 – 5085 rpm
  - Normal steam inlet condition
    - Inlet : 103 kg/cm^2G , 503℃
    - Outlet : 45 kg/cm^2G
  - Plant start : from 2013

History

Run 1 (Working Rotor)	March 2014	• The Turbine trips on high vibrations after the turbine has been in service about one year • Restart attempted and unsuccessful due to high vibrations at low speeds. Decided to overhaul turbine.
Run 2 (Spare Rotor)	April 2014	• Turbine re-commissioned. Valve sequence changed.

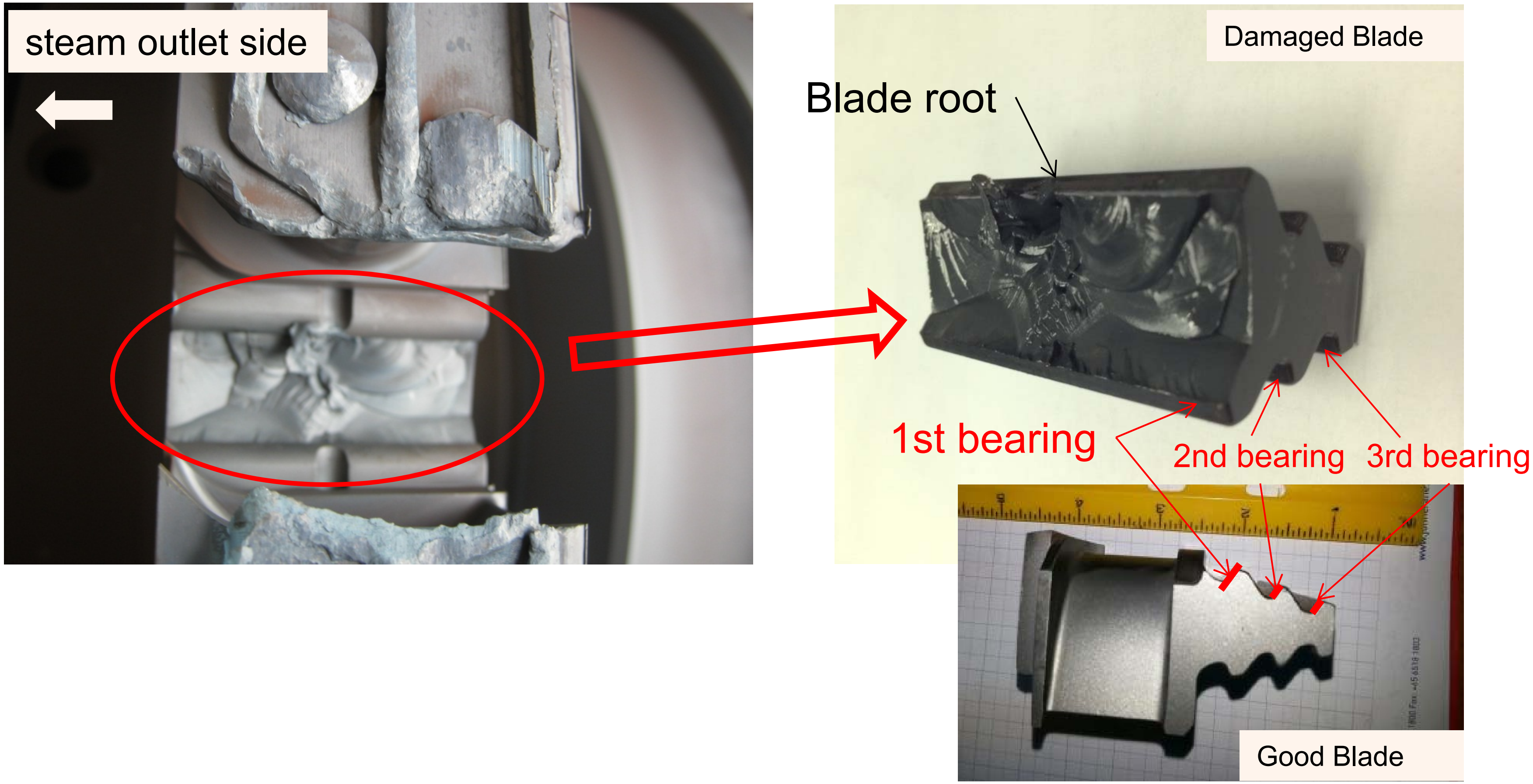
History Data of steam system indicates low temperature of steam conditions observed in Feb 2014

3. Observations during overhaul (1/3)



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

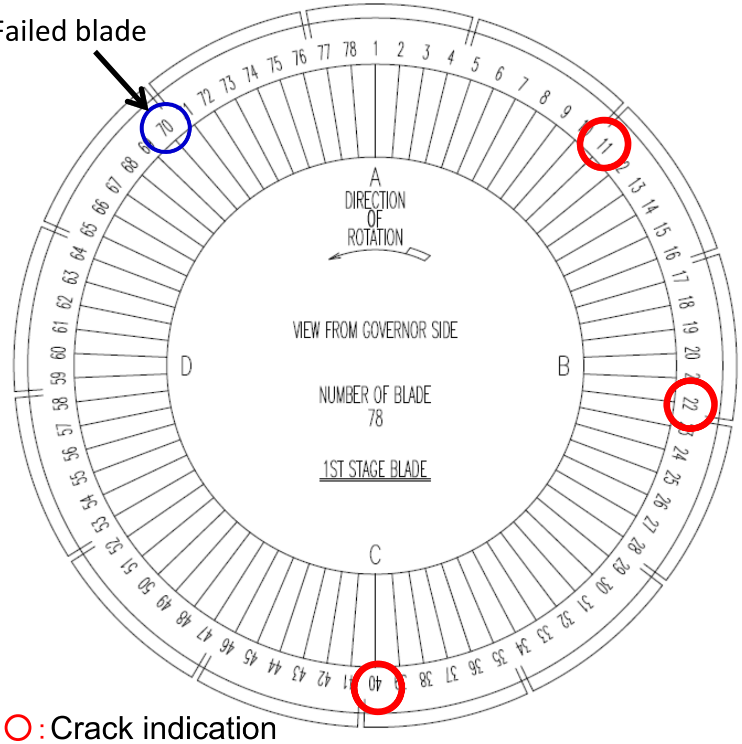
3. Observations during overhaul (2/3)



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

3. Observations during overhaul (3/3)

Failed blade



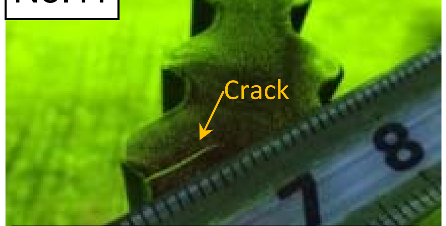
○ : Crack indication

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

No.70 blade root

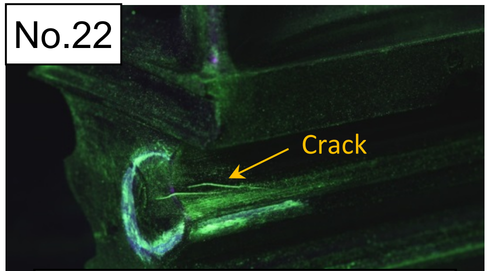
Failed blade was No.70 on blue colored circle part.

No.11



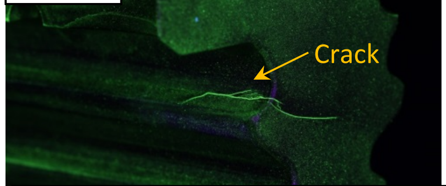
Convex side, Steam inlet side

No.22



Concave side, Steam inlet side

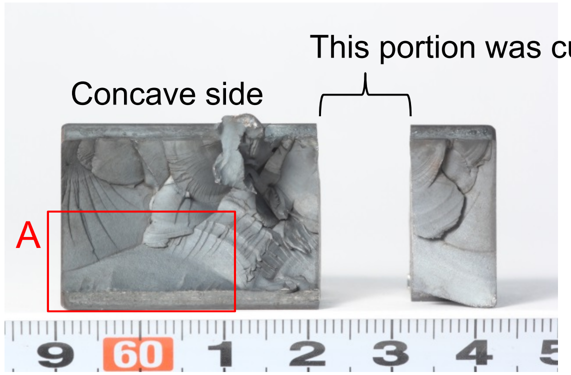
No.40



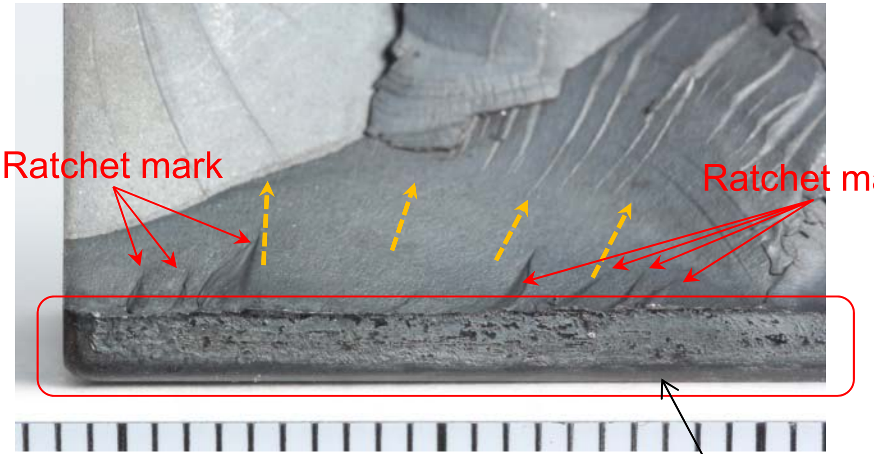
Concave side, Steam outlet side

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

4-1. 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.

4-2. 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.

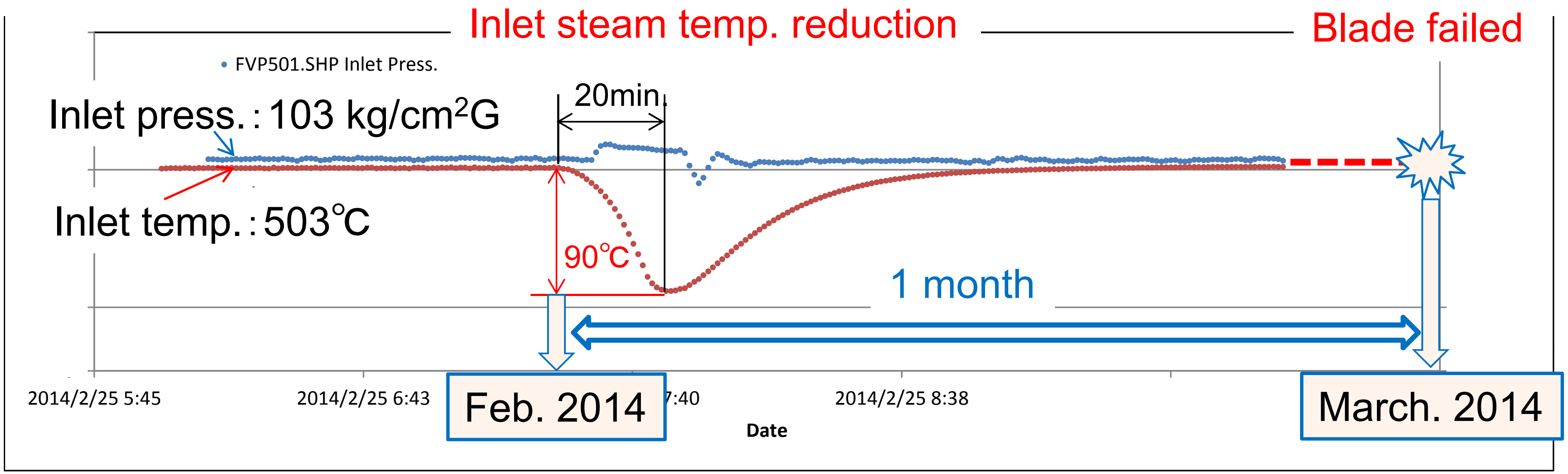
4)The failed blade steel is made of good quality.

5)No evidence of an external factor related to steam quality was found.

Fig.1 Fracture surface of No.70 blade

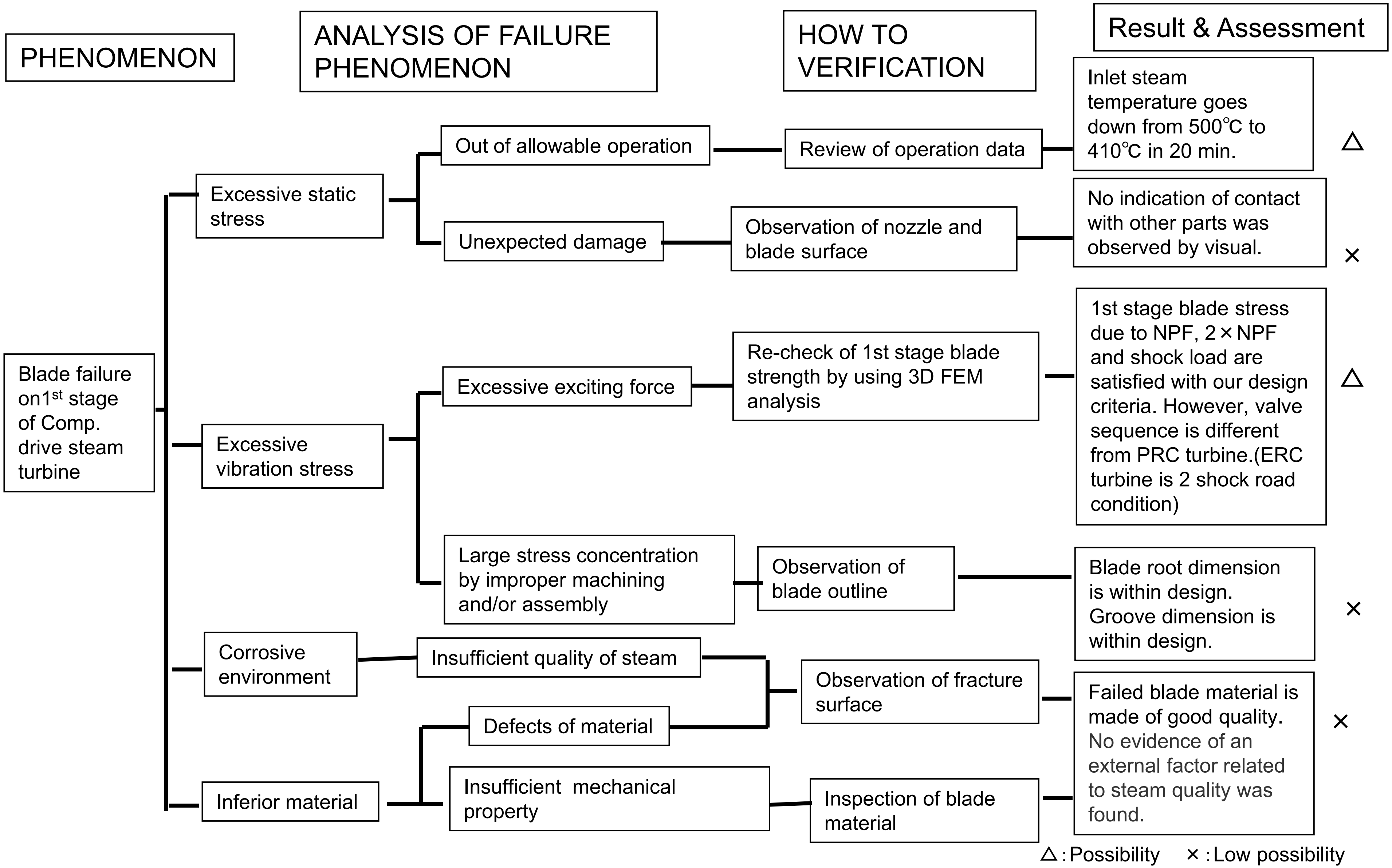
5. Review of operation data

- <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.

6. Possible cause (1/2)

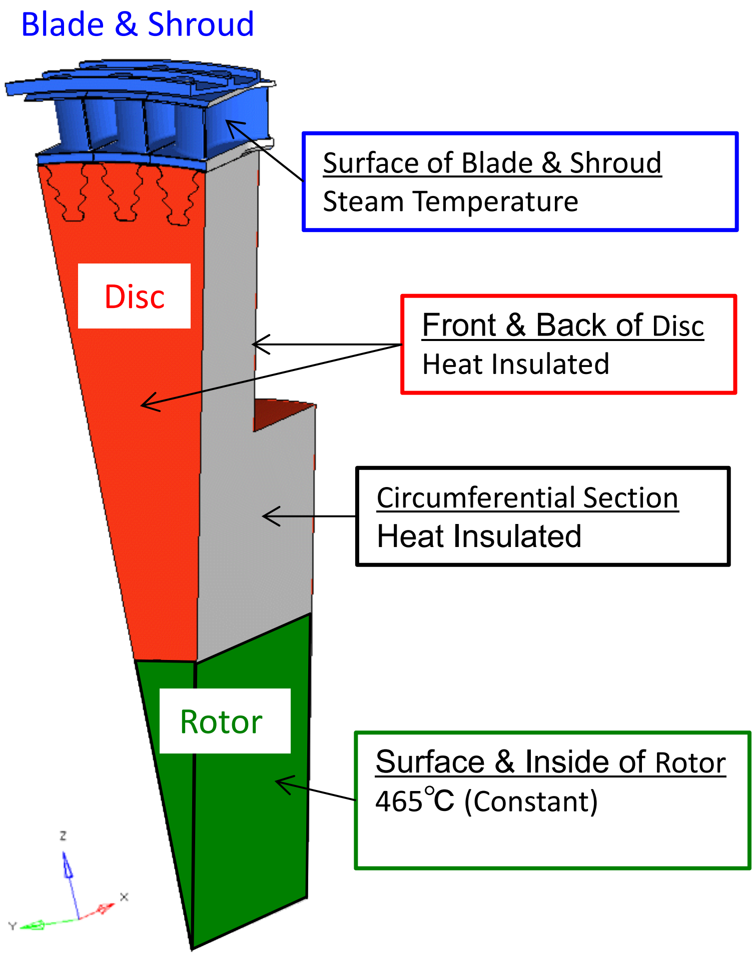


6. Possible cause (2/2)

	Operation	Stress	Fracture
Step 1	Steam inlet temp. 90°C reduction (-4°C/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

7. Heat transfer stress analysis (1/2)

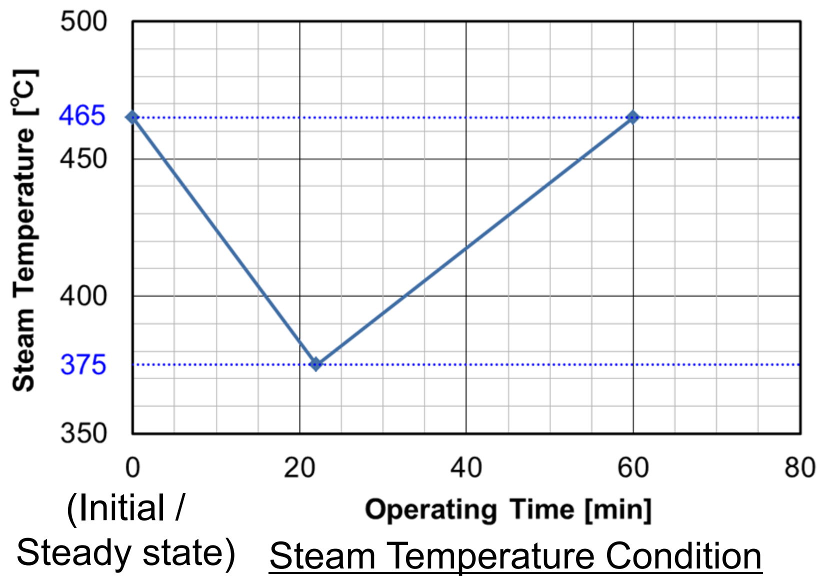
<Analysis Model>



Analysis Model & Thermal Boundary Condition

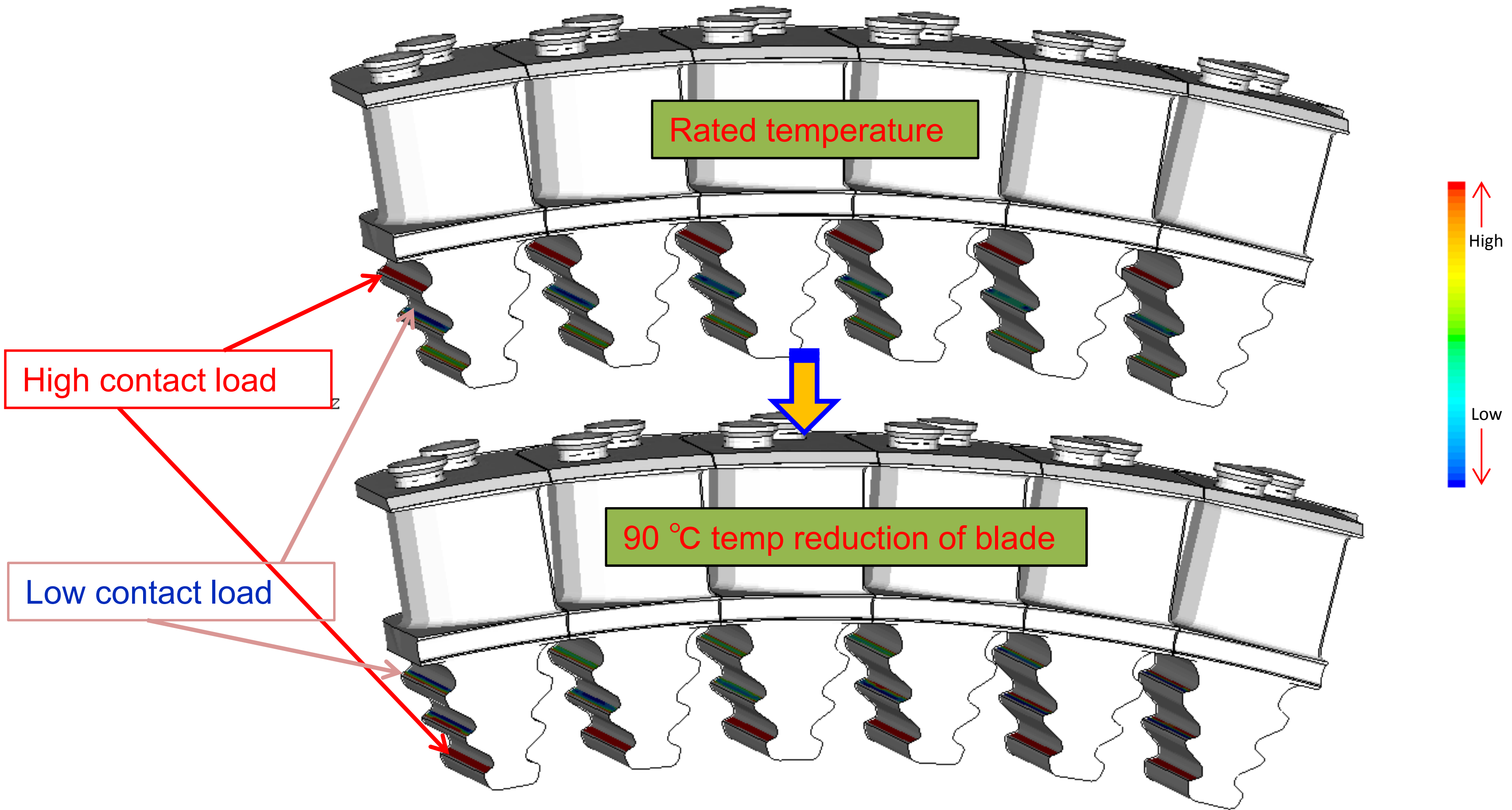
<Analysis condition table>

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

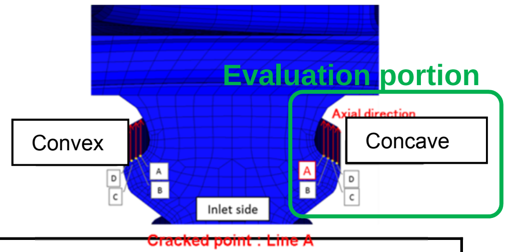
7. Heat transfer stress analysis (2/2)



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.

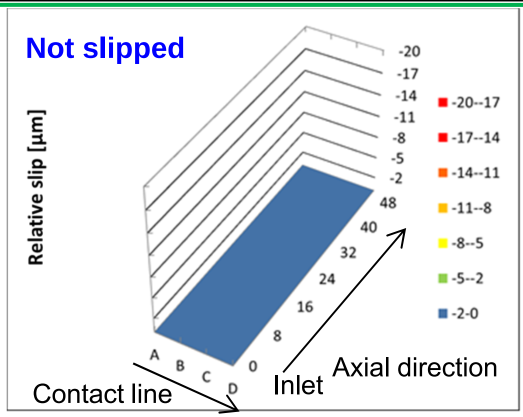
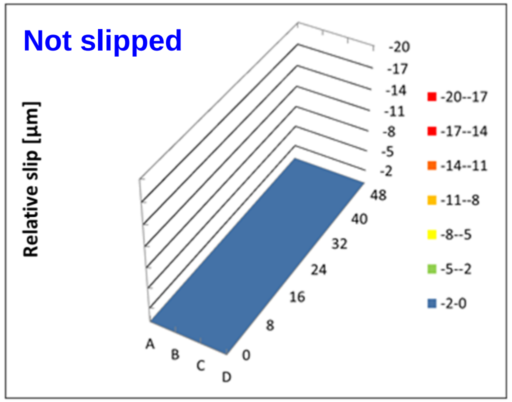
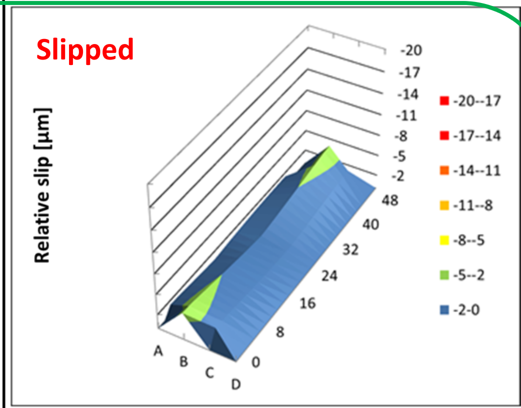
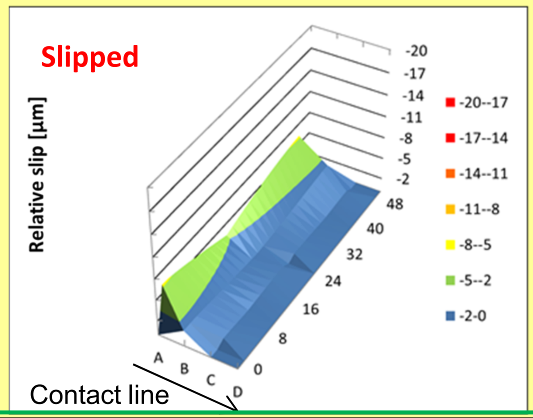
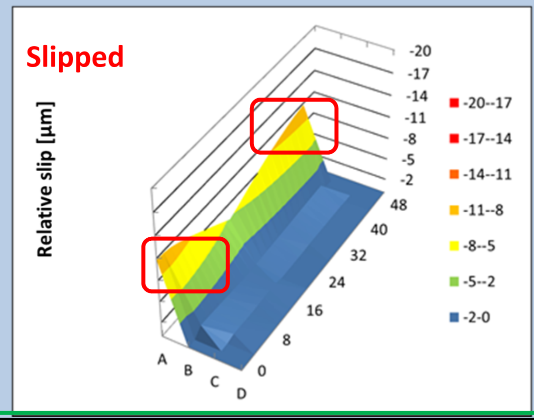
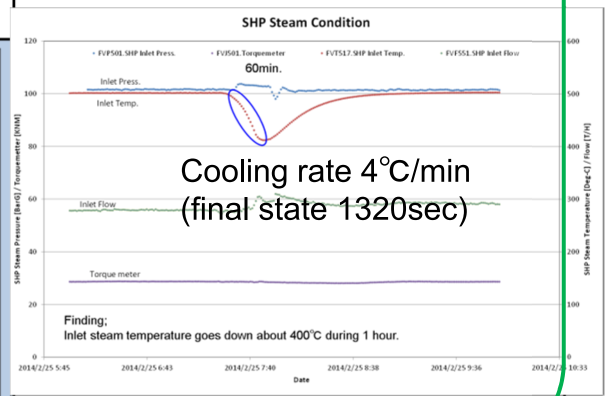
Slip evaluation result

- Relative slip occur at 307sec (cooling rate is 4 degree Celsius / min).



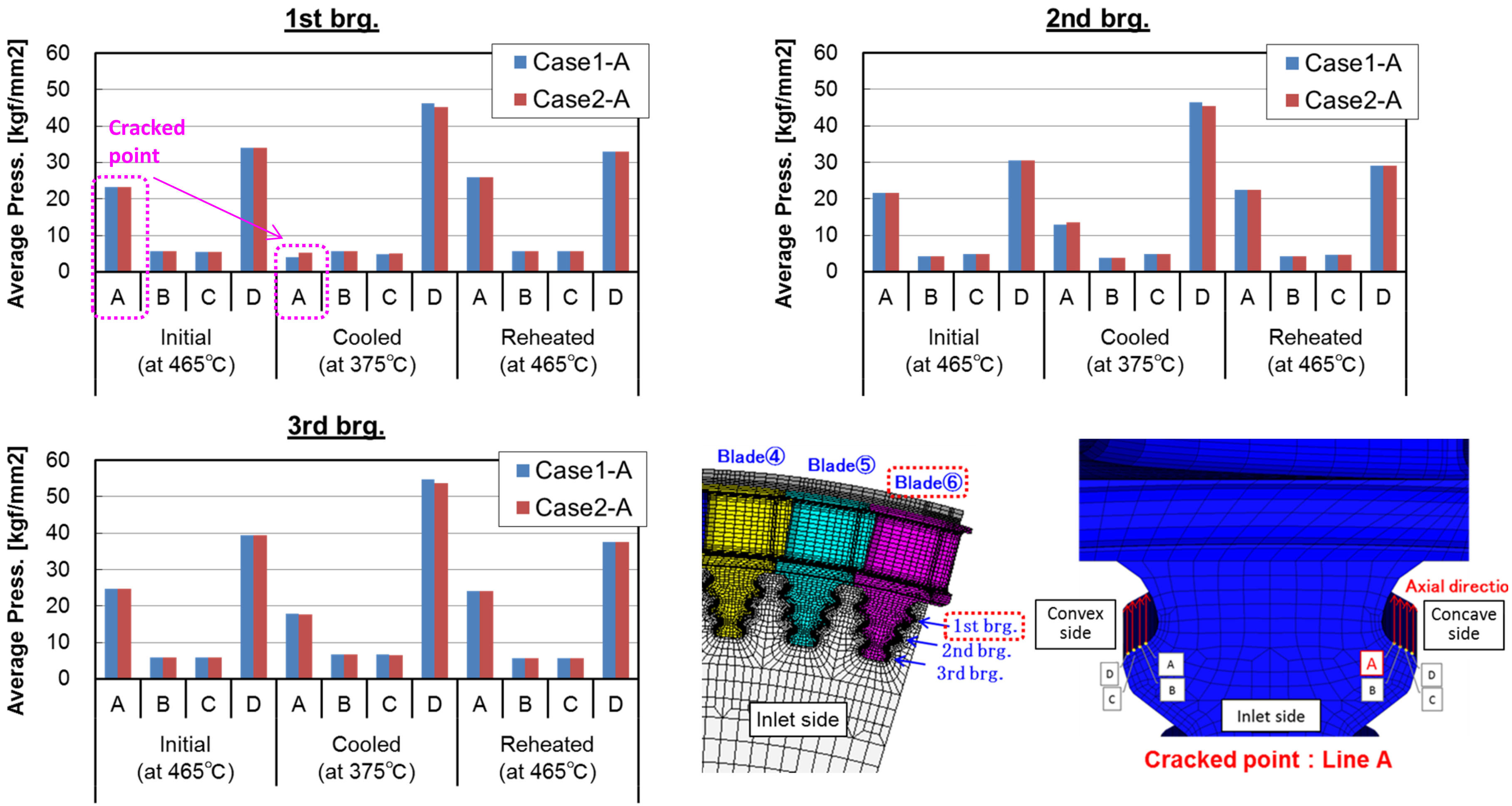
Slip level for contact area

Rotated speed: Normal speed.

<table>
<tr><td></td><td>Steady state</td><td>51sec</td><td>307sec</td></tr>
<tr><td rowspan="4">Concave side of blade ⑥</td><td>
</td><td>
</td><td>
</td></tr>
<tr><td>819sec</td><td>1320sec</td><td></td></tr>
<tr><td>
</td><td>
</td><td>
</td></tr>
</table>

Contact force reduction
(Focused on first/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)

8. Fretting stress analysis (1/2)

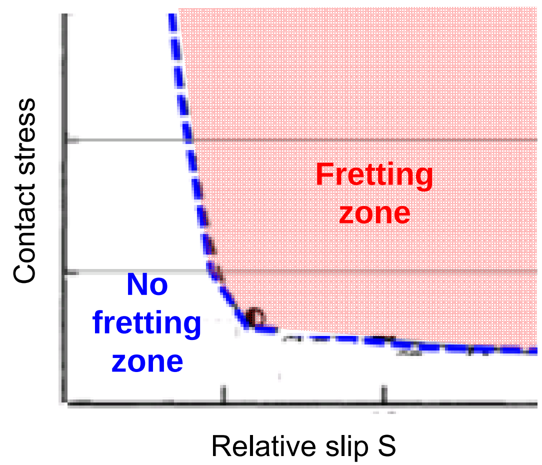
Fretting evaluation

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

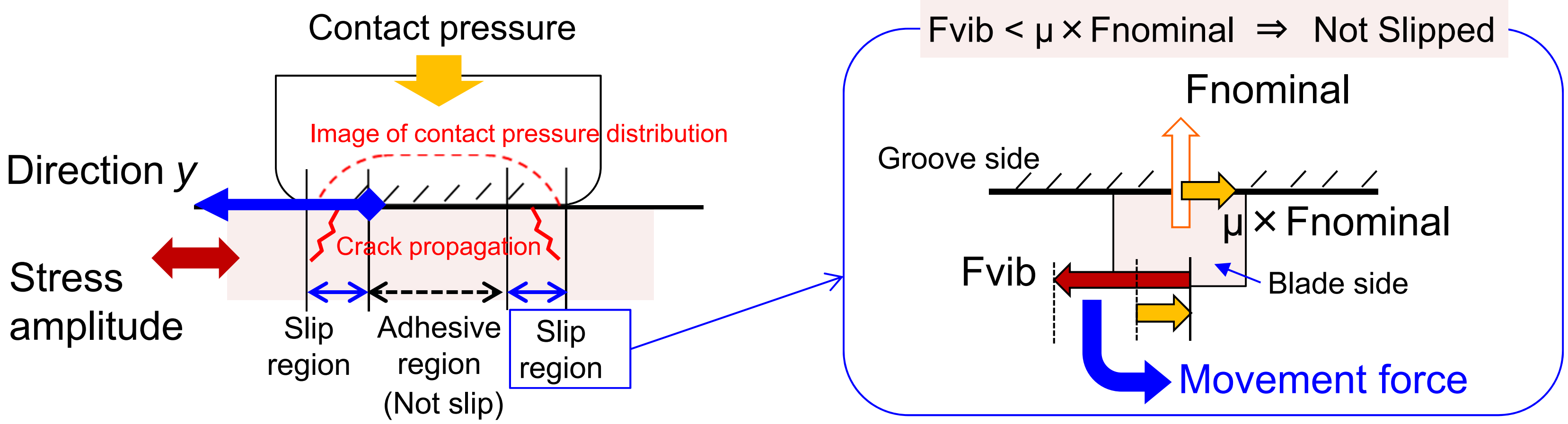
Relative slip *S* is,

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

Fretting map

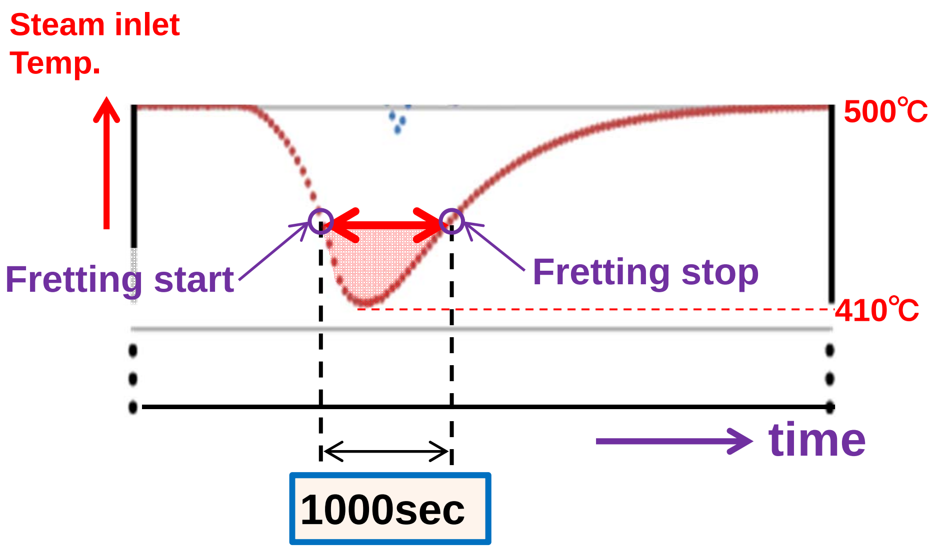


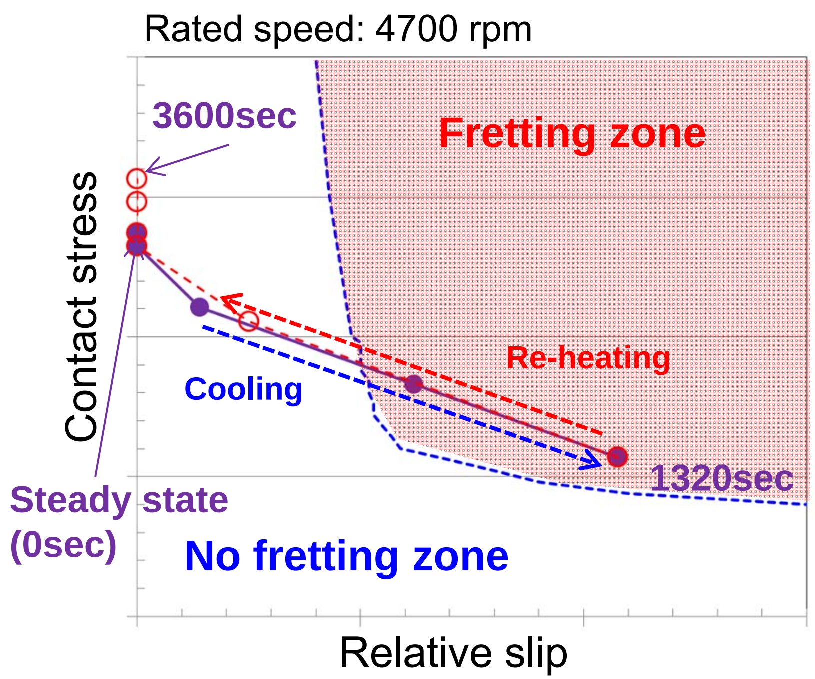
Schematic of fretting crack



8. 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

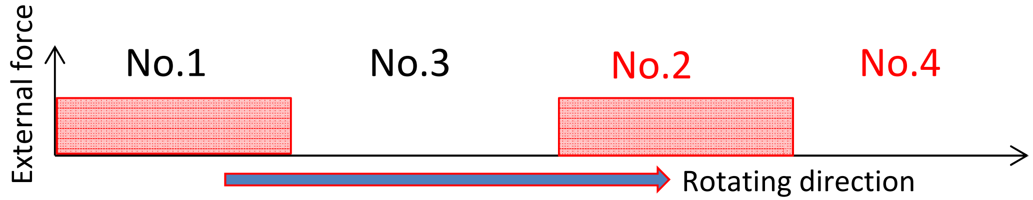
Commonly, cyclic number for fretting fatigue crack initiation is $10^4 \sim 10^5$ cycle.

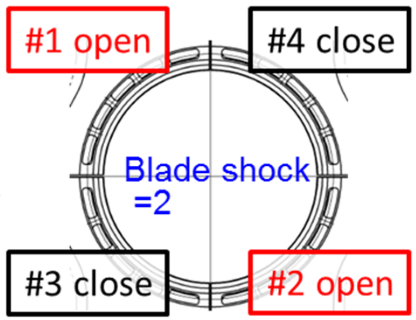
➡ Enough time to initiate fretting crack

9. Solution to avoid fretting (1/2)

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

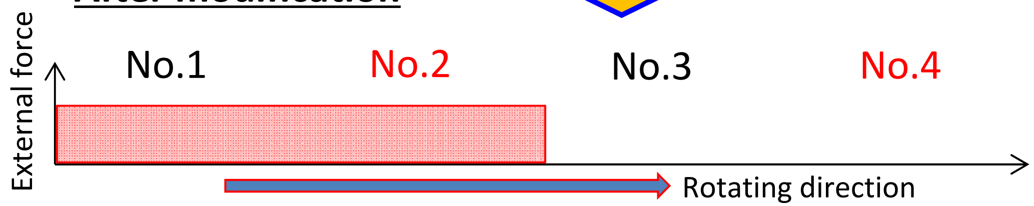
Original

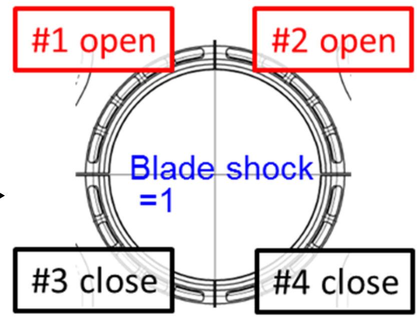




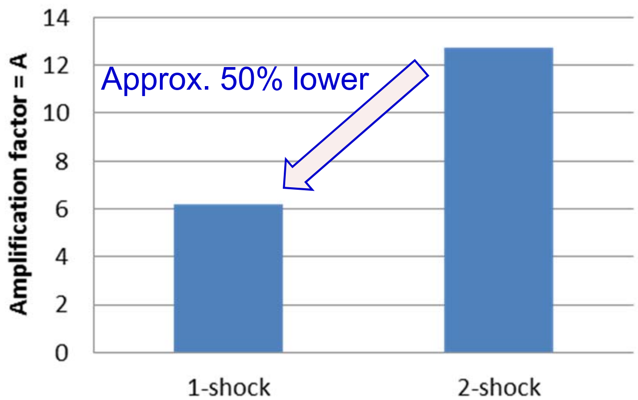
2 time external force occurs on blade during one rotation

After modification





1 time external force occurs on blade during one rotation



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

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

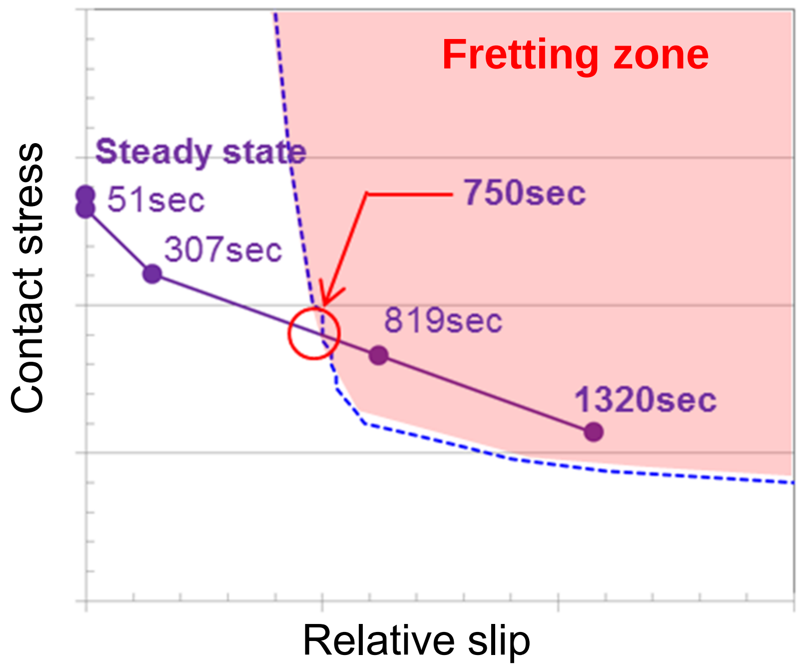
σv: Shock stress

σb: Bending stress

9. Solution to avoid fretting (2/2)

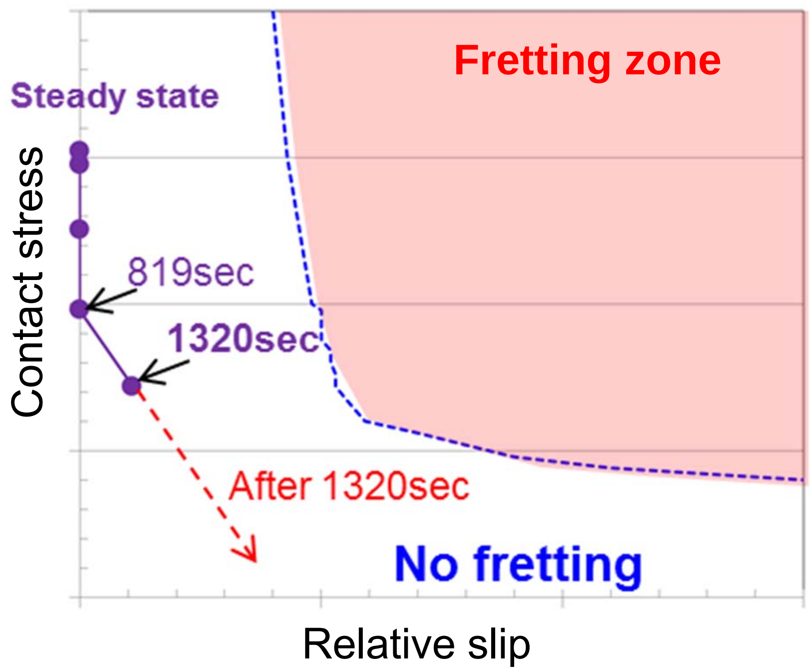
- Comparison of fretting evaluation

Fretting analysis result
Original case



Fretting occurs from 750sec

Fretting analysis result
Improvement case



Fretting does not occur.

10. 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.

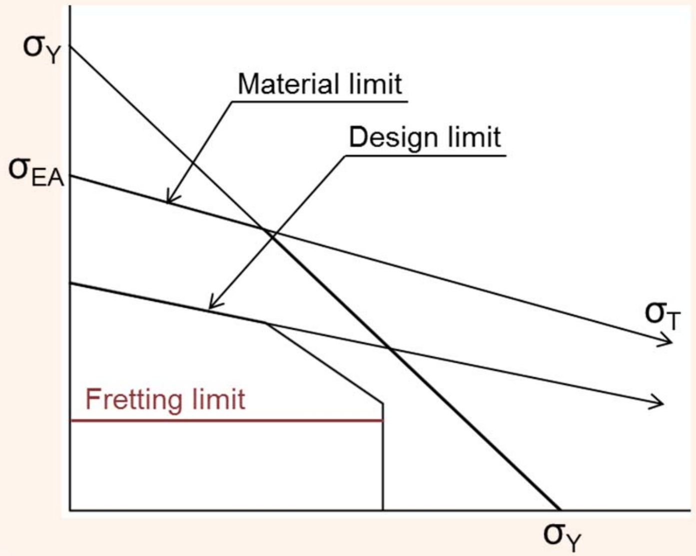
4. Reduction of contact pressure at the first/last blade of shroud group due to temperature change, and crack location are matching with the analysis result.

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.

11. 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